CIRCULAR CULVERTS AND STORM SEWERS

Ministry of Transportation Ontario
Highway Design Office
St. Catherines, Ontario

September 2005
FOREWORD

These guidelines were prepared by Golder Associates Ltd. with continuous involvement from a Ministry of Transportation Ontario (MTO) Steering Committee and an Ontario pipe industry Advisory Committee, under Agreement No. 9015-A-000191. The guidelines provide information and establish general procedures to assist in the roadway drainage design functions for Ministry of Transportation Ontario projects. It is neither intended as, nor does it establish, a legal standard for these functions. The design methods and information contained herein are for the guidance of Ministry personnel and their design consultants; they are subject to amendment as conditions and experience warrant. The guidelines were based on existing information obtained from current literature supplied by industry representatives, from a separate literature review and review of pipe selection practices in Ontario and in other jurisdictions. No new research or site specific field investigations were undertaken as part of the development of these guidelines. The guidelines are not a substitute for engineering knowledge, experience, or professional judgment, which shall govern the applicability of using these design guidelines on a case by case basis.

DISCLAIMER

The MTO Gravity Pipe Design Guidelines (the guidelines) have been developed for use by the Ministry of Transportation of Ontario for its provincial roadway projects. Other prospective users should determine for themselves whether the guidelines are applicable to their practices before they make use of them. The responsibility for the decision to use the guidelines rests with the practitioners. Golder Associates Ltd. expressly disclaims responsibility for any inaccuracy or error which the guidelines may contain or for the fitness of the guidelines or the validity of the information contained in the guidelines for any particular purpose, or for any damage or loss which any person may suffer as a result of reliance upon any statement which the guidelines may contain.

ACKNOWLEDGEMENTS

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BACKGROUND

The design and material type selection of relatively small diameter gravity pipe (i.e. culvert and storm sewer pipe) on Ontario Provincial highways has not received much attention. In the early 1980’s, the MTC Drainage Manual was developed to assist highway designers in the hydraulic design of gravity pipe. The MTO Drainage Management Manual was the update of this manual in 1997 and is regarded as the basis for establishing pipe size for gravity pipe applications for Ontario highways.

An internal review of current Ministry guidelines and practices revealed a lack of uniformity and supporting logic in the use and selection of relatively small diameter gravity pipe types. It indicated a lack of awareness among designers of the technological advances in the pipe manufacturing industry, and misconceptions with respect to pipe performance and in the selection of appropriate materials. In the mid 1990’s an attempt was made, initiated by industry and supported by the Ministry of Transportation Ontario (MTO), to develop a gravity pipe selection guide. However, this initiative was subsequently abandoned due to an inability to obtain consensus.

In 2003, the MTO, with the support of the pipe industry, retained Golder Associates Ltd., under Agreement No. 9015-A-000191, to develop gravity pipe design guidelines and an associated software design package. The guidelines are the result of cumulative information from five component tasks/reports provided to MTO as part of this assignment. The component tasks/reports summarize: a review of current practice in other jurisdictions and transportation authorities in North America, Europe and Australia; a review of current MTO guidelines and practices; and a review of available literature and software programs. The scope of the literature review included pipe structural and hydraulic design, risk factors, pipe material service life, life cycle costing and cost/benefit methodologies that are used for the selection of suitable pipe material for gravity pipe applications. The results of the research were summarized in progress reports that formed the basis of these guidelines.

Although Golder Associates managed the assignment to develop the guidelines, the work was completed as a team with active involvement from the MTO Steering Committee and the pipe industry Advisory Committee. Comments and edits were received from both committees on an on-going basis and relevant information was directly incorporated into the guidelines. Frequent progress meetings were held, with both MTO and industry representatives present, over a two year period so as to achieve consensus on the final design guidelines. The overall objective was to present a selection process that was technically sound and provided an equal opportunity for all pipe products to be considered and evaluated.

It should be noted that the guidelines will be subject to revision on an on-going basis, as new research, field experience, and data become available. It should also be noted that the guidelines only address gravity pipes that are circular in cross section and are less than 3 m in diameter. Pipes with a span/diameter greater than 3 m shall be
designed using the procedures outlined in Section 7 “Buried Structures” of the Canadian Highway Bridge Design Code (CHBDC) and are outside the scope of these guidelines.

INTRODUCTION

The guidelines are intended for use on MTO projects to provide a rational process for the evaluation of various pipe materials for culverts and storm sewer applications. These guidelines are intended to aid the designer in selecting appropriate and cost-effective pipe material type options for specific applications and site locations.

The guidelines only address gravity pipes used within provincial highway rights-of-way, that are circular in cross section and less than 3 m in diameter. The guidelines should be used in conjunction with the MTO Drainage Management Manual (1997) for culvert and storm sewer applications. In cases of discrepancy, the methods and practices outlined in the MTO Drainage Manual shall govern. In addition to these guidelines and the MTO Drainage Management Manual, the designer must also be familiar with the requirements of the MTO Contract Design Estimating and Documentation (CDE&D) manual, Ontario Provincial Standard Specifications and Drawings, Construction and Material Specifications, Standard Special Provisions, and the Occupational Health and Safety Act.

In the interests of achieving best long term value for investment, all available pipe materials should be considered in a systematic manner for all culvert and storm sewer applications. The pipe materials to be considered comprise of those manufactured from concrete, steel, high density polyethylene, and polyvinyl chloride. The evaluation should consider functionally equivalent performance in three areas: durability, structural strength, and hydraulic capacity. The list of pipe alternatives that meet the above functional requirements can be included as acceptable pipe materials and types in contract documents. In addition, strategies such as pipe replacement by conventional means or by re-lining can be evaluated using a Life Cycle Cost comparison. If alternative strategies have lower net Life Cycle Costs, these alternative strategies can be chosen, subject to an assessment of the risk factors, and specified in contract documents. The objective is to facilitate selection of the most appropriate and cost-effective pipe material(s) and strategies for a particular application and site condition.

These guidelines are organized into nine chapters, as follows:

1. Design Procedure
2. Project Description/Evaluation
3. Environmental Considerations
4. Site Geotechnical/Physical Characteristics
5. Hydraulic Evaluation
6. Structural Design Evaluation
7. Durability Design Evaluation
8. Life Cycle Cost Analysis (LCCA)
9. Pipe Alternatives

The first chapter (Design Procedure) provides an overview of a step-by-step process that the designer can follow to select the appropriate pipe material type(s) for a specific project or site location. The remaining chapters provide background information about each step of the design procedure and the risks that designers should consider when selecting appropriate pipe material types. Specifically, Chapters 2 through 4 (Project Description/Evaluation, Environmental Considerations, and Site Geotechnical/Physical Characteristics) provide a discussion of pipe material types, application, manufacture, installation, and construction. Chapters 5 through 7 (Hydraulic Evaluation, Structural Design Evaluation, and Durability Design Evaluation) provide the designer with a description of the important parameters and general design procedures for each of the four basic pipe material types. The hydraulic and structural design components are well established procedures that are currently used in Ontario. However, the durability design chapter provides recent information and presents some new design methodologies that need to be incorporated into gravity pipe design. These chapters identify appropriate pipe materials and sizes for further analysis, as required. Chapters 8 and 9 (Life Cycle Cost Analysis and Pipe Alternatives) outline a life cycle costing procedure and summarize other design considerations and risk analysis components to aid the designer in selecting pipe material type alternatives for a site specific application.

Worked examples of the step-by-step design procedure are provided in Appendix A. Design figures and tables are provided in Appendices B and C, respectively. General maps to aid the designer in interpreting measured parameters for pipe selection are provided in Appendix D, and definitions and a list of abbreviations used in the guidelines are provided in Appendix E.
Chapter 1.0 Design Procedure

The following sections provide a brief overview of the main steps to be followed when designing gravity pipe less than 3 metres in diameter. By following this simplified step-by-step method all available pipe types can be considered and the most appropriate material type(s) for a specific site location will be identified. The design steps described in this section assume detailed geotechnical, environmental, and physical information has been obtained or is available for a specific project. This is not always the case, especially during preliminary design stages of a project. When site specific data is not available, the information contained in the following Chapters (referenced accordingly in each design step) should be used as a guide for selecting appropriate design parameters and for rational decision making in completing the design. A flow chart illustrating the general decision making process for the pipe selection and evaluation procedure is shown in Figure 1.1.

It is recognized that on a typical highway rehabilitation or construction project that a relatively large number of gravity pipe installations will be required. The designer can group those applications with similar functional requirements, and with generally similar site, hydraulic and structural conditions, so as to reduce the level of effort in applying the guidelines.
Figure 1.1 - Flowchart for Gravity Pipe Selection Procedure
The following abbreviations are used in the step-by-step pipe selection procedure and throughout the guidelines:

ALT2 = Aluminized type 2 coated steel pipe
CIO = Corrugated inside and outside HDPE pipe
CPSIO = Closed profile smooth inside and outside
CSP = Corrugated steel pipe
DSL = Design Service Life
EMSL = Estimated Material Service Life
HDPE = High density polyethylene
LCC = Life Cycle Cost
LCCA = Life Cycle Cost Analysis
P = Polymer laminated steel pipe
pH = measure of acidity or alkalinity
PG = Plain galvanized coated steel pipe
PVC = Polyvinyl Chloride
R = Electrical resistivity
SICO = Smooth inside and corrugated outside
SIRO = Smooth inside and ribbed outside
SR = Spiral rib steel pipe
SWSI = Solid wall smooth inside

For a complete list of abbreviations and definitions of terms used in the guidelines, please refer to Appendix E.

1.1 Limitations

This design process should be used with caution for high risk or extreme physical/environmental conditions such as:

- Burial soil or contact water with pH < 4, pH > 10, or R < 300 ohm-cm;
- Abrasion levels above Moderate (Abrasion Level 3 on Table C8);
- Applications that have unusual risk factors (refer to Chapter 9);
- Applications with pipe cover less than the minimum specified in the OPSDs (refer to Table 6.1 in Chapter 6 for current standards) and OPSS 514; and
- Applications where continuous water flow through the pipe is expected or the groundwater table is above the invert of the pipe.

When the above conditions exist, the designer may still use the step-by-step procedure but should refer to the related Chapters in the guidelines for more information to assess the risks and adjust the pipe design accordingly. A more conservative design method, non standard special provisions or increased
inspection during construction are options a designer may consider to address high risk applications.

The design procedure does not directly consider pipe jointing; therefore, where a designer determines that a particular pipe type does not have a joint type acceptable for a particular application (see Chapter 4 for more details), that pipe type should be eliminated from further consideration.

In general, the minimum design input data required for the design procedure is listed below:

- Type of installation and highway class;
- Hydraulic design inside pipe diameter for a specific inside pipe wall roughness;
- Maximum / minimum depth of burial (i.e. height of fill above top of pipe); and
- Anticipated pH and resistivity of surrounding soil and water.

### 1.2 Step-by-Step Pipe Selection Procedure

#### Step 1 Project Description / Evaluation (Defining Design Parameters)

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| • Document pipe location(s) for future reference using the Linear Highway Reference System (LHRS – chainage and offsets), Global Positioning system (GPS) coordinates (i.e. using NAD83 MTM co-ordinate system) to geodetic datum, or local co-ordinate system.  
• Determine the Design Service Life (DSL) for the project from Table C5 (Appendix C).  
• Decide whether products with Estimated Material Service Life (EMSL) < DSL will be acceptable.  
• If pipe replacement is acceptable within the DSL, a Life Cycle Costing Analysis (LCCA) will be required. Otherwise a LCCA will not be necessary. | Issues to be considered when accepting EMSL < DSL:  
• Pipe burial depths are less than about 3 m, i.e. easy access for replacement.  
• Traffic volume is relatively low or pipe can be replaced without impacting traffic operations.  
• A large number of installations are involved (i.e. LCCA savings could be significant).  
• In the subject region, one pipe type is significantly less costly than another.  
• Pipe size can be selected to accommodate future relining.  
• Refer to Chapter 2 and corresponding figures and tables for more details |

#### Step 2 Eliminate Pipe Types Based on Size Availability

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| • If design inside diameter is greater than the largest available size in the Material Availability Tables in Appendix C, then that material type can be eliminated from further consideration.  
• Currently, if design inside diameter is >1200 mm, eliminate | Pipe Material Availability Tables in Appendix C should be updated on a regular basis, as new pipe products become available. |
PVC, HDPE-CIO, HDPE-SICO, and Non-Reinforced Concrete pipes.

### Step 3 | Determine Pipe Durability

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| • Determine EMSL for each pipe product.  
• If EMSL < DSL, eliminate the pipe product unless pipe replacement within the DSL period is permitted.  
• Where pipe replacement is permitted, pipe products with a minimum EMSL of 25 years are required. | • The EMSL can be calculated or estimated using existing methods and calibrated using local data / previous experience. Refer to Chapter 7 for more details.  
• Review project site information, including geotechnical reports, geo-environmental data (i.e. pH, resistivity, and chloride and sulphates concentrations). Refer to Chapters 3 and 4 for more details.  
• If the project involves a replacement of an existing pipe, or if pipes in similar applications are in service in the area, review the existing pipe material types, age, condition and maintenance records. This provides useful information concerning in-service conditions and potential risk factors.  
• Identify any relevant risk factors at the site based on information contained in the guidelines (Chapters 3, 4, 7 and 9 and corresponding figures and tables). |

**CONCRETE**

• Given pipe slope, pipe inside diameter (i.e. rise), pH value, determine EMSL for concrete pipe from Table C10 (based on Hurd’s Model) or from another predictive model provided in Chapter 7.  

**HDPE**

• Assume an EMSL of 75 years as outlined Chapter 7.3.3.  

**PVC**

• Assume an EMSL of 75 years as outlined in Chapter 7.3.4.  

**HDPE**

• Must be 320 kPa HDPE pipe certified to CSA B182.6-02, CSA B182.8-02, ASTM F894 or equivalent.  
• This EMSL is subject to Special Provisions requiring post construction verification of satisfactory installation.

**PVC**

• Must be 320 kPa PVC pipe certified to CSA B182.2-02 or B182.4-02.  
• This EMSL is subject to Special Provisions requiring post construction verification of...
SATISFACTORY INSTALLATION.

1. Determine years to perforation (Base Life Years) for 1.6 mm thick (16 gauge) plain galvanized steel from Figure B6 and for 1.6 mm ALT2 Coated steel pipe from Figure B7, respectively.

2. Steel – P Lamination
   Calculate X1 Factor = (EMSL / Base Life Years)
   • If 4<pH<10 and R>100 ohm-cm, Steel-P is assumed to add 50 years to the EMSL for plain galvanized steel, determine minimum steel wall thickness to meet desired EMSL = (EMSL - 50).
   • If pH and R are outside of the range specified above (see also Table 7.4), consideration could still be given to using Steel-P; however, the EMSL must be greater than or equal to the DSL (i.e. pipes must be designed without replacement).
   • Determine minimum wall thickness (gauge) from insert table in Figure B6 by choosing closest Factor ≥ X1 Factor.

3. Steel – ALT2 Coating
   Calculate Y1 Factor = EMSL / (Base Life Years)
   • If 5<pH<9 and R>1,500 ohm-cm, ALT2 Coated steel pipe can be considered directly from Figure B7; then, determine minimum steel wall thickness to meet desired EMSL.
   • If pH and R are outside of the range specified above (see also Table 7.4), Steel-ALT2 Coating should not be used.
   • Determine minimum wall thickness (gauge) from insert table in Figure B7 by choosing closest Factor ≥ Y1 Factor.

4. Steel – PG Coating
   Calculate X1 Factor = EMSL / (Base Life Years)
   • If 6<pH<12 and 2,000<R<10,000 ohm-cm, Steel – PG pipe can be considered directly from Figure B6; then, determine minimum steel wall thickness to meet desired EMSL.
   • If pH and R are outside of the range specified above (see also Table 7.4), consideration could still be given to using Steel-PG; however, the EMSL must be greater than or equal to the DSL (i.e. pipes must be designed without replacement).
   • Determine minimum wall thickness (gauge) from insert table in Figure B6 by choosing closest Factor ≥ X1 Factor.

For abrasion levels above moderate (Abrasion Level 3 on Table C8), refer to Chapter 7 for more details on restrictions to coatings/laminations.

Minimum Base Life Years = 10 years for the plain galvanized steel component of the Steel-P Laminated pipe (i.e. an additional 50 years is then added to the EMSL for the polymer lamination).

X1 Factor is the minimum calculated number required to achieve a specified EMSL. The X1 Factor is compared to the Factors listed in the insert table on Figure B6, which have a corresponding steel wall thickness and gauge type. The closest Factor (which is greater than or equal to the X1 Factor) should be selected and the corresponding wall thickness used in the design. If the X1 Factor is calculated to be less than or equal to 1, then 1.6 mm thick steel is sufficient.

Y1 Factor is the minimum calculated number required to achieve a specified EMSL. The Y1 Factor is compared to the Factors listed in Figure B7, and the same method outlined above for the X1 factor should be applied.

EMSL_m = modified estimated material service life for calculating minimum wall thickness based on type of steel coating/lamination. If EMSL_m is less than zero, then 1.6 mm thick steel is adequate.

Minimum Base Life Years = 25 years for Steel-PG and Steel-ALT2.
### Step 4  List Pipe Types With Acceptable Durability Requirements

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<td>• Eliminate pipe products from the following list that do not meet the DSL or required minimum EMSL for pipe replacement (if being considered) based on durability requirements from Step 3:</td>
<td>• If risk factors identified in Step 3 are considered to be too great for a specific pipe product, eliminate pipe product from further evaluation.</td>
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<tr>
<td>Concrete – R</td>
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<tr>
<td>Concrete – NR</td>
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<td>HDPE – CIO</td>
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<td>HDPE – SICO</td>
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<td>HDPE – CPSIO</td>
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<td>PVC – SIRO</td>
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<td>PVC – SISW</td>
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<td>Steel – PG</td>
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### Step 5  Hydraulic Evaluation

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<td>• For each pipe type listed from Step 4, complete hydraulic evaluation to identify suite of acceptable pipe products.</td>
<td>• Refer to Chapter 5 and corresponding figures and tables for more details.</td>
</tr>
<tr>
<td>• If a detailed hydraulic analysis has been performed using MTO Drainage Management Manual for each pipe product type, list pipe products with corresponding design diameters and go directly to Step 6; otherwise,</td>
<td>• Hydraulic evaluation using Figure B1 is based on assumptions that may not reflect the true hydraulic performance of the pipe under actual field conditions. Appropriate detailed hydraulic analysis should be performed to verify design.</td>
</tr>
<tr>
<td>• Using Figure B1 (Appendix B), determine the equivalent pipe diameter for a specific pipe product relative to a given design diameter (i.e. it is assumed that at least one hydraulic analysis has been performed separately and the designer can use a given design diameter and associated Manning number).</td>
<td>• Manning Number varies with pipe diameter for some pipe products</td>
</tr>
<tr>
<td>• Refer to tables in Appendix C for applicable Manning Numbers to use for each pipe product as referenced below:</td>
<td>• For Steel pipe products; helical, spiral rib and structural plate pipe options should be considered where appropriate, annular riveted pipe is not applicable for MTO projects.</td>
</tr>
</tbody>
</table>

CONCRETE: Table C1
HDPE-CIO: Table C3.0
HDPE-SICO: Table C3.1
HDPE-CPSIO: Table C3.2
PVC-SIRO: Table C4.0
PVC-SISW: Table C4.1
STEEL-P: Table C2.2
STEEL-ALT2: Table C2.1
STEEL-PG: Table C2.0
• Confirm that minimum diameter is met from Table C7.
• Add product to approved list.
### Step 6 Structural Evaluation

<table>
<thead>
<tr>
<th>Process</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>For each pipe type listed from Step 5, complete structural evaluation to identify suite of acceptable pipe products.</td>
<td>Refer to Chapter 6 and corresponding figures and tables for more details.</td>
</tr>
<tr>
<td>Confirm that product is structurally adequate from Ontario Provincial Standard Drawing (OPSD) Fill Height Tables (if not, select another product and re-confirm).</td>
<td>Determine the minimum pipe class, thickness, corrugation profile, etc. for the different pipe materials meeting the structural requirements for the application. Refer to Chapter 6 for more details.</td>
</tr>
<tr>
<td>Maximum fill height tables are referenced in the current OPSDs as summarized in Table 6.2 (in Chapter 6) and below. Most of these OPSDs are in the process of being updated and are currently under revision by MTO and OPS:</td>
<td>If OPSD tables are not available for a specific pipe product, design criteria should be submitted to MTO for approval prior to being considered for a project.</td>
</tr>
</tbody>
</table>
| CONCRETE: OPSD 807.01, 807.03 and 807.04  
HDPE: OPSD 806.02  
PVC: OPSD 806.040 and 806.06  
STEEL: OPSD 805.010 and 805.030 | |
| Add product to approved list. | |

### Step 7 Perform Life Cycle Cost Analysis, if required

<table>
<thead>
<tr>
<th>Process</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undertake LCCA, where pipe replacement within the DSL period is an acceptable option (i.e. in cases where the EMSL&lt;DSL for at least one option).</td>
<td>Perform the LCCA in accordance with the method described in Chapter 8 of the guidelines; however only initial costs and replacement costs need be considered. All common costs including operation, maintenance, and terminal costs need not be included in the LCCA.</td>
</tr>
</tbody>
</table>

### Step 8 List Acceptable Products for Tender Documents

<table>
<thead>
<tr>
<th>Process</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Include all acceptable pipe products in tender documents as equal alternatives.</td>
<td>Where LCCA demonstrates that pipe replacement within the DSL period has significant cost advantages and is an acceptable strategy given the class of road and installation type, specify this strategy in the contract documents.</td>
</tr>
<tr>
<td>Specify the pipe material types including nominal pipe diameter, pipe material type and subcategory type (e.g. Steel/Spiral Rib Pipe or High Density Polyethylene/Closed Profile/smooth inside and outside wall, etc.), class or wall thickness, corrugation type (if applicable), coatings / lamination required (if applicable), and type of joints required (if applicable).</td>
<td>Assess risks identified in previous steps and include in the tender documents any additional special provisions or non-standard special provisions for shipping, handling, installation, inspection, and post-construction inspection. Include in the tender documents, any liability to the supplier and/or installer for any improper installation or poor performance related to a specific pipe material.</td>
</tr>
<tr>
<td>Tender documents should include reference to appropriate OPSD, OPSS, and any special provisions associated with each pipe option.</td>
<td></td>
</tr>
</tbody>
</table>
The designer, through engineering judgment, may need to eliminate pipe products based on risk factors, special design appurtenant structures or restrictions, high life cycle costs, or local experience.

Refer to Chapter 9 and corresponding figures and tables for more details.

Worked examples (Examples 1 to 4) using the above gravity pipe selection procedure are provided in Appendix A.
Chapter 2.0  Project Description / Evaluation

2.1  Gravity Pipe Drainage Application

As described in the MTO Drainage Manual, drainage components of a highway (roadway) project include culverts and storm sewers as defined below:

**Culvert** – a water crossing component of a drainage work that is associated with a *highway crossing* of a stream, river, creek or lake. (The term ‘culvert’ is also used to describe that component of the road drainage system that takes storm water flow from one side of a road, driveway, entrance, etc., to the other.)

**Storm sewer** – a surface drainage component of a drainage work that collects and transports stormwater runoff from the *highway right-of-way* and surrounding catchments to a receiving body of water such as a stream, river, or lake.

These guidelines are intended to guide the designer in the selection of culverts/storm sewer pipes with circular cross-sections less than 3 m in diameter, subject to gravity water flow conditions.

2.2  Roadway Classification and Design Service Life

Culverts and storm sewers should be designed for a Design Service Life (DSL) appropriate for the pipe function or roadway application. The requirements for DSL may vary between projects as well as within a project, depending on the roadway classification and function of the pipe. The DSL is defined as the expected relatively maintenance-free service life of each pipe installation. It can be quantified as the minimum life (in years) that a pipe must remain serviceable, without undergoing failure, major distress, distortion or degradation such that it can no longer perform the intended function without major maintenance intervention.
The required DSL for a pipe application is based on the highway classification, traffic volumes, and any other relevant considerations, such as access for replacement and the consequences of premature failure. Table C5 in Appendix C provides recommended pipe Design Service Lives for a range of typical MTO pipe applications. These values can be varied for specific applications or special circumstances at the designer’s discretion and where justified.

The Design Service Life is not to be confused with the Estimated Material Service Life (EMSL) that is described in Chapter 7. Under normal circumstances, the EMSL must meet or exceed the required Design Service Life. However, where there are significant cost advantages and minimal risk, the designer may elect to select pipe options that may not meet the DSL. As technologies for pipe in situ re-lining and trenchless technologies improve, these strategies may become more viable in the future.

2.3 Pipe Material Options

These guidelines consider the four main pipe material types of Concrete, Steel, High Density Polyethylene, and Polyvinyl Chloride. Other pipe materials or composite materials have not been assessed since they are not used on MTO highway projects or are relatively new without a proven MTO record of reliability and performance. These materials, if they prove to be acceptable for MTO purposes, would be incorporated into the design and selection process during a future update of these guidelines.

2.3.1 Concrete

Description: For the purposes of these guidelines, concrete pipe is pre-cast, steel-reinforced, or non-reinforced. Pre-cast concrete pipe (smooth inside wall) is typically used for culvert and storm sewer applications. Concrete pipe manufactured in Ontario is typically produced from low-water-content (zero slump) concrete (no air entrainment) which is often referred to as dry cast. Materials for the concrete mixtures are in CAN/CSA-A257.1 and CSA-A257.2 (2003 Series) and the pipes are manufactured for a range of minimum pipe strengths and cement types (depending on environmental conditions) for both reinforced and non-reinforced concrete pipe.

REINFORCED CONCRETE

Different wall thicknesses can be specified for pre-cast reinforced concrete pipe as Wall Types A, B, or C. The different wall thicknesses have the same structural capacity for a certain pipe class strength; however, the amount of reinforcing steel used in the pipe changes with wall type.
NON-REINFORCED CONCRETE

Non-reinforced concrete contains no reinforcing steel and relies on the inherent strength of the concrete and pipe structure.

As listed in Table C1 in Appendix C, reinforced and non-reinforced concrete pipe manufactured in Ontario is available in different sizes and wall thicknesses.

2.3.2 Steel

Description: Steel pipe is fabricated as two types: Corrugated Steel Pipe (CSP) or Spiral Rib Pipe (SRP). Both are constructed from sheet steel with a continuous seam. For culvert and storm sewer applications (less than 3,000 mm span), prefabricated CSP and SRP are typically used, although Structural Plate Corrugated Steel Pipe (SPCSP) can also be considered for diameters larger than 1,500 mm. For the purposes of these guidelines, CSP refers to both prefabricated CSP and SPCSP, (which is field assembled and bolted together). Different corrugation types are available as a result of the need for additional stiffness and strength for larger diameter pipes, and to provide required flow characteristics for design. SRP has a smooth inside wall, whereas CSP has a rough inside wall. The seams are lock-seamed for helical corrugated pipe, and riveted for annular corrugated pipe. Spirally rib-walled pipe is formed using the lock-seaming process.

Protective coatings/laminations may be applied to CSP, SPCSP, and SRP to protect steel pipes against the effects of corrosive action and/or abrasion. The following coatings/laminations are available in Ontario and can be specified according to the requirements of CAN/CSA-G401-01.

POLYMER LAMINATED STEEL

A polymer film is applied as a sheet to the galvanized steel prior to the formation of the pipe as CSP or SRP. The minimum polymer lamination thickness is typically 0.25 mm (250µm) on each surface. Polymer lamination provides increased resistance to abrasion, as well as to corrosion.

ALUMINIZED TYPE 2 STEEL

Similar to galvanizing, Aluminized Type 2 is the hot-dip application of a thin layer of aluminum to both sides of the steel sheet. Unlike galvanizing, the aluminizing process (Aluminized Type 2) creates an alloy layer between the exterior aluminum and the base steel (AASHTO, 2000). It is produced with a coating weight of 305 g/m² each side which provides a thickness of 47 µm on each surface.
GALVANIZED STEEL

Zinc galvanizing consists of the application of a thin layer of zinc to the steel by a hot-dip process. It is produced with a minimum coating of 305 g/m² on each side of the steel sheet which provides a thickness of 43 µm on each surface. Heavier zinc coating weights may be specified for structural plate corrugated steel pipe (CSPI, 2004).

As listed in Table C2.0 to C2.2 in Appendix C, Polymer laminated, Aluminized Type 2 coated, and plain galvanized coated CSP, SPCSP, and SRP manufactured in Ontario are available in different corrugations, sizes and wall thicknesses.

2.3.3 High Density Polyethylene (HDPE)

Description: High Density Polyethylene Pipe (HDPE) is a thermoplastic pipe that is manufactured using resin material in the form of pellets.

There are currently three main types of HDPE pipe available; namely, i) Corrugated inside and outside wall, ii) Open Profile Wall - corrugated outside and smooth inside, and iii) Closed Profile Wall – smooth inside and outside.

CORRUGATED INSIDE AND OUTSIDE

Corrugated inside and outside HDPE pipe has a corrugated inner wall and currently there are no national standard requirements for the manufacturing process; however, work is underway to adopt a CSA standard for this product.

OPEN PROFILE WALL – CORRUGATED OUTSIDE AND SMOOTH INSIDE

Corrugated outside and smooth inside wall HDPE pipe allows smooth wall hydraulic performance. This profile wall type can be certified to CSA B182.6 and CSA B182.8 and is available in a minimum 210 kPa and 320 kPa pipe stiffness.

CLOSED PROFILE WALL – SMOOTH INSIDE AND OUTSIDE

Smooth inside and outside profile wall HDPE pipe conforming to ASTM F894 is available in pipe Ring Stiffness Constants (RSC) RSC40 through RSC400. For comparison purposes, the minimum equivalent pipe stiffness (i.e. Class defined by CSA standards) is provided in Appendix X1 in ASTM F894.

As listed in Tables C3.0, C3.1, and C3.2 in Appendix C, the different types of HDPE pipe manufactured in Ontario are available in different classes and sizes.
2.3.4 Polyvinyl Chloride (PVC)

Description: Polyvinyl Chloride (PVC) is a thermoplastic pipe that is manufactured using a blend of materials whose major ingredient is polyvinyl chloride. For storm sewers and culverts in gravity flow conditions, PVC manufactured in Ontario is currently available as Profile Wall (smooth inside and ribbed outside) and Solid Wall - Standard Dimension Ratio (DR) type pipe.

PROFILE WALL – SMOOTH INSIDE AND RIBBED OUTSIDE

Smooth inside and ribbed outside profile wall PVC pipe allows smooth inner wall hydraulic characteristics and is currently available in minimum 320 kPa pipe stiffness.

SOLID WALL

Solid wall PVC pipe is subdivided into various standard dimension ratio (SDR or DR) designations which are related to the structural capacity and wall thickness of the pipe.

The currently available PVC pipe types in Ontario are listed in Tables C4.0 and C4.1 in Appendix C.

2.3.5 Incorporating New Pipe Material Options

Tables C1 to C4.1 form a catalogue of available pipe material types and sizes that are currently available for use on highway projects in Ontario. These catalogue tables have been compiled from information provided by industry representatives at the time these guidelines were prepared. These tables will need to be updated and/or added to on a regular basis as new products are introduced and existing products are discontinued.

2.4 Joints

All pipes are manufactured in a variety of lengths and are joined on site to form continuous conduits. Depending on the application and site conditions, it may be desirable that joints provide:

- resistance to infiltration of groundwater or soil;
- resistance to exfiltration of flow water (i.e. prevention of leakage);
- flexibility to accommodate lateral deflection or longitudinal movement without creating leakage and/or structural problems;
- resistance to shear stresses between adjoining pipe sections; and
• hydraulic continuity.

The performance requirements for mechanical joints will depend on the specific pipe application, and the nature of the bedding material and surrounding soil.

In any comparison of pipe materials, the cost, performance and installation process of the entire pipe system, including joints, must be considered.

CONCRETE

Joint configurations include bell and spigot and tongue and groove, with rubber gaskets in accordance with Ontario Provincial Standard Specification (OPSS) 1820 (i.e. CAN/CSA A257 Series, A257.3-03). Joints, meeting CSA requirements, can be specified that will not leak under a pressure equal to 103 kPa (10.5 m of head). Large-diameter, pre-cast concrete pipe is constructed in short lengths to reduce the weight of the pipe for easier transportation, storage, and placement.

STEEL

For CSP/SRP, the most common jointing method is a corrugated steel coupling band which can be specified with or without gaskets. Other less common methods include flat bands, flanges, threaded sections, internal couplers, bolted joints and butt welding. The most common gasket types include O-rings and neoprene sleeves. For SPCSP, the most common jointing method is with bolts. Although there is no leak test in the current CAN/CSA3-G401-01 standard, gaskets can be used to improve leak susceptibility of coupler joints. Joints should meet the OPSS 1801 material specification for corrugated steel pipe.

HIGH DENSITY POLYETHYLENE (HDPE)

Corrugated (corrugated inside and outside) or Open Profile (corrugated outside and smooth inside) HDPE pipe can be joined with coupling bands or gasketed joints as indicated in Tables C3.0, C3.1, and C3.2 in Appendix C.

Corrugated (corrugated inside and outside) HDPE pipe does not currently have CSA certified joints but an amendment to the standard is underway to include the single wall pipe and joining system requirements. A construction-applied non-woven geotextile wrap can be used to enhance the soil tightness of the coupler band design.

Open Profile (corrugated outside and smooth inside) Wall pipe joints are available with CSA B 182.8-02 certified gasketed joints. The requirement is that the joints will not leak under a pressure equal to 74 kPa (7.5 m of head). This standard is currently not in OPSS 1840; however, OPSS 1840 is currently under revision. Open profile (corrugated outside and smooth inside) wall pipe joints are also available with CSA
B182.6-02 certified gasket joints. The requirement is that the joints will not leak under a pressure equal to 100 kPa (10 m of head) and this CSA standard is currently referenced in OPSS 1840.

Closed Profile (smooth outside and inside wall) HDPE pipe conforming to ASTM F894 can be joined by screw type couplers or welding on one or both outer diameter (OD) and inner diameter (ID) surfaces. Welding can provide a leak-free connection that is able to transmit axial loads.

POLYVINYL CHLORIDE (PVC)

PVC is joined using bell and spigot joints, either with or without a compressed gasket. Joints can be certified to CSA B182.4, which requires that the joints not leak under a pressure equal to 74 kPa (7.5 m of head). This CSA standard is currently specified in OPSS 1841.

2.5 Pipe Material Quality Assurance / Quality Control

Manufacturing Quality Control. The Estimated Material Service Life (see Chapter 7) of a pipe is highly dependant on the quality of the installed pipe product. Although these guidelines focus on design and selection, the manufacturing and installation process are considered to be critical ingredients for effective design. For each pipe type, material properties will vary depending on the industry standard to which the pipe is manufactured. The basis of design used in these guidelines assume:

- All concrete pipe product used on provincial highway projects in Ontario meets OPSS 1820 and CSA A257 Series-03, specifically CSA-A257.1-03 and CSA-A257.2-03.

- All steel pipe product used on provincial highway projects in Ontario meets the material specification OPSS 1801-1 and CAN/CSA-G401-01.

- All HDPE pipe used on provincial highway projects in Ontario meets OPSS 1840 and CSA B182.8-02 (“Profile Polyethylene Storm Sewer and Drainage Pipe and Fittings”), CSA B182.6-02 (“Profile Polyethylene Sewer Pipe and Fittings for Leak Proof Applications”), or ASTM F894-98a (“Standard Specification for Polyethylene (PE) Large Diameter Profile Wall Sewer and Drain Pipe”), which precludes the inclusion of recycled material.

It should be emphasized that there is a lack of consistency in quality systems and standards between the various pipe manufacturers. MTO recognizes this as a concern. When a pipe product is delivered to a construction site, it is assumed to meet an acceptable quality standard, since there is no process to review product manufactured quality as part of the construction Contract Administration process. MTO is undertaking a separate review of pipe manufacturing quality to determine if further measures are required to achieve uniform quality standards across the industry, inclusive of all product types. Arising from this review, in 2003, MTO initiated a series of trial projects that required pipe suppliers to provide more stringent and consistent product quality assurance documentation for designated contracts. There are likely to be ongoing developments in this area in the future. For the purposes of these guidelines, it is assumed that all pipe products are manufactured to an acceptable and specified quality standard meeting the current requirements of the relevant materials testing standards and OPS.
Chapter 3.0  Environmental Considerations

These guidelines are intended to cover typical gravity pipe installations for the conveyance of water on highway projects. Environmental impacts shall be considered for all new pipe installations, pipe replacements, liners, and extensions. Environmental considerations for a specific drainage pipe application may include fish passage, pedestrian/livestock/animal passage, navigable waterways, maintenance of natural stream passage, etc. Sometimes environmental requirements will override hydraulic, structural, and durability design considerations. For example, open-bottom culverts or culverts designed to simulate a natural stream bed are sometimes used for fish passage applications, and the design is governed by the Ministry of Natural Resources, Department of Fisheries and Oceans, and/or local conservation authority requirements (refer to the MTO Drainage Management Manual 1997). In addition, river and stream geomorphology considerations may require a minimum size of culvert for a specific location (refer to the MTO Drainage Management Manual 1997). If the pipe under consideration is to be used for an application other than those defined as being a culvert or storm sewer, a site-specific analysis is required.

These guidelines only address the hydraulic, structural and durability design requirements. Site-specific studies, beyond the scope of the guidelines, may be needed to address other site requirements.

In addition to the impact the gravity pipe application may have on the environment, the designer also needs to address the effect that environmental conditions may have on the pipe material type. The subsurface conditions for routine, small diameter gravity pipe design are determined for MTO projects as part of the scope of a geotechnical/pavement design investigation. A more detailed foundation investigation may be warranted for larger diameter pipes, or where swamps or high fills are involved. The scope of these conventional pavement design and foundation investigations should be expanded to include geo-environmental testing to identify the main corrosion indicators affecting pipe material service life (see Chapter 7). These requirements are discussed in more detail in the following sections.
3.1 Environmental Chemistry

Corrosion and deterioration of pipe containing steel and concrete are governed primarily by pH, resistivity, and the concentration of sulphates and chlorides. The resistance to chemical corrosion and the durability of high density polyethylene and polyvinyl chloride are sensitive to certain solvents, chemicals, and petroleum products.

The pH and resistivity values of the surrounding soil, groundwater and flow water are widely accepted to be important indicators of corrosion potential and, as a minimum, need to be determined for any gravity pipe service life estimation. Exposure of pipe to sulphates, chlorides, and other chemicals or solvents should be assessed on a case-by-case basis and appropriate testing and evaluation undertaken where these parameters are considered to be a concern.

3.2 Geo-Environmental Field Review and Testing

Site-specific environmental conditions need to be estimated, either by direct testing of the site soils/water or by reviewing local data at or near the proposed culvert/storm sewer location(s). Information may be available from previous studies, government databases, geographic maps, etc. However, given the relatively low cost of testing (i.e. as part of geotechnical investigations or pipe condition surveys), it is strongly recommended that these parameters be measured rather than relying on an assumed value. At pipe replacement sites, past performance of existing material should always be considered. Future land use (such as mining, urban development, etc.) should be considered as to its potential impact on future surface runoff water and groundwater quality. The parameters used in the durability design (Chapter 7) should be representative of the worst conditions anticipated during the pipe service life. For example, when assessing environmental exposure conditions on new road alignments, the effect of road salt application on the future water quality should be considered when selecting appropriate parameters for culvert and storm sewer design.

The pH and resistivity values for the local groundwater (and/or expected flow water through the pipe) and surrounding soils (i.e. water-side and soil-side) are very important for reliably estimating material service life. These parameters are also easy to obtain. The values used for analysis should be based on measured data and be representative of anticipated long term in-service conditions. It is recommended that these parameters be measured using a portable pH/conductivity meter, and that local experience be considered when interpreting the data.
3.2.1 Measuring pH

The instrument used to measure pH should be capable of determining pH within an accuracy of 0.1 units. A section should be included in the Pavement Design Report or Foundations Report, as appropriate, that describes the results of the pH testing, reviews the factors likely to affect pH values in the future, and describes methods used to obtain representative values for pipe design.

For preliminary design or if there is no site specific data available at the time of the field review or geotechnical investigation, Figure D1 or a similar map may be used to aid the designer in determining approximate pH values of rainfall (i.e. potential storm water). Figure D2 can be used to predict the influence the surficial soils would be expected to have on the rainfall pH at a general site location (i.e. acid reducing potential or potential to increase pH).

3.2.2 Measuring Resistivity

It is recommended that environmental conductivity/resistivity tests be carried out on soil and water at pipe structure locations, on soils surrounding the pipe (e.g. bedding, embedment, cover soils), and on subsurface materials along drainage alignments. A section should be included in the Pavement Design Report or Foundations Report, as appropriate, that describes the results of the resistivity testing, reviews the factors likely to affect resistivity values in the future, and describes methods used to obtain representative values for pipe design.

For preliminary design or if there is no site specific data available at the time of the investigation, the generalized soil maps (Figures D3 to D7 in Appendix D) or similar maps can be used and correlated with Tables 3.1, 3.2 and 3.3 to estimate resistivity values.
Table 3.1
Resistivities of Soil and Water

<table>
<thead>
<tr>
<th>Classification</th>
<th>Resistivity (ohm-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>Surface water</td>
<td>R&gt;5,000</td>
</tr>
<tr>
<td>Brackish water</td>
<td>R=2,000</td>
</tr>
<tr>
<td>Seawater</td>
<td>R=25</td>
</tr>
<tr>
<td>Soil</td>
<td></td>
</tr>
<tr>
<td>Rock</td>
<td>R&gt;50,000</td>
</tr>
<tr>
<td>Sand</td>
<td>50,000&gt;R&gt;30,000</td>
</tr>
<tr>
<td>Gravel</td>
<td>30,000&gt;R&gt;10,000</td>
</tr>
<tr>
<td>Loam</td>
<td>10,000&gt;R&gt;2,000</td>
</tr>
<tr>
<td>Clay</td>
<td>2,000&gt;R&gt;750</td>
</tr>
</tbody>
</table>

Table 3.2
Soil Corrosiveness and Resistivity

<table>
<thead>
<tr>
<th>Soil Corrosiveness</th>
<th>Resistivity (ohm-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>10,000&gt;R&gt;6,000</td>
</tr>
<tr>
<td>Low</td>
<td>6,000&gt;R&gt;4,500</td>
</tr>
<tr>
<td>Moderate</td>
<td>4,500&gt;R&gt;2,000</td>
</tr>
<tr>
<td>Severe</td>
<td>2,000&gt;R</td>
</tr>
</tbody>
</table>


Table 3.3
Corrosiveness of Soils

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Description of Soil</th>
<th>Aeration</th>
<th>Drainage</th>
<th>Colour</th>
<th>Water Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>I Mildly Corrosive</td>
<td>1. Sands or sandy loams</td>
<td>Good</td>
<td>Good</td>
<td>Uniform colour</td>
<td>Very low</td>
</tr>
<tr>
<td></td>
<td>2. Light textured silt loams</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Porous loams or clay loams thoroughly oxidized to great depths</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II Moderately Corrosive</td>
<td>1. Sandy loams</td>
<td>Fair</td>
<td>Fair</td>
<td>Slight mottling</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>2. Silt loams</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Clay loams</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III Extremely Corrosive</td>
<td>1. Clay loams</td>
<td>Poor</td>
<td>Poor</td>
<td>Heavy texture Moderate mottling</td>
<td>0.6 m to 1 m (2 feet to 3 feet) below surface</td>
</tr>
<tr>
<td></td>
<td>2. Clays</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV Severely Corrosive</td>
<td>1. Muck</td>
<td>Very poor</td>
<td>Very poor</td>
<td>Bluish-gray mottling</td>
<td>At surface or extreme impermeability</td>
</tr>
<tr>
<td></td>
<td>2. Peat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Tidal marsh</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Clays and organic soils</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Reference: Corrugated Steel Pipe Institute, 2002, “Handbook of Steel Drainage & Highway Construction Products”
3.2.3 Measuring Other Parameters

Where there are indications of likely high chloride or sulphate concentrations, such as swamps or areas with mining activity, testing for these parameters should be undertaken, since they will affect the estimated material service lives for concrete and steel pipe.

On sites with any indication of apolar solvents and chemicals, such as petroleum products and gasoline, or sites where exposure to such contaminants is possible, appropriate testing should be undertaken. The presence of these contaminants is a risk factor affecting the durability and estimated material service life for HDPE pipe products.

On sites with indications of the presence of aromatic or chlorinated hydrocarbons, ketones and esters, or potential for exposure to such chemicals, appropriate testing and evaluation should be undertaken. These contaminants constitute risk factors affecting the durability and estimated material service life for PVC pipe products.

3.2.4 Analysis of Data

Analysis of the geo-environmental test data should take into consideration the anticipated in-service values for the native soils, backfilling soils, and for the groundwater/flow water. Seasonal variation in the flow and water table can affect test data values. Surrounding land use should also be considered when reviewing the data (FDOT, 1999). Test values are seasonally affected by such factors as rainfall, flooding, drought, road salts, and decaying vegetation. Whenever possible, environmental tests should be taken during periods when no unusual weather conditions exist. Backfilling material from borrow or commercial sources should be tested for verification that the materials are of equal or less corrosiveness than the native material at the project site.

Generalized soil/water maps are presented only as a guide to aid the designer in interpreting actual measured parameters for pipe selection. A conservative approach should always be used.

Communications should begin as soon as possible between the designer and the geotechnical engineer. Prior to conducting geotechnical investigations, the geotechnical engineer should know where, and to what depths, pipes are to be placed so that relevant test data and recommendations can be provided.
4.1 Geotechnical Considerations

The design of buried gravity pipes requires consideration of several geotechnical engineering aspects, such as the ability of the subgrade soils to support the pipe and/or embankment fills (if applicable), the long-term settlement potential of the founding soils beneath the pipe, the requirements for bedding, the interaction between the backfill and the conduit wall, and the soil arching (i.e. transfer of stress from the soil to the pipe wall) due to deformation and settlement.

4.1.1 Geotechnical Investigation

Geotechnical investigation of the founding soils for gravity pipe selection is typically included within the scope of a conventional pavement design field investigation for road rehabilitation, or for new road alignment projects. Each Region has its own guidelines for such investigations. The geotechnical investigation can be supplemented by information from other sources, such as geological mapping and previous pipe performance records or pipe condition surveys. More extensive subsurface investigation may be warranted at sites with marginal or organic soils, or sites with previous pipe performance problems. In cases of pipes within embankments higher than about 4 m and for swamp terrain, specific Foundation investigations would also be required. The need for a Foundations investigation is governed by MTO and Regional Geotechnical Section policy.
Subsoil conditions should be known to an adequate depth to ensure that soft or deleterious soil layers are identified, and that their potential influence on the future performance of the pipe is assessed at the design stage. Borehole depths and frequency are governed by Regional Geotechnical Section guidelines. Should bedrock or other relatively incompressible material be encountered at a shallow depth, the investigation should confirm the continuity and reliability of such incompressible strata. The subsurface investigation report should include borehole logs of all borings and test pits made at the site, the results of laboratory tests on soil and rock samples, and a written description of the site conditions, including frost penetration depths. In addition, a geotechnical assessment should be made as to the nature, extent, and potential behaviour of the foundation materials under the proposed buried pipe, both during and after construction. The assessment should comment upon the stability of supporting fills, the total and differential long-term settlements beneath and adjacent to the pipe, and the time rate of such settlements. Recommendations should be made with respect to excavation of unsuitable materials, groundwater control, frost tapers, backfilling, and appropriate in-place treatment of the foundation soils to improve their bearing and compressibility characteristics, as required. In most applications, the geotechnical recommendations with respect to small diameter gravity pipe are routine and no special geotechnical design considerations are required.

For gravity pipes, less than 3 m in span, the net loading on foundation soils will vary depending on whether the pipe is installed using trench or embankment installation methods. Typically, the net loading and settlement will be dependent on the height of embankment and trench width which, in turn, is dependent on the pipe material type. The bedding/embedment details for the different pipe material types founded on a range of soil conditions are discussed in Section 4.2.1

### 4.1.2 Soil Properties

Some soil properties, such as water content, grain size distribution and Atterberg limits (MTO Laboratory Testing Manual, Sections LS-701/702/703/704), are needed to classify the soil properly and to facilitate pipe material selection. The Ontario Provincial Standard Drawings (OPSDs) currently rely on classifying the subgrade soils as Type 1, 2, 3 or 4, according to the descriptions given in the Ontario Occupational Health and Safety Act (1991). In general, the current OPSD references for excavation construction requirements for the different pipe material types are consistent when installed in Types 1 to 4 soils and bedrock.
Depending on the type and thickness (cover) of overburden soil above the top of pipe, overburden unit weights should be estimated and checked for consistency with the assumptions made in the OPSD maximum fill height tables (see Ontario Provincial Standard Drawings, latest version). For example, the unit weight of overburden materials vary with soil type. Within each Region, there are variable soil types readily available for selection; however the OPSDs assume one material type in some cases. The selection of backfill / fill soils is largely dependent on cost and availability of fill material and what the fill will support in a specific application (e.g. rock fill, OPSS Granular B, SSM, sand or clayey fill, etc. may be acceptable, depending on support requirements). In addition, settlements associated with high embankments are dependent on the weight of the embankment material and may influence the selection of pipe material type in relation to allowable camber angles (see Section 4.1.3) between adjacent pipe segments for different pipe material types. The ability of pipe joints/connections to resist separation and/or rotation is also a design consideration if lateral spreading or differential settlement is a concern. The material and joint specifications for each pipe material type should be checked to ensure they meet the minimum design requirements and in-service conditions.

4.1.3 Camber

As discussed in the CHBDC, due to its trapezoidal cross-section, a road embankment subjects the foundation beneath its centre to greater stresses than beneath the adjacent toes of the side slopes. These differential stresses in the foundation can cause differential consolidation and/or elastic compressions, resulting in non-uniform (differential) settlement along the length of the conduit. This non-uniform settlement can be corrected by cambering appropriately the bedding profile in the longitudinal direction to enhance the achievement and maintenance of the designed invert gradient in the long term. The camber used during construction should be designed based on the anticipated final settlement along the conduit; taking into account the pipe material allowable radius of curvature and joint rotation criteria that are based on preventing leakage (refer to pipe material properties in Chapter 2). In general practice, the upstream half of the conduit length is placed on an almost horizontal bedding grade, whereas the other half is placed on a sloping grade. Upon completion of settlement, the invert should assume a continuous profile along the conduit length.

4.1.4 Control of Soil / Water Migration

When soils with significantly different gradations are placed against one another, the fines from one soil can migrate into the voids of the adjacent soil, even under small
hydraulic gradients. Continued soil migration can remove the soil support required to maintain the stability of the pipe structure or the haunch and side support of the pipe. This is particularly important for pipe systems that depend on the lateral support from the backfill for structural capacity. It is important to analyze the natural and imported soil, including bedding, to mitigate against fine particle soil migration. Generally, fine particle soil migration can be minimized with the use of graded granular filters, or by providing a suitable non-woven geotextile placed between the different soil types.

Also, seepage can occur along the pipe barrel which sometimes leads to removal of backfill material and the formation of a void around the pipe. This is often referred to as “piping”. Fine soil particles are washed out and the erosion inside the backfill may ultimately cause failure of the conduit or the embankment. This is particularly important as it can lead to the sudden collapse of the roadway via potholes or sinkholes, leading to unsafe conditions for vehicular traffic. Pipe perforation or joint opening could also lead to road failure by the piping or void formation mechanism.

Piping potential can be reduced by decreasing the velocity of the seepage flow. Impermeable trench plugs can be installed to break the flow continuity of the pipe bedding.

Piping is usually associated with culvert applications. Its likelihood for occurrence along the entire length of the conduit is generally increased when water is ponded above the culvert crown for an extended length of time, such as when the culvert inlet is blocked by debris or ice or where the side ditches do not have adequate drainage outlets.

Headwalls, impervious materials at the upstream end of the culvert and anti-seep or cut-off collars (‘trench plugs’) increase the length of the flow path, decrease the hydraulic gradient and the velocity of flow which, in turn, decreases the probability of piping developing. The possibility of piping being caused by open (separated) joints may be reduced through careful design and specification of an appropriate type of pipe joint. A description of the available joint types for each pipe material type is discussed in Chapter 2 and associated recommendations are provided in Section 4.1.5. In general, to reduce the chances of piping, gasketed pipe joints, welded/fused connections, fewer joints, and leak testing of joints should be considered. To reduce the chances of pipe disjointing or separation in settlement/lateral spreading prone areas, joints with adequate tensile and shear strengths should be specified.
4.1.5 Groundwater / Flow Water Conditions - Joints

Consideration as to whether the water flow through a culvert/storm sewer is continuous or intermittent, and the frequency or design storm event should be taken into consideration when selecting pipe material and joint types.

For gravity flow conditions, the designer should consider the expected flow water velocity and bedload, hydrostatic pressure and groundwater level. Fluctuating groundwater levels may lead to settlement/swelling of the soils. High flows and high groundwater levels may lead to piping and increased potential for chloride penetration in concrete. Flow water velocity and bedload affect estimated material service life as discussed in Chapter 7. Groundwater and surface water information can be gathered in the geotechnical or geo-environmental investigation for use in estimating material service life design and considered when specifying joint/connection types.

Proper jointing techniques (between pipe segments for all pipe types) must be specified to suit the expected site conditions. For most situations, standard “soil tight” joints are adequate (AASHTO, 2000). These joints may allow some degree of water movement, but will limit soil migration through the joint and slow the water movement to the extent that piping should not develop. Soil migration can also be restricted by the use of a filter fabric wrap at the joint.

Where some degree of differential settlement, uneven loading conditions or other disjoining forces may be present, a more positive connection that meets higher shear, moment and tensile strength requirements is usually specified (AASHTO, 2000). Where groundwater is expected to be above the invert, or where infiltration or exfiltration cannot be tolerated, use of rubber “profile” type gaskets, “O-ring” gaskets, or welded/fused joints are typically specified to provide a “watertight” joint (AASHTO, 2000). There is no absolute definition of watertight or soil tight. For culverts, according to AASHTO, 2000, watertight is typically meant to provide short term protection against leakage that might occur due to limited pressure differential (20 kPa to 70 kPa). Where resistance to longer term or higher pressure leakage is desirable, additional measures will typically be required.

For Ontario, current CSA Standards for Concrete, HDPE and PVC pipe can be specified that provide for qualification leak testing of joints (similar to AASHTO's interpretation of “watertight” joint). Pre-qualified laboratory testing or field testing in accordance with OPSS 410.07.15 can be specified for all pipe materials to verify that joints do not leak. Minimum leak requirements are given in the specification.
In all applications, the designer should determine if extra stringent (i.e. over and above standard manufacturer-supplied) joint types are required to prevent pipe joint leakage. With pipe systems subject only to gravity flows, standard joints for the selected pipe type should satisfy normal requirements. For pipe systems with joints that allow leakage, wrapping with a construction applied non-woven geotextile could be considered and may need to be specified.

4.1.6 Seismic Requirements

For gravity pipe road applications in Ontario, less than 3 m in span, seismic loads are generally not considered in design. However, for high risk applications where there is potential for upstream flooding or for permanent ground displacement, it is recommended that a seismic design be incorporated into the structural analysis (see Seismic requirements in Chapter 7 of the CHBDC).

Seismic loads on buried pipes arise from inertia forces due to earthquake shaking and/or from large permanent ground movement generally associated with strength and stiffness loss of loose or sensitive saturated foundation soils. Liquefaction and lateral spreading are the main causes of pipe failures, and these failure modes should be considered in design.

4.2 Installation

For gravity pipe installations for culvert and storm sewer applications, OPSS 421 “Construction Specification for Pipe Culvert Installation in Open Cut” and OPSS 410 “Construction Specification for Pipe Sewer Installation in Open Cut”, respectively, should be followed including any Standard Special Provisions (SSP). Currently, the OPSD sub-divide pipe installation into two categories: trench (i.e. excavation) or embankment construction. Trenching consists of excavation, preparation of the pipe bedding, placement of the pipe, joining of the pipes, and backfilling. Installation in embankment conditions is similar, except that shallow excavation may be required only to improve the bedding. Installation procedures should be considered in design and properly carried out. Installation has a significant impact on construction cost and pipe performance. Factors influencing the ease of installation are pipe weight and handling ability, pipe lengths and number of joints, and joint installation procedures.

Trench width, bedding, and condition of the soil surrounding the pipe (especially haunch area) are critical factors that control the stresses and deformation of the pipe.
Pipes may also be subjected to adverse conditions, such as extremely low temperatures, impact loads and UV radiation at the construction site.

These guidelines use current OPSDs and CSA requirements (see Section 2.5) for Concrete, Steel, HDPE and PVC pipe installation details. Schematic diagrams of typical pipe installation details are shown in Figure 4.1 for Concrete and in Figure 4.2 for Steel, HDPE, and PVC pipe. Alternative methods, based on AASHTO and/or ASTM procedures, that permit the designer to select alternative soil materials based on local availability, cost and fill heights, are available. However, they are outside the scope of these guidelines.
Figure 4.1 – Schematic diagram of typical Concrete pipe installation

Figure 4.2 – Schematic diagram of typical Steel, HDPE, or PVC pipe installation
4.2.1 Bedding / Cover / Embedment / Backfill

The OPSDs (800–series) provide the bedding, embedment, cover and backfill standards for the different pipe materials. A summary of the applicable OPSDs for each pipe material is provided in Table 4.1, which should be read in conjunction with OPSS 514 (April 1999). This OPSS provides the definitions of bedding, embedment, cover, granular and backfill materials.

Table 4.1 – Summary of Excavation and Backfilling OPSD References

<table>
<thead>
<tr>
<th>Pipe Material</th>
<th>Bedding / Embedment Option</th>
<th>OPSD Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>Earth Excavation (Soil Type 1 or 2)</td>
<td>802.030</td>
</tr>
<tr>
<td></td>
<td>Earth Excavation (Soil Type 3)</td>
<td>802.031</td>
</tr>
<tr>
<td></td>
<td>Earth Excavation (Soil Type 4)</td>
<td>802.032</td>
</tr>
<tr>
<td></td>
<td>Rock Excavation</td>
<td>802.033</td>
</tr>
<tr>
<td></td>
<td>Embankment</td>
<td>802.034</td>
</tr>
<tr>
<td>Steel</td>
<td>Earth Excavation (Soil Type 1 to 4)</td>
<td>802.010</td>
</tr>
<tr>
<td>HDPE</td>
<td>Rock Excavation</td>
<td>802.013</td>
</tr>
<tr>
<td>PVC</td>
<td>Embankment</td>
<td>802.014</td>
</tr>
</tbody>
</table>

Installation has a significant impact on construction costs and pipe performance. Specified trench widths, bedding class and thickness, embedment material, cover depths, and handling requirements, etc. may influence the choice of pipe materials. The selection of pipe material(s) should consider construction equipment costs and the costs associated with the required backfill. The cost of backfill depends on local availability of suitable materials and disposal of unsuitable site materials.

The results of a literature review performed by the National Research Council of Canada (NRCC, 1998a, co-funded by the Canadian Concrete Pipe Association) relating to installation benefits/risks for gravity pipes provides useful background information for consideration when selecting appropriate pipe type. Some of the findings of this study are included in the following paragraphs.

Bedding (or embedment) and backfilling (cover or embedment) are critical procedures 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. Low-quality bedding materials, though less expensive, require more compactive effort and the use of a stronger pipe. The MTO Contract Design Estimating and Documentation
manual (CDE&D) states that for pipes with diameters less than 600 mm, earth or native backfill may be used for embedment and cover material. However, for diameters greater than 600 mm, the use of granular material for embedment and cover material is required. Special provisions for any installation may be made by the Regional Geotechnical Section for extraordinary conditions.

The quality of embedment, cover and backfill materials is crucial not only for the pipe, but also for the adjacent surface structures. Excessive settlements may occur due to inadequate compaction and the use of poor embedment, cover or backfill materials. Small deflections of large diameter pipe itself may lead to excessive surface settlements. The pipe deflection limit is established to prevent distress to the pipe and to limit surface settlements.

Concrete – The different bedding types result in different earth pressure distributions around the pipe. Therefore, pipe strengths need to be designed based on the bedding type. Currently, the OPSDs use only types ‘B’ and ‘C’ bedding which require granular material. Each bedding type is associated with a different bedding factor, which determines the required pipe strength as measured by the three-edge-bearing test (D-Load test). The higher the bedding factor, the lower the required Class or strength of the pipe. During design, an assessment should be made to determine if site conditions warrant a low-quality bedding with a high-strength pipe, or vice versa.

The current OPSD installation procedures for concrete pipe are based on the traditional Marston–Spangler theory of earth loads that were developed in the 1920’s and 1930’s (OCPA, 1986) for trench and embankment installations. These methods are considered to be conservative (Zhao and Daigle, 2001). Modern soil-structure interaction analyses can be performed using finite element models for soil and structure, incorporating nonlinear behaviour, that account for changes in soil properties with stress level and the reduction in stiffness in reinforced concrete associated with cracking (CHBDC Section 7).

In lieu of the OPSD for circular pre-cast concrete pipe, “Standard Installations” for circular pre-cast concrete pipe are promoted in the American Society of Civil Engineers (ASCE/ANSI) Standard 15-93 and is often referred to as the Standard Installation Direct Design (SIDD) method. The SIDD method permits the use of many different bedding and embedment soils having specified levels of compaction that are appropriate for the specified standard installation type. This permits a designer to select appropriate soil materials based on local availability, cost and fill heights. Considering the wide range of soil conditions encountered in the different Regions of
Ontario, the SIDD method could be considered with modifications, but it has not yet been recognized as a provincial standard for roadway applications (Zhao and Daigle, 2001).

**HDPE and PVC** – Flexible pipes ‘shed’ load to the embedment materials surrounding the pipe. The amount of pipe deflection required to mobilize the support of the embedment materials reduces with an increase in the stiffness of the embedment material. Embedment material stiffness is achieved by proper selection and compaction of the embedment materials. Excessive compaction during installation or the presence of large particles in the embedment materials, may damage or distort the pipe (causing vertical or horizontal ‘ovalisation’); however, if adequate compaction is not achieved it may affect the long-term performance of the pipe structure. Embedment compaction should be monitored to ensure that pipe distortions beyond recommended limits do not occur. The pipe deflection should be within the specified limits (maximum of 5% in OPSS 514).

**Steel** - The stability and load-carrying capability of steel pipe depends on the lateral support of the backfill material. Satisfactory performance of steel pipe material types is achieved by proper selection and compaction of embedment materials. Excessive compaction during installation or the presence of large particles in the embedment materials, may damage or distort the pipe (causing vertical or horizontal ‘ovalisation’); however, if adequate compaction is not achieved it may affect the long-term performance of the pipe structure. Adequate on-site inspection during installation should be performed to ensure that pipe distortions beyond recommended limits do not occur. The pipe deflection should be within the specified limits (maximum of 5% in OPSS 514).

### 4.2.2 Frost Considerations

Special bedding requirements are needed when the top of the pipe (crown) is located above the frost penetration depth; however, the requirements are independent of pipe material type. The frost treatment required for Concrete, Steel, HDPE and PVC installations is provided in OPSD 803.030 and 803.031 (same for all pipe types). Particular attention is needed for pipe replacements or extensions during road rehabilitation works to ensure that the frost treatment details are maintained uniformly between old and new construction. The risks associated with freeze-thaw conditions are discussed later in the durability section of the guidelines.
4.2.3 Ultraviolet Radiation

The impact of exposure to ultraviolet (UV) radiation from sunlight on the different pipe materials was addressed in the NRCC Literature Review (NRCC, 1998b) and is summarized below.

There are no reports of UV degradation of concrete and steel. HDPE and PVC pipe when exposed to long term UV radiation, typically at the exposed ends of culverts, may 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.

With the use of carbon black (a UV stabilizer), HDPE pipe is protected against prolonged exposure to sunlight and the potential for UV degradation of mechanical properties.

UV stabilizers are used in PVC pipe materials to protect against UV degradation, although the longevity of these additives has not been proven. However, it is considered prudent, to protect the exposed ends of installed PVC (and to a lesser extent HDPE) pipe that include UV stabilizers. Once buried, except for exposed ends, exposure of plastic pipe to sunlight does generally not occur. Exposure issues can often be overcome if concrete or steel end walls are used. Outdoor storage practices should be managed by the manufacturers to ensure that the pipes are not subject to prolonged UV exposure prior to delivery to site.

4.2.4 Other Factors During Construction

During construction, culverts and storm sewer pipes may be subject to adverse conditions such as impact loading or extremely low temperatures (see Table 4.2). The selection of pipe material types may also be influenced by other factors. These factors are briefly discussed below.

ACCESS/CONSTRUCTION EQUIPMENT

OPSS 514 “Construction Specification for Trenching, Backfilling and Compacting” specifies a minimum fill height of 900 mm above the crown of the pipe before power operated tractors or rolling equipment can be used for compaction. OPSD 808.010 specifies different minimum heights of fill for different pipe material types for pipe protection against heavy equipment crossing as follows.
Concrete: Minimum height of fill = 1000 mm;

Steel, HDPE and PVC: Minimum height of fill = 800 mm or inner diameter (D)/4 plus 300 mm, whichever is greater.

These minimum fill heights are different than those shown in Table 6.1, which should be used for final design purposes.

The specified minimum heights for heavy equipment crossing may affect gravity pipe selection and may require the placement of temporary fill protection for pipes during construction. Depending on final grade restrictions, fill material costs and construction traffic, these minimum fill heights may influence the initial installation costs and should be considered in the life cycle cost analysis.

EXISTING “PIPE SYSTEM” CONDITIONS

Where new pipe is to be installed and incorporated into an existing pipe system, an assessment should be made of the existing pipe material type prior to design. If the existing pipe material is considered to be performing satisfactorily, preference should be made to using the same pipe material to minimize the risk of construction and performance issues related to connections, joints, geometrics, differential settlement, etc.

IMPACT RESISTANCE (BRITTLENESS) AND TEMPERATURE EFFECTS

During construction, pipes are required to withstand forces that are normally expected during shipment, handling and installation. In addition, rock fill is often used above the pipe cover material and impact from rock fragments that are used to form the side slopes and embankments will frequently roll onto exposed pipe ends or penetrate through the overlying cover/embedment soil of the pipe. Temperature effects all pipe materials differently. For normal operating temperatures experienced during highway construction projects in Ontario, the use of concrete, steel, high density polyethylene, and polyvinyl chloride is considered acceptable. Special provisions should be made when pipe installations are required in rare extreme temperature conditions (i.e. below -30°C) for emergency situations. The following table should be used as a guideline for minimum installation temperatures.
Table 4.2 – Minimum Pipe Installation Temperatures

<table>
<thead>
<tr>
<th>Pipe Material</th>
<th>Minimum Installation Temperature (^1) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>-30</td>
</tr>
<tr>
<td>HDPE</td>
<td>-30</td>
</tr>
<tr>
<td>PVC(^2)</td>
<td>-18</td>
</tr>
<tr>
<td>Steel</td>
<td>-30</td>
</tr>
</tbody>
</table>

Notes:  
1. Minimum operating temperature for workplace assumed to be -30 °C.  
2. AASHTO (2000) reports PVC as becoming brittle at exposure to temperatures less than 3 °C.

Concrete material compressive and tensile strengths are reported to increase with a reduction in operating temperatures. The effect of temperature on the impact strength of steel material is not considered an issue and the pipe itself can be designed to withstand handling and installation forces according to ASTM A796-93 (defined as the flexibility factor). HDPE material has an impact resistance ranging from about 0.27 to 0.80 Nm/mm; however, this can be reduced significantly by oxidation due to sunlight or by overheating during the manufacturing extrusion process. PVC material has an impact resistance of about 0.026 Nm/mm but can be increased to about 1.07 Nm/mm by blending with an impact modifier during the extrusion process. However, it should be noted that impact modifiers may reduce chemical resistance, increase susceptibility to oxidation, and increase permeability.

**ADJACENT EXCAVATION**

The influence of new excavations on existing buried Concrete, HDPE, PVC and Steel pipes has been well recognized. As discussed previously, HDPE, PVC, and Steel pipe rely on the load-transfer to the soil surrounding the pipe. Consequently, the installation of underground utilities may have more of an impact on adjacent, existing, buried HDPE, PVC, and Steel (i.e. flexible) pipe than on Concrete (i.e. rigid) pipe. In any case, once exposed, all pipe materials 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. Due to loss of lateral support, partial excavation and exposure, some pipes are likely to result in excessive deformation, disjointing, or may lead to collapse if
suitable protective measures are not undertaken. Protective measures include temporary shoring and/or minimum set-back criteria which depend on the size and depth of the pipe installation.

Another difficulty is related to locating existing pipe in the ground, and to prevent damage during excavation. Thicker walled or higher class pipe should be considered in areas where re-excavation is anticipated.

**USE OF CONTROLLED LOW-STRENGTH MATERIAL (UNSHRINKABLE FILL)**

Construction costs associated with backfilling may be reduced by using a controlled low-strength material (CLSM), otherwise known as “unshrinkable fill”. This material is a mixture of Portland cement, aggregates, water and optional admixtures. 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. Consideration can be given to using unshrinkable fill to effectively backfill Concrete, HDPE, PVC and Steel pipe, especially in the haunch area. The use of unshrinkable fill can greatly simplify the backfilling procedure. This is especially useful when working in confined urban areas. Approval from the MTO Regional Geotechnical and Structural Sections must be obtained in order to use unshrinkable fill. Costs can be reduced due to the fact that no compaction is required, and it may be possible to reduce the width of the trench subject to ground conditions. Caution must be exercised when using CLSM in Ontario because its use may result in differential frost heave, differential pavement performance and freezing of water in pipes due to its relatively high thermal conductivity. Another problem is that the use of CLSM tends to float the pipe, particularly if the pipe is light-weight. A staged process for installing CLSM for these conditions may be necessary to prevent flotation.

**PIPE FLOATING (BUOYANCY)**

Pipe flotation may occur for all pipe types in cases of high water table and low cover, when using “unshrinkable fill”, or during the backfilling procedure. Depending on the pipe material type, protection measures and the costs associated with providing these measures should be included in any cost comparison.
TRENCH BOX INSTALLATION

The use of trench box installation procedures is common in Ontario; however, there are concerns related to embedment, bedding, and cover soils being disturbed upon removal of the trench box after compaction. The improper use of the trench box can create voids that can lead to a reduction in lateral support, which is important to pipe structural design requirements. Consideration should be given to increasing the trench widths and/or providing stepped trench box removal to allow for adequate compaction around the pipe. Other construction methods exist that will mitigate the effect of improper trench box use.

GEOMETRICS OF PIPE WALL AND EMBEDMENT SOIL

Another issue regarding rib- and profile- walled pipe for Steel, HDPE and PVC, is the relationship between the geometrical design of the pipe wall and the gradation of the surrounding embedment soil. Poor compaction around the pipe may occur, if the rib/corrugation spacing is the same as the effective particle size of a well sorted soil gradation. Poor compaction of the backfill adjacent to the sides of the pipe may result in a large initial pipe deformation rate, until the embedment soil becomes denser as the springline region moves outward.

CONSTRUCTION AND POST CONSTRUCTION INSPECTION/TESTING SERVICES

Excessive pipe deflection can result in a loss of structural integrity for all pipe materials. Pipe deflection can be the result of excessive loading, poor backfill quality or compaction or the stiffness of the backfill material or it can be an indication that load is being transferred into the surrounding embedment soil. According to AASHTO (2000) deflections of less than 5% from design shape are generally not considered to be detrimental to pipe performance or longevity. However, greater deflections can lead to stress concentrations and increased potential for corrosion or cracking in all pipe materials. Similarly, localized distortions in the pipe wall may result in perforation and therefore a reduction in material service life. Deflections that increase over time indicate a potential problem in the backfill surrounding the pipe, such as soil migration, stability issues, water table fluctuations, etc.

A common method for testing of deflection tolerances in small pipes after installation and backfill is to draw a mandrel of a nominal size (typically 5% less than the mean pipe diameter) through the pipe to ensure there are no pinch spots. This approach is
also consistent with the MTO adoption of End Result Specification for other aspects of road construction. If the deflection is more than 5%, then further investigation, such as video inspection, should be performed to discover the reason for the deflection. Depending on the severity and extent of the pipe distortion, the pipe section may need to be replaced or designated for further monitoring. If future measurements show that the deflection continues to increase, then pipe replacement should be undertaken. Large diameter pipes may be examined for changes in long term deflection by visual inspection.

Satisfactory post-construction or maintenance inspection of the pipeline for all pipe types can be achieved using Closed Circuit Television techniques (i.e. video inspection). OPSS 409 “Construction Specification of Closed Circuit Television Inspection of Pipelines” can be used to check the condition of the pipeline. Defects such as cracking, corrosion, localized sags, perforations, misaligned joints, leakage and the overall condition of the pipe can be checked.

Experience has shown that the critical issue impacting long term pipe performance is the quality of the installation. If the pipe can be installed without damage and with adequate foundation and lateral soil support, it will perform very well during the estimated material service life. For this reason, routine post-construction mandrel testing on flexible pipe and video inspection on all pipes is specified by many municipalities for critical pipe systems. The use of such installation verification testing should be considered where pipe is used for critical sections of storm sewer or culverts, such as beneath median barrier wall or under 400 Series highways.

PIPE REHABILITATION / REPLACEMENT CONSTRUCTION TECHNIQUE

In cases where the Ministry has determined that remedial action is required on a section of pipe or when the Estimated Material Service Life has been exceeded, the method of construction to rehabilitate or replace the section of pipe must be considered. The identification of practical pipe rehabilitation/replacement strategies is especially important for life cycle costing analysis. The Federation of Canadian Municipalities (FCM) and the National Research Council (NRC) prepared a report entitled “Selection of Technologies for Sewer Rehabilitation and Replacement, A Best Practice by the National Guide to Sustainable Municipal Infrastructure” (NRC, 2003, www.infraguide.ca). As described in this best practices document, the following items should be considered before selecting the appropriate rehabilitation/replacement technology which is directly related to pipe material type options:
• Construction issues including safety, operability, neighbourhood disruption, cost, and efficiency;

• The size of the contract, as smaller contracts may preclude some technological alternatives due to the cost of mobilizing specialized equipment and personnel;

• Risk impacts and mitigation options related to the project, focusing on environmental and constructability issues, and anything that may adversely affect the project’s objectives;

• Local availability of the various technologies, as some technologies are not yet available in certain geographic areas of Canada;

• The depth of the pipe installation, which may limit the technologies available to rehabilitate/replace that pipe;

• The density of lateral connections, which can substantially increase the overall cost of construction of some of the new technologies, if excavations are required to reconnect the sewer laterals; and

• Roadway condition (traffic volumes, surface conditions, and remedial requirements), which may encourage or discourage the open cut method.

After considering the above issues, the technologies available for the rehabilitation/replacement of pipes can be determined based on the specific situation. The above referenced publication identifies problems, addresses possible causes of problems, provides structural capacity mitigation options (full replacement/structural rehabilitation, non-structural, or semi-structural rehabilitation), and identifies the possible technologies to remedy the situation. The following technologies are available and discussed further in the best practices document, including the benefits and drawbacks for each:

• Open cut construction;
• Sliplining;
• Diameter reduction sliplining;
• Fold and form sliplining;
• Cured-in-place pipe (CIPP);
• Pipe bursting;
• Horizontal drilling (a.k.a. horizontal directional drilling);
• Internal joint seals;
• Panel and section insert linings;
• Chemical grouting;
• Full tunneling and micro-tunnelling;
• Auger boring; and
• Pipe eating.

There is rapid technological development in all types of in-situ pipe replacement and repair. Thus, over time, alternatives to open cut replacement will become more available and more cost-effective.
Chapter 5.0 Hydraulic Evaluation

5.1 Introduction

The detailed hydraulic design of gravity pipe systems is outside the scope of these guidelines. A hydraulic analysis, performed by a qualified and experienced drainage engineer, is required for all culvert and storm sewer systems using the procedures and standards outlined in the MTO Drainage Management Manual, 1997 and is usually performed as part of the Drainage Design Report. In these guidelines, simple hydraulic equivalencies are used to ensure that the range of pipe types and size alternatives from all pipe options are considered in a Drainage Design Report. However, it is stressed that all viable pipe options that are brought forward from using these guidelines for inclusion in a project specification, must have their hydraulic capacity and performance confirmed by a drainage engineer and adjustments made to pipe diameters, where deemed necessary. Different pipe materials may have different inlets, outlets, connections, roughness coefficients, etc. which may need to be analyzed separately to determine the minimum hydraulic design diameter for a certain pipe material, taking into account the entire water system (e.g. inlet control, outlet control, headwater and tailwater elevations, etc.).

5.2 Hydraulic Considerations

The objective of the hydraulic evaluation component of these guidelines is to identify a series of alternative pipe materials which may have a range of inside wall roughness characteristics, but which all have the same overall hydraulic capacity.

Considering that different pipe materials have different inlet structures, Manning coefficients, standard inside diameters, etc., the drainage engineer must perform the required number of analyses to determine minimum design inside diameters for the available pipe material options.
Starting from a hydraulically designed pipe section, the Manning Equation may be used as a method to determine the equivalent, hydraulic efficiency of different pipe materials under uniform flow conditions. The Manning Equation is shown below.

\[ Q = \frac{1}{n} \left( A \right)^{2/3} \left( R \right)^{1/2} \left( S_o \right)^{1/2} \quad \text{(SI Units)} \]

where

- \( Q \) = total discharge flow (m³/s)
- \( n \) = Manning roughness coefficient (i.e. Manning number)
- \( A \) = Inside area of the pipe (m²)
- \( R \) = Hydraulic radius (m)
- \( S_o \) = Slope of pipe (m/m)

Nomographs provided in the MTO Drainage Management Manual (e.g. Design Charts 2.29 and 2.30 for circular pipes) can be used to obtain preliminary inside pipe diameters for a given flow rate and gradient for different pipe materials (i.e. different Manning coefficients). A range of roughness coefficients for different pipe materials and sizes is provided in Table C6 in Appendix C. As referenced in the step-by-step design procedure in Chapter 1, Figure B1 (Appendix B) provides a chart for calculating equivalent pipe diameters based on the Manning Equation assuming circular pipe, full flow conditions, constant slope, and constant total flow.

The hydraulically equivalent pipes identified are checked against all pipe manufacturers’ product listings to determine if the required diameter is actually produced. Due to the complex nature of culvert and storm sewer hydraulics, a drainage engineer must confirm the hydraulic acceptability of the pipe materials identified through the use of appropriate analysis methods as outlined in the MTO Drainage Management Manual.

Due to serviceability/maintenance requirements, the MTO specifies minimum pipe diameters for culverts based on the highway application, as shown in Table C7 in Appendix C. The table was taken from the MTO Contract Design Estimating and Documentation Manual (CDE&D). Where the calculated hydraulic design diameters are less than the minimum serviceability design diameters given in Table C7, the minimum serviceability design values shall be used.
Chapter 6.0 Structural Design Evaluation

Structural design needs to be performed once the hydraulic analysis establishes the inside pipe diameter. In the structural design of underground pipe systems, one must recognize that an integral relationship exists between the behaviour of the pipe and the behaviour of the soil in which it is buried (i.e. soil-structure interaction). Traditionally (and in accordance with the current OPSD-800 series), two general pipe structural design procedures are used depending on whether the pipe is considered rigid or flexible. Referring to the language used in the current OPSDs, Concrete (reinforced and non-reinforced) is referred to as rigid pipe, and HDPE, PVC and Steel are referred to as flexible pipe.

The structural design of concrete pipe has traditionally required the pipe to be significantly stiffer than the surrounding soil; the pipe is designed to resist the applied loads from the surrounding soil. The design of Steel pipe, HDPE and PVC (i.e. flexible pipe) relies on the capacity of the surrounding soil to carry a major portion of the load applied to the pipe.

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 Concrete, HDPE, PVC, and Steel pipe systems.

Current practice in Ontario, for confirming the structural design of a particular pipe type, is to refer to “fill height tables” that indicate the maximum acceptable loading for each of the pipe products generally available in Ontario. The current OPSDs provide the maximum and minimum fill heights (measured from top of pipe) based on the installation standards outlined in Section 4.2 for each type of pipe. The OPSD maximum fill height tables are based on traditional trench and embankment soil loading methods for Concrete, HDPE, PVC, and Steel pipe materials. The OPSD fill
height tables are updated from time to time and are generally considered to be conservative for initial conditions.

The minimum and maximum fill height tables facilitate the structural design of the different pipe material types, diameters, bedding/embedment conditions, and trench/embankment installations. Based on these factors, the designer can select the minimum pipe design requirements (e.g. pipe wall thickness and/or corrugation profile and/or Class of pipe) for a specific pipe application.

Pipe materials that satisfy the structural design requirements, including all available wall thicknesses, coatings/laminations, profiles, classes, etc. must then be evaluated to establish the Estimated Material Service Life (EMSL). In most design cases, the EMSL should meet or exceed the Design Service Life (DSL) considering all relevant environmental factors for the site.

### 6.1 Minimum Fill Height

Minimum fill heights, to prevent damage to pipe from traffic loading, are referenced in the current OPSDs as summarized in Table 6.1 below. These values may be adjusted in the future based on submissions, review and acceptance by the OPS committee.

#### Table 6.1 – Minimum Fill Height OPSD References

<table>
<thead>
<tr>
<th>Pipe Material</th>
<th>Minimum Fill Height (H&lt;sub&gt;min&lt;/sub&gt; = top of pipe to top of subgrade at low point of low shoulder)&lt;sup&gt;1&lt;/sup&gt;</th>
<th>OPSD Reference&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>600 mm</td>
<td>807.01, 807.03, 807.04</td>
</tr>
<tr>
<td>Steel</td>
<td>300 mm to 600 mm</td>
<td>805.010, 805.030</td>
</tr>
</tbody>
</table>
| HDPE<sup>3</sup> | 300 mm or diameter of pipe (whichever is greater) for Class ≥ 320 kPa  
800 mm or diameter of pipe (whichever is greater) for Class < 320 kPa | 806.02 |
| PVC           | 300 mm or diameter of pipe (whichever is greater) for Class ≥ 320 kPa  
800 mm or diameter of pipe (whichever is greater) for Class < 320 kPa | 806.040, 806.06 |

<sup>1</sup>The minimum fill height for all entrance pipes is 300 mm (MTO Contract Design and Estimating Manual, pg. B421-7).

<sup>2</sup>Most of these OPSDs have been updated and are currently under revision by OPS.

<sup>3</sup>For HDPE Closed Profile pipe (smooth inside and outside), there is currently no OPSD minimum fill height provided. Any design criteria should be submitted to MTO and OPS for approval prior to being considered for a project.
The minimum fill height given in the OPSDs is measured from the top of the pipe to the top of subgrade at the low point of the low shoulder (i.e. hingepoint) as shown below in Figure 6.1. For all pipe materials, frost protection measures must be provided where necessary according to OPSD 803.030 and 803.031. The requirements are the same for all pipe material types.

![Figure 6.1 – Schematic diagram of minimum fill height measurement location](image)

### 6.2 Maximum Fill Height

Maximum fill height tables are referenced in the current OPSDs as summarized in Table 6.2 below. Most of these OPSDs are in the process of being updated and are currently under revision by MTO and OPS.

<table>
<thead>
<tr>
<th>Pipe Material</th>
<th>Maximum Fill Height Conditions</th>
<th>OPSD Reference</th>
</tr>
</thead>
</table>
| Concrete<sup>1</sup> | Reinforced Concrete – Confined Trench  
Reinforced Concrete – Positive and Zero Projecting Embankment  
Non-Reinforced Concrete – Confined Trench, Positive and Zero Projecting Embankment | 807.01  
807.03  
807.04 |
| Steel | Corrugated Steel Pipe based on trench width specified in OPSD. | 805.01 |
| HDPE | Class 210 kPa or 320 kPa can be chosen based on trench width which affects loading conditions. | 806.02 |
| PVC | Class 320 kPa values are given (Class 210 not available in Ontario) based on trench width  
Maximum Standard Dimension Ratio (SDR)<sup>3</sup> can be chosen | 806.040  
806.06 |

Notes:
1. $H_{\text{max}}$ = Maximum Cover (m) as referenced in OPSDs.
2. Confined trench, positive and zero projecting embankment conditions are shown in Figure 6.2. Currently, maximum fill heights are only given for pipe diameters up to 1,800 mm for concrete pipe in the OPSDs.
3. $SDR = \frac{\text{Outside diameter of pipe (mm)}}{\text{Wall thickness (mm)}}$. 

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The maximum height of fill is measured from the top of the pipe to the top of the pavement or roadway surface. The maximum height of fill over the top of the pipe is dependent on bedding details and installation methods. As a result, designers shall specify on the plans, as appropriate, the bedding detail and installation method for each pipe material selected.

Concrete Pipe – The current OPSS and OPSDs for concrete pipe are based on the Marston–Spangler method for earth loads in trench and embankment installations (Zhao and Daigle, 2001). This method is referred to as the “indirect design method” because the strength of a pipe is determined by the three-edge bearing test (D-Load test), and then related to the field strength through bedding factors. Based on this method, originally four types of bedding were developed for the OPSDs. However in typical practice, types ‘B’ and ‘C’ are used. The current OPSD fill height tables reference different fill heights for Bedding types ‘A’, ‘B’ and ‘C’. Type ‘A’ consists of concrete cradles, but is rarely used in practice.

The minimum Class of pipe to be chosen by a designer for a maximum cover (i.e. fill height) is specified as 50-D, 65-D, 100-D or 140-D for reinforced concrete pipe. These designations relate to the D-Load test which is performed in a controlled environment by the manufacturer. Other Classes are available for reinforced concrete pipe that are not referenced in the OPSD specifications.

For non-reinforced concrete pipe, only one Class (Class 3) of pipe is available in Ontario. For this case, only the trench width (i.e. embankment or confined trench conditions) and bedding type need to be selected by the designer.

Steel Pipe – The maximum fill height tables for CSP and SPCSP in the current OPSDs are dependent on corrugation profile and wall thickness for a range of nominal diameters. The designer should select the corrugation profile and the corresponding
minimum thickness of steel (i.e. gauge) required to support the fill height (i.e. depth of cover) anticipated for any given project. In Ontario, there are two corrugation profiles available for CSP (68x13 and 125x25), one profile available for Structural Plate CSP (152x51), and one corrugation profile for SRP (19x19x190). Fill height tables for other corrugation profiles and SRP should be established by the manufacturer and submitted for review and acceptance by OPS.

**HDPE Pipe** – The maximum fill height tables for HDPE in the current OPSDs are dependent on pipe stiffness (i.e. Class) and trench width. Typically, the minimum trench width is assumed based on the minimum allowable width from the OPSD installation requirements. From the table, the HDPE pipe Class (Class 210 or Class 320 for corrugated inside and outside wall and Open Profile - corrugated outside and smooth inside wall pipe) is checked by the designer to confirm that the maximum fill height (i.e. maximum cover) that the pipe can support is greater than the anticipated field height of fill.

For HDPE Closed Profile pipe (smooth inside and outside), there is currently no OPSD maximum fill height tables; however, design tables have been submitted to OPS and are currently under review. The design for this profile wall pipe (ASTM F894) should conform to the design requirements outlined in AWWA C950, Appendix C. If OPSD maximum fill height tables are not available for a certain product, any design criteria should be submitted to MTO and/or OPS for approval prior to being considered for a project.

**PVC Pipe** – The maximum fill height tables for PVC in the current OPSDs are dependent on pipe type (profile or solid wall pipe). For Profile Wall pipe, pipe stiffness (i.e. Class) and trench width are the key variables. Currently, only Class 320 PVC pipe is available in Ontario. For Solid Wall PVC pipe, the type of backfill and Standard Dimension Ratio (SDR) are the controlling factors for maximum fill height. An understanding of the cost differences related to jointing and the pipe material assists the designer in selecting the most appropriate PVC pipe type.

Typically, the minimum trench width is assumed based on the minimum width given in the OPSD specification. For the design of Profile Wall pipe, trench width is checked by the designer to confirm that the maximum fill height that the pipe can support is greater than the anticipated fill height in the field. If Solid Wall pipe is considered in the design, the maximum SDR value must be specified, and the type of cover material (rock fill, sand and gravel, or clay) should be verified in the field to ensure that the cover material is consistent with the design assumptions.

A summary of the design parameters that need to be specified for each material are provided in Table 6.3 (based on OPSD minimum and maximum fill height tables).
Table 6.3 – Pipe Material Properties to be specified during Structural Evaluation

<table>
<thead>
<tr>
<th>Pipe Material</th>
<th>Manufacture Type(^a)</th>
<th>Class(^3)</th>
<th>Pipe Wall Thickness</th>
<th>Corrugation Profile</th>
<th>Trench Width</th>
<th>Bedding Type</th>
<th>Joint Type(^1)</th>
<th>Fill Type(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>Reinforced</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Non-reinforced</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Steel</td>
<td>CSP (68x13, 125x25)</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>SPCSP (152x51)</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Spiral Rib (19x19x190)</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>HDPE</td>
<td>Corrugated Inside and Outside</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Open Profile - corrugated outside and smooth inside</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Closed Profile – Smooth inside and outside</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>PVC</td>
<td>Profile Wall</td>
<td>Yes</td>
<td>No</td>
<td>Yes (SDR)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Solid Wall</td>
<td>No</td>
<td>Yes (SDR)</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

NOTES:

1Joint type is not dependent on structural design; however, it should be specified at this point in order to choose the correct material and manufacture type.

2Fill type used for the maximum fill height calculation is only an option for solid wall PVC in the current OPSDs. This may become an option for all pipe material types in future versions of the OPSDs and maximum fill heights should possibly be scaled in accordance with the assumed and actual embankment unit weights.

3The Class of the pipe referring to D-Load testing for Concrete or pipe stiffness for HDPE and PVC must be specified.

4All pipe manufacture types not included in the OPSDs need to be evaluated using procedures outlined in Section 6.3.
6.3 Other Structural Design Methods

Maximum and minimum fill heights for pipe materials and sizes not listed in the OPSDs should be evaluated using methods that are approved by MTO. Common structural design methods used in the industry are provided in the following references:

- Canadian Highway Bridge Design Manual (CSA, 2000), Section 7 “Buried Structures” (for Steel and Concrete);
- AASHTO (2003) structural design and materials specifications for CSP, HDPE and PVC);
- ASTM A 796-93 / A 796M or latest version (for CSP);
- Corrugated Polyethylene Pipe Association (CPPA, 2000) publication “Structural Design Method for Corrugated Polyethylene Pipe” (for HDPE);
- Uni-Bell (Uni-Bell, 2001) software program “External Load Designs for Flexible Conduits” (for PVC and HDPE);
- American Concrete Pipe Association (ACPA 1990) software program “SPIDA” (for Concrete);
- Handbook of Steel Drainage and Highway Construction Products (CSPI/AISI 2002); and
- Direct Design or Finite Element Analysis models.

Application of these methods must be approved by the MTO. The current OPSDs and any alternative structural design methods should be checked to ensure that the parameters used in the structural design meet the short-term and long-term conditions assumed for the Estimated Material Service Life. Predictions of future structural performance are based on proven field performance, laboratory studies and theory associated with a given pipe type. An increased level of risk exists when predicting long-term structural performance based on less established methods.

For live loading such as railway loading, aircraft loading, impact or seismic loading (other than typical highway traffic live loading), a detailed design is required to determine minimum and maximum allowable fill heights. Railroad or highway loads may be ignored when the induced vertical stress fields are equal to or less than 4.8 kPa (USACE, 1998).
Chapter 7.0 Durability Design Evaluation

Durability is defined as the ability of a pipe to withstand, to a satisfactory degree, the effects of service conditions to which it is subjected; it is the ability of a pipe to resist wear and decay (NRCC, 1998b). The long-term performance and durability of storm sewer/culvert pipes (i.e. service life) are directly related to their corrosion resistance to various chemical and biological action (from soil and water), as well as mechanical resistance to abrasion, fire, temperature extremes and sustained loading. According to AASHTO (2000), some of the factors influencing corrosion and physical degradation that must be considered in any estimation of service life are:

- Hydrogen-ion concentration (pH) of the surrounding soil and water;
- Soil and water resistivity, chloride and sulphate concentrations;
- Abrasion (i.e. bedload characteristics and velocity/frequency of flow);
- Anticipated changes in watershed water quality upstream due to development, industry, mining, or logging;
- Presence of chemicals or contaminants;
- Possible effects of severe climates (e.g. freeze–thaw, acid rain); and
- Material property characteristics (pipe type).

7.1 Corrosion

Corrosion is the destruction of pipe material by electrical and chemical action. Most commonly, corrosion attacks steel pipe, or the steel reinforcement in concrete pipe, during the process of returning metals to their native state of oxides or salts. Similar processes can occur to the cement in concrete pipe if subjected to highly alkaline soils. Other pipe materials (i.e. PVC and HDPE) can react similarly if subjected to certain chemicals and solvents (e.g. petroleum products or certain chemicals as a result of highway spills) and prolonged long-term exposure to chemicals related to pesticide use.

According to AASHTO (2000), for corrosion to occur, an electrolytic corrosion cell must be formed. This requires four basic components:
1. **Electrolyte** – soil moisture in the vicinity of buried pipes, or liquid within the pipe, carrying ionic current between the anode and the cathode;

2. **Anode** – a region of a metallic surface (possibly the pipe itself) on which oxidation occurs, giving up electrons with metal ions going into solution or forming an insoluble compound of the metal;

3. **Cathode** – a region of a metallic surface (possibly the pipe itself) that accepts electrons and does not corrode;

4. **Conductor** – a metallic connection (possibly the pipe itself) that permits electrical current to flow by completing the circuit.

Corrosion prevention for buried pipes is accomplished by rendering ineffective one or more of the four components noted above. As electrons move from the anode to the cathode, metal ions are released into solution, resulting in characteristic pitting or the formation of an oxide at the anode location.

Corrosion can affect the inside (water-side), the outside (soil-side), the internal wall structure of a pipe, or all of the above. The potential for corrosion to occur, and the rate at which it will progress, is variable and dependent upon a variety of factors. Depending on a given corrosive environment, increased pipe wall thickness, additional cover on reinforcing steel or special coatings/laminations may be required to provide adequate corrosion protection. Good quality backfill (i.e. clean, high resistivity embedment, bedding and cover soils) and installation procedures will also enhance durability of the pipe material.

### 7.1.1 Hydrogen Ion Concentration (pH)

The pH value is defined as the log of the reciprocal of the concentration of hydrogen ion in a solution, with a value of 7 representing a neutral solution. Values of pH in natural water generally fall within the range of 4 to 10. A pH of less than 5.5 is usually considered to be strongly acidic, while values of 8.5 or greater are strongly alkaline (AASHTO, 2000).

The exact role pH plays in corrosion is inconclusive; however in general, a pH reading that is either highly acidic or alkaline is indicative of an increased potential for corrosion. The lowest pH levels (most acidic) are typically in areas that have relatively high rainfall levels. The runoff and percolation leach the soluble salts, with the resultant soil becoming acidic. Other potential sources of acidic runoff include mine wastes, which often contain sulphuric and sulphurous acids. Milder acids can be found in runoff, from marshy or swampy areas, that contain humeric acid, and in mountain runoff containing carbonic acid.
Conversely, arid areas are much more likely to be alkaline due to soluble salts contained in groundwater being drawn to the surface through capillary action, and precipitating after evaporation occurs.

Generally, soil or water pH levels between 5.5 and 8.5 are not considered to be detrimental to culvert durability (AASHTO, 2000).

The water that becomes the flow water in a culvert or storm sewer, originates as precipitation. However, its chemical composition changes as it goes from precipitation to runoff. In Ontario, the pH of flow water typically follows a cycle as illustrated schematically in Figure 7.1. Specifically, the effects of acid rain (from industrial emissions and other air pollution), road salts (from winter maintenance operations), exposed bedrock and soils, and soft water, tend to control the overall acidity of the flow water in pipes in road applications in Ontario. As water flows over and through carbonate soils and rock, the pH level and water hardness tend to increase. As flow water picks up and dissolves salts, its resistivity tends to decrease. Surface and subsurface water throughout Ontario is generally in the pH range of 6 to 8 (CSPI, 2004). The pipe exposure conditions are made worse when side ditches are poorly maintained and road salt contaminated water stagnates and evaporates in the ditches and connecting culverts.
7.1.2 Soil and Water Resistivity

As described in AASHTO (2000), resistivity of soil is a measure of the soil’s ability to conduct electrical current. It is affected primarily by the nature and concentration of dissolved salts, as well as the temperature, moisture content, compactness, and the presence of inert materials such as stones and gravel. The greater the resistivity of the soil, the less capable the soil is of conducting electricity and the lower the corrosive potential.

The unit of measurement for resistivity is ohm-centimetres (the electrical resistance between opposite faces of a one-centimetre cube). Typical resistivity values for soil and water are provided in Tables 3.1 and 3.2 in Chapter 3. Table 3.3 correlates the resistivities provided in Table 3.2 to the general corrosiveness of different soil types.
As described in Chapter 3, these tables are for general guidance only, to aid the designer in understanding the relevance of differentiating between soil types and the typical range in resistivity values. According to AASHTO (2000), soil resistivity values in excess of 5000 ohm-cm are considered to present limited corrosion potential. Soil and water resistivities below the range of 1000 to 3000 ohm-cm will usually require some level of pipe protection, depending upon the corresponding pH level and pipe material type.

Conductivity, the reciprocal of resistivity, is often used as the criterion for corrosive potential. Conductivity is a measure of a material’s potential to carry electrical currents. It is typically measured in units of millisiemens per centimetre (mS/cm) or Total Dissolved Solids (TDS) in ppm. To convert into resistivity units, one siemen is equal to the inverse of one ohm.

7.1.3 Electro-Chemical Corrosion of Steel

Steel corrosion, whether it is CSP or steel reinforcing in concrete, can be accelerated in the presence of many aggressive chemicals, such as chloride ions, inorganic acids or low-pH and high-humidity environments.

Corrosion of steel is an electro-chemical process where the metallic iron is oxidized to form iron oxide or ferrous ions, depending on the pH level 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). In an acidic environment (i.e. low pH), steel dissolution occurs, while in an alkali environment (i.e. high pH), steel forms an oxide film.

Steel dissolution is severe in an acidic solution; whereas in an alkaline solution, it can be stabilized because of the oxide film formed on the surface of the steel member. However, this protective film can be broken down in the presence of such aggressive ions as chloride ion and when pH is reduced below 8.

Reinforced concrete has a concrete cover that acts as a physical barrier to protect the reinforcing steel from aggressive chemicals, and provides a highly alkaline environment that inhibits the reinforcing steel from corrosion. Because concrete is permeable to moisture (particularly cast-in-place concrete), it can serve as an electrolyte when in contact with the reinforcing steel. Dry-cast concrete used in the production of pre-cast pipe has a lower permeability and provides protection for the embedded steel. Bare steel, which occurs at locations where concrete cover has spalled off reinforcing bars, is likely to form a potent corrosion cell, resulting in accelerated degradation (TRB, 1998).

Therefore, bare steel is vulnerable to aggressive chemical attack. Galvanized zinc coatings for steel pipe are standard practice in Ontario. When zinc or aluminized coatings are applied to the interior and exterior of the steel pipe, corrosion resistance is increased. The coatings provide a sacrificial metallic layer for acidic environments.
Polymer laminates applied to the interior and exterior of the steel pipe provide a protective barrier against corrosion in aggressive environments.

Table 7.1 summarizes the risks associated with corrosion susceptibility of the four pipe materials.

### Table 7.1 Corrosion Susceptibility of Various Pipes

<table>
<thead>
<tr>
<th>Corrosion Type</th>
<th>Concrete</th>
<th>Steel</th>
<th>HDPE</th>
<th>PVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid Corrosion</td>
<td>✓</td>
<td>✓</td>
<td>✓ (Note 1)</td>
<td></td>
</tr>
<tr>
<td>Sulphate Ion Corrosion</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloride Ion Corrosion</td>
<td>✓ (Note 4)</td>
<td>✓ (Note 5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaching</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bacteria-Induced Corrosion</td>
<td>✓</td>
<td>✓</td>
<td>(Note 2)</td>
<td>(Note 2)</td>
</tr>
<tr>
<td>Certain Solvents</td>
<td>✓ (Note 6)</td>
<td>✓ (Note 1)</td>
<td>✓ (Note 3)</td>
<td></td>
</tr>
<tr>
<td>Slow Crack Growth</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

**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 sulphuric acid may also affect the properties of HDPE pipe. It should be noted that different resins are used for manufacture of HDPE pipe conforming to CSA and ASTM Standards, which affect pipe performance.
2. Both PVC and HDPE pipe resins have high resistance to bacterial attack (TRB, 1998).
3. PVC pipe has good resistance to most chemical attacks, except aromatic or chlorinated hydrocarbons, ketones and esters.
5. Polymer laminates on steel pipe provide a barrier against chloride corrosion.
6. Polymer laminates on steel pipe are susceptible to certain solvents and chemicals described in Note 1.

Descriptions of the various chemical, biological and physical degradation factors, included in Table 7.1, are provided in NRCC (1998b) and are summarized as follows:

#### 7.1.4 Acid Corrosion

Concrete - Although more severe in domestic and industrial sewer applications, acid corrosion occurs mainly at the interior surface above the flow line of the pipe, due to the aggressive nature of the sewage or flow water. There are two major causes of
internal corrosion (mainly for sanitary sewers), one is the conventional acid attack, caused by low pH and the other is generally referred to as aerobic bacteria-induced sulphuric acid corrosion (described later in this section). The effects of dilute sulphuric or carbonic acid attack are less severe if siliceous aggregates are used, as opposed to aggregates such as limestone or dolomite.

### 7.1.5 Sulphate Corrosion

Sulphates can occur naturally or may result from man’s activities, most notably mine wastes. Sulphates, in the form of hydrogen sulphide, can also be created from biological activity. This is more common in wastewater and sanitary sewers, or under marshy or swampy conditions. Sulphates can combine with oxygen and water to form sulphuric acid (see bacteria induced corrosion).

Sulphates are typically more damaging to concrete (typically cast-in-place), although high sulphate concentrations can lower pH and, thus, be of concern to metal culverts (AASHTO, 2000).

Soils containing a high concentration of sulphates, such as sodium sulphate, calcium sulphate and magnesium sulphate, initiate sulphate attack at the exterior of the embedded concrete pipe surface. Because it is the groundwater that dissolves and carries sulphate into the soil, sulphate attack on concrete structures occurs only when the groundwater level rises above the pipe invert. Sulphate attack on concrete pipe is physically identifiable as a whitish appearance on the concrete surface. Damage usually begins at the edges and is followed by progressive cracking and spalling. This condition eventually reduces the concrete to a friable or soft state as a result of sulphate combining with the lime in cement to form calcium sulphate, which is structurally weak.

According to AASHTO (2000), concrete pipe is normally sufficient to withstand sulphate concentrations of 1000 ppm or less. For higher concentrations of sulphate, the use of sulphate resistant cement is advisable and should be specified.

The following guidelines (see Table 7.2) are provided in AASHTO (2000), which are similar to the guidelines provided in CSA A23.1 and CSA A3001-03 “Cementitious Materials for Use in Concrete” for the requirements of concrete subjected to sulphate attack:
Table 7.2 – U.S. Bureau of Reclamation Criteria for Sulphate Resisting Concrete Pipe

<table>
<thead>
<tr>
<th>Relative Degree of Sulphate Attack</th>
<th>Water-Soluble Sulphate (as $SO_4^-$) in Soil Samples (%)</th>
<th>Sulphate (as $SO_4^-$) in Water Samples (ppm or mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negligible</td>
<td>0.00 to 0.10</td>
<td>0 to 150</td>
</tr>
<tr>
<td>Moderate¹</td>
<td>0.10 to 0.20</td>
<td>150 to 1,500</td>
</tr>
<tr>
<td>Severe²</td>
<td>0.20 to 2.00</td>
<td>1,500 to 10,000</td>
</tr>
<tr>
<td>Very Severe³</td>
<td>2.00 or more</td>
<td>10,000 or more</td>
</tr>
</tbody>
</table>

Notes:

¹ Use Type II cement (or CSA A3001-03 specified Type MS/MSb, MH/MHb or HS/HSb).
² Use Type V cement (or CSA A3001-03 specified Type HS/HSb), or approved Portland-pozzolan cement providing comparable sulphate resistance when used in concrete.
³ Use Type V cement (or CSA A3001-03 specified Type HS/HSb) plus approved pozzolan which has been determined by tests to improve sulphate resistance in concrete when used in concrete with Type V cement.

7.1.6 Chloride Corrosion

Chlorides primarily attack exposed metal, whether it be steel pipe or reinforcing steel in concrete pipe. In particular, steel pipes without polymer laminate or concrete pipes where cover is inadequate, cracked or highly permeable.

Dissolved salts containing chloride ions can be present in the soil or water surrounding a pipe. Chlorides will also be of concern at coastal locations or near brackish water sources such as flow water affected by road salts.

Dissolved salts can enhance durability if their presence decreases oxygen solubility. However in most cases, corrosive potential is increased as the negative chloride ion decreases the resistivity of the soil and/or water and destroys the protective film on anodic areas (AASHTO, 2000). Dissolved salts have also been attributed with promoting oxidation on polyethylene (Henry and Garton, 1989).

In an environment with pH > 8, it is generally believed that chloride ions interact with the hydrous oxide layer, in competition with the OH- ions. The chloride ion destroys the iron oxide film to form a highly water-soluble product ($FeCl_3$), which diffuses from the steel surface and reacts with any encountered OH- or water ($H_2O$) to form a
corrosion product, Fe(OH)$_2$ (Gu et al., 1994). Thus, bare steel is not durable, unless protective coatings are applied.

Reinforced concrete pipe is, to a certain degree, vulnerable to chloride ingress from the external environment. The chloride can enter concrete through a combination of convection, diffusion and capillary action. Convection is limited to those conditions where a hydrostatic pressure difference drives chloride into the concrete (e.g. high water table or constant stream flow). Diffusion is the dominant mechanism when concrete is saturated, and a chloride concentration gradient exists. However, due to the alkaline environment of the concrete, reinforcing steel is protected by a passive oxide layer. The high resistance of this layer limits corrosion. However once penetrated, the corrosion of the reinforcing steel causes cracking and spalling of the concrete layer due to volume expansion as a result of the chemical process.

Pre-cast (zero slump) concrete pipe is generally not subject to significant chloride corrosion. For cast-in-place structures, the effects of these conditions can be mitigated by ensuring adequate compressive strength, limiting the water/cement ratio (to control porosity and permeability), and the proper use of admixtures (Potter, 1988).

### 7.1.7 Leaching of Concrete

The chemistry of both the pipe flow water and groundwater (if applicable) surrounding the concrete influences the leaching rate of concrete. Concrete constituents such as alkali oxides, potassium, sodium and free lime (Ca(OH)$_2$) can be leached out of concrete over time. The leaching of the concrete constituents, especially Ca(OH)$_2$ increases the porosity of the concrete matrix. As a result, the concrete has lower strength, and ingress of deleterious chemicals, such as sulphate and chloride ions, is accelerated. Leaching increases as the pH of the flow water and groundwater becomes more acidic (i.e. pH decreases). The acidification of water is especially prevalent when bicarbonates are present from CO$_2$ dissolution or vegetation decay. Studies suggest that a water concentration of 20 ppm, or more, of dissolved CO$_2$ is sufficient to cause significant deterioration of concrete through leaching. The deterioration of concrete in soft water is essentially caused by dissolution and subsequent leaching of free lime. When the concrete is in contact with air, the carbonation process (i.e. free lime reacting with CO$_2$) may form a carbonate layer which acts as a barrier to leaching of the free lime when the concrete is exposed to soft water (Zhang, 1996).

### 7.1.8 Biological Deterioration (Bacteria-Induced Corrosion)

As discussed in NRCC (1998b), biological deterioration refers to the breakdown of pipe materials promoted by the presence of bacteria, which is usually present on the interior walls of culvert and sewer pipe. The mechanism of bacteria induced corrosion (or microbial induced corrosion) is not always clear; however, the process can:
• Produce acids (such as sulphuric, formic, and acetic acids);
• Destroy protective coatings;
• Create corrosion cells;
• Produce hydrogen sulphide (H\textsubscript{2}S);
• Concentrate anions and cations; and
• Oxidize metal to ions.

In other words, microorganisms do not create a new corrosion mechanism but only accelerate the processes which cause corrosion (Peng et al., 1993). The bacteria that induce corrosion are usually among three groups; namely, sulphate reducers (to form hydrogen sulphide in anaerobic conditions), acid producers (forms sulphuric acid), or metal ion concentrators/oxidizers. Sufficient moisture is essential for the growth of the bacteria and there must be an adequate supply of hydrogen sulphide, carbon dioxide, nitrogen compounds and oxygen (present in some swamp or marsh areas). Bacteria Induced Corrosion usually occurs in high sulphate concentration in water with pH between 5.5 and 8.5. These bacteria are most commonly found in sewage systems; however, they can also be found in storm and culvert applications.

Typically, hydrogen sulphide is produced biologically from compounds containing organic sulphur from the hydrolysis of proteins or from the degradation of soap, cellulose, starch, etc. This process occurs under anaerobic conditions. The hydrogen sulphide then fixes itself to the inner pipe walls, where it is oxidized and converted to sulphuric acid. This acid attack can cause severe damage to concrete and steel with metallic coatings. The Wisconsin Department of Transportation initiated a project in 1989 to research in-situ steel culvert pipes for a better understanding of microbi ally influenced corrosion (MIC) in Wisconsin (Peng et al., 1993). The results of the study indicated that biodeterioration at southern sites with high alkalinity; high TDS, Ca, and Mg (i.e. related to high CaCO\textsubscript{3} precipitation and hard water) was found to be much less than the northern sites with low alkalinity; low TDS, Ca, and Mg (i.e. related to low CaCO\textsubscript{3} deposit and soft water).

Both HDPE and PVC are considered to be highly resistant to bacteria-induced corrosion for plastic resins used in pipe meeting CSA and ASTM Standards. It should be noted that additives, if specified, used to enhance certain properties of plastic pipes may affect the pipes resistance to other environmental factors.

7.1.9 Solvents

PVC may be affected by certain solvents such as aromatic or chlorinated hydrocarbons, ketones and esters. These solvents swell or dissolve PVC. Over time, dry-cleaning fluids and pesticides can permeate through PVC pipe.

HDPE is a hydrocarbon apolar polymer. As such, it may be affected by apolar solvents such as alcohols, detergents, halogens and aromatics, and chemicals such as
petroleum products and gasoline. These solvents swell HDPE and permeate through the pipe wall, and may cause environmental stress cracking where the pipe wall is subjected to sustained tension.

7.1.10 Slow Crack Growth and Oxidation of Thermoplastics

Slow crack growth is a fracture mechanism that can occur in polymer materials under the influence of sustained tensile stress that is less than the short term strength. A period of time is required for crack initiation, then the crack opens in the presence of the tensile stress, and finally it slowly propagates with time (Peggs and Carlson, 1989). Environmental stress cracking is a similar process, but where chemical attack accelerates the rate of crack propagation. Susceptibility to stress cracking depends on the molecular structure of the polymer. For HDPE, the apolar materials mentioned in Section 7.1.9 are considered to be environmental stress-cracking agents. Polyethylene pipe, if placed in hydrocarbon-contaminated ground, may cause swelling and softening and possibly lead to accelerated crack growth (TRB, 1998).

Oxidation renders the thermoplastic susceptible to stress cracking, the oxidation process being controlled by the initial amount of anti-oxidants and the rate at which they deplete over time. Hsuan and Koerner (1998) describe the three stages of aging, namely the time over which the antioxidants are depleted, an induction time prior to the onset of mechanical damage, and finally the time it takes for the mechanical property in question to reduce to an unacceptable level. The rate of antioxidant depletion and subsequently the oxidation is dependent on the thickness of the polymer element in question (the transport processes by which antioxidants are removed and oxygen is supplied to the polymer is affected by the length of travel). Temperature has a significant effect on antioxidant depletion (Hsuan and Koerner, 1998) and the low average temperatures experienced in Ontario may extend the life span of the material greatly.

Of course, the amount of tensile stress also influences service life, since fracture will only develop if there is a sustained zone of tension. Longevity studies conducted in gas pressure pipes provide conservative estimates of crack growth times for gravity flow pipe structures. Tensile stresses in gravity flow pipes will be associated with bending stress distributions, and fracture growth will induce decreases in tensile stress rather than the increases seen in a pressure pipe. The level of conservatism associated with the use of pressure pipe stress limits for gravity flow pipes has yet to be established, so allowable stress from pressure pipe testing is generally used without adjustment in assessment of limiting long term stresses in gravity flow structures. It is also common to employ the same factor of safety, 2, to calculate allowable stress from the long term fracture stress, despite the differences in the consequences of fracture (fracture has potentially catastrophic consequences in pressure pipes, but less severe implications in gravity flow storm sewers and culverts).
7.2 Mechanical Resistance

7.2.1 Abrasion

Abrasion is described as the gradual wearing away of the pipe material wall due to the impingement of bedload and suspended material. Abrasion will almost always occur in the invert of the pipe. As with corrosion, abrasive potential is a function of several factors, including culvert material, frequency and velocity of flow in the culvert and composition of the bedload. The bedload can be increased by soil particles from soil erosion and winter maintenance sand. Abrasion increases as the flow velocity increases and as the pipe diameter increases. Coatings/laminates can provide some degree of abrasion protection to the pipe.

Based on reported wear characteristic, the abrasion resistance of HDPE ranks the highest, followed by PVC, then Steel, and then Concrete. Putting aside the impact of abrasion on hydraulic performance, the abrasion rate is less important than the residual strength of the pipe at the end of the estimated material service life.

The abrasive environments may accelerate corrosion, or vice versa. Typically, for steel and concrete, the combined effect of corrosion and severe abrasion is believed to be more than the sum of separate effects. Wear and erosion often begin with the formation of corrosion products of the steel or concrete in the presence of the offending chemical (TRB, 1998). These corrosion products are often more brittle or less competent, and are then carried off by the abrading action of the traveling aggregates thus leaving the surface exposed for subsequent cycles of corrosion and abrasion. Typical pipe flow abrasion levels are provided in Table C8 in Appendix C, and are referenced in the design section of these guidelines.

Concrete pipe is known to be susceptible to abrasion. However, a maximum flow velocity of approximately 2.5 m/s to 3.0 m/s (comparable to Abrasion Level 3 on Table C8) may not cause significant wear of concrete pipe. Addition of slag has been reported to decrease the abrasion resistance. The effect of severe abrasion on structural performance can be compensated for by using a thicker wall (Wall thickness A, B or C for precast pipe in CSA Standards) and the effect of severe abrasion on hydraulic performance can be compensated for by using a higher Manning's 'n' value and specifying a larger pipe diameter.

Steel pipe is known to be susceptible to abrasion. To resist abrasion and corrosion, steel pipe is protected with galvanized, Aluminized Type 2, or Polymer laminate.
Polymer laminated steel pipe is generally used for sites with moderate abrasion (up to Level 3 as shown on Table C8); Aluminized Type 2 and plain galvanized are generally used for sites with low abrasion (up to Level 2 as shown on Table C8).

Thermoplastic pipes (including PVC and HDPE) are highly resistant to abrasion. The long-chain molecules that make up the polymer chain are able to resist the impact of heavy bedloads.

7.2.2 Fire Resistance

Gravity pipe storm sewers and culvert in Ontario are generally only subjected to fire damage in rare occurrences associated with traffic accidents and gasoline or chemical spillage. Gasoline based fire can readily induce temperatures above 600°C (the temperature of a typical camp fire).

Neither concrete or steel will support combustion. According to Buchanan (2001), concrete will not sustain damage unless subjected to temperature exceeding 350°C, and loses about half its strength at a temperature of 625°C. Steel remains undamaged under a temperature of 400°C, and experiences a drop of about 50% in yield stress at 625°C (given normal stability factors of about 2, this temperature is a typical design limit for considerations of fire-resistance). HDPE pipe, the polymer laminate on steel pipe, and to a lesser extent PVC pipe, have medium susceptibility to fire, since they will generally not self-sustain fire, but will burn when exposed to flame from another combustion source and where the air flow is adequate. Nelson (1995) describes these polymers as “intrinsically flame retardant” since the combusted material tends to remain in place over the residual material. Tested to ASTM D1929, the flash points of HDPE and PVC are 340°C and 395°C respectively. PVC has one of the lowest fire susceptibilities among thermoplastic materials. HDPE is less fire resistant, and has melt temperatures between about 130°C and 200°C.

Florida Department of Transportation Report 94-7A (FDOT 1994) describes a detailed investigation of potential damage to HDPE culverts from grass fires. That report concludes that damage during grass fires of expected intensity is unlikely, and that typical burn rates of 0.52 m per hour are insufficient to generate damage prior to arrival of fire fighting equipment and personnel (although this may not be the case in remote areas of Ontario). They do conclude, however, that grass fire damage can result to mitred end sections, and recommend use of end sections that do not support combustion in that case.
7.2.3 Humidity and Temperature

High humidity (100% relative humidity) and high atmospheric temperatures (>30°C), are not uncommon within gravity pipes, such as in swamp or marsh areas with partially submerged, stagnant or low flow conditions. As discussed in NRCC (1998b), in such an environment, hydrogen sulphide released from stagnant, sewage-like conditions is absorbed by the film of moisture on that portion of the pipe lying above the water. In the presence of aerobic bacteria, the hydrogen sulphide is converted to sulphuric acid. This can lead to deterioration of concrete and steel, although the pipe materials are not directly affected by humidity and temperature.

Typically, buried pipe is not exposed to freeze-thaw conditions when installed as a storm sewer below the frost penetration depth. Culverts are frequently installed within the frost zone and deeper installations are exposed to frost action at the inlets/outlets.

Failure to meet the OPSD (803.030 and 803.031) requirements for frost protection for all pipe materials may lead to differential settlement causing joint separation, longitudinal cracking of the pipe, localized overstressing and decreased hydraulic performance. It can also lead to differential performance of the road pavement above the pipe.

7.2.4 Summary of Mechanical Resistance

A summary of the comparative risks for the main mechanical resistance of the four pipe types is presented in Table 7.3.

Table 7.3 Mechanical Resistance of Various Pipes

<table>
<thead>
<tr>
<th>Type of Resistance</th>
<th>Pipe Material Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Concrete</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>medium</td>
</tr>
<tr>
<td>Freeze-thaw resistance</td>
<td>high²</td>
</tr>
</tbody>
</table>

Notes:
1. Resistance of the pipe material to degradation from freeze-thaw cycles. It is assumed that all buried pipe systems are designed to avoid differential frost heaving.
2. For pre-cast (zero slump) concrete according to Potter (1988)
7.2.5 Time-Dependant Mechanical Properties

Thermoplastic materials (HDPE and PVC) are viscoelastic; that is, their mechanical properties are time-dependent and incur strain and creep deformation under a sustained load, or exhibit stress and load relaxation under a sustained deflection. HDPE and PVC pipes have deformations controlled by the surrounding soil, so can be expected to experience stress relaxation over the life-time of the pipe. Established practice (AASHTO, 2003) is to account for the long term material response by employing a long-term 'effective' modulus of elasticity selected in accordance with the design life of the system (the longer the time period, the lower the modulus).

Thermoplastics are relatively resistant to corrosion and abrasion in buried highway drainage applications; therefore, the effective modulus of elasticity may control the long term stability (this material response over time can be considered to be one factor dictating the estimated material service life). This ‘modulus of relaxation’ can be obtained experimentally by dividing a residual stress in the pipe wall by the strain at that location, and can be estimated from measurements made using constant deflection tests conducted on the pipe as part of an ASTM or CSA quality assurance process (TRB, 1998). Moore and Hu (1996) have examined the time dependent behaviour of various HDPE materials, and provide viscoelastic parameters that can be used to estimate ‘relaxation modulus’ at various time intervals. AASHTO (2003) provides short and 50-year values of modulus for both PVC and HDPE materials, and 100-year values have recently been proposed by McGrath and Hsuan (2003).

7.3 Estimated Material Service Life

To predict the effective service life of a manufactured product, it is necessary to understand and characterize the performance properties of the materials, and to assess how they may change when subjected to adverse environmental conditions and applied stresses. It is also necessary to define the critical distress modes and assess what degree of that distress constitutes product failure (i.e. the point when the product ceases to perform as intended without major maintenance intervention).

The performance criteria or limits, and distress modes related to environmental durability are different for different pipe material types. The limit of effective product serviceable life is defined as the Estimated Material Service Life.

The Estimated Material Service Life (EMSL) is defined as the number of years that a material, system or structure will provide satisfactory service before rehabilitation or
replacement is necessary (Material Service Life as defined in ASTM, 1996). This is also
defined as the relative Maintenance Free Service Life (see definition in Appendix E).
In the context of MTO and their mandate to deliver a serviceable and safe road
network, durability is one of the most important factors in selecting an appropriate
pipe material. EMSL is the parameter used to quantify durability.

Under normal circumstances and where a broad range of alternative pipe products are
available at competitive prices, for a pipe to be considered for a particular project
application, its EMSL should meet or exceed the minimum desired length of
satisfactory service expectations for that application. This minimum desired length of
service for a pipe application is referred to as Design Service Life (DSL). Clearly, the
DSL for high volume freeways will be longer than for lower volume arterial roads.
Project DSLs for a range of typical MTO pipe applications are shown in Table C5.
These values can only be varied for specific applications or special circumstances at the
designer's discretion and as justified. The exceptions to this might be where the pipe
can be easily replaced or rehabilitated without disruption to traffic operations and
where regular pipe inspections are undertaken so as to detect any premature pipe
deterioration at an early stage.

It is noted that, especially in the case of culvert pipes, in-situ remediation is possible.
Re-lining of existing culverts is being used extensively in Ontario as a means of
extending culvert pipe service life (EMSL) without traffic disruption. However, re-
lining is not a guaranteed rehabilitation technique in every instance. It depends on the
mode of failure of the existing pipe, the pipe hydraulic capacity and on having
sufficient working area on one side of the pipe to allow sufficient access to the re-lining
contractor. Although improvements in re-lining technologies, such as using shorter
liner sections, are making the procedure more universal. The pipe selection process can
consider a re-lining alternative to extend the EMSL to achieve the required DSL,
however it is considered outside the normal routine design practice of these guidelines,
partly because the associated infrastructure management system is not in place to allow
the programmed pipe replacement to take place prior to potential pipe failure that
could necessitate emergency road repairs. In cases where EMSL's less than the DSL
are judged to be acceptable strategies, consideration should be given to increasing the
hydraulic design diameter one size for any pipe being designed for future relining,
except in the case where the inner wall is initially corrugated, and improvement in flow
characteristics of a smooth liner compensate for loss of area. The re-lining costs would
need to be included in the Life-Cycle Costing Analysis, and the risk of potential
premature pipe failure assessed.

The EMSL for a particular pipe type can be predicted using equations based on
empirical correlations; however, the predictions are only useful when the expected
conditions in the field are similar to the environmental conditions used to develop the
correlations. Because of the wide range of variables involved, any pipe service life
prediction methodology should be regarded as very approximate and appropriate safety factors should be included. Concrete and CSP have the longest history of use and have more established methods of service life prediction. The EMSL of HDPE and PVC is a more recent research issue, and documented case studies longer than about 30 years are difficult to find. Considerable research work has been undertaken to assess performance of HDPE and PVC components in landfills (e.g. Hsuan and Koerner, 1998 and Rowe and Sangam, 2002). Those findings for environmental applications are currently being extrapolated to better understand these materials in culvert applications (e.g. McGrath and Hsuan, 2003).

The reliability of Life-Cycle Cost Analysis (LCCA) and the consequent selection of applicable pipe types are very sensitive to the assumed or projected EMSL value. For this reason, the predicted values must be considered in the light of historical experience that reflects local conditions, and the calculated values adjusted, as appropriate.

Factors such as climate and frequency of storm events, soils and geology, water impurities, manufacturing defects, construction materials and quality of installation, scour, piping, etc. can gradually reduce a pipe’s strength and make it susceptible to premature failure. Therefore, periodic routine inspections and preventative maintenance are necessary to identify the progression of a problem before damage to the roadway occurs. Other factors that can shorten pipe service life, such as vehicle impact or vandalism cannot be predicted; such random occurrences must be dealt with as site-specific risk factors.

The following sections provide methods for EMSL prediction for each of the pipe material types (i.e. Concrete, HDPE, PVC and Steel) based on durability related parameters.

### 7.3.1 Concrete Pipe (Reinforced and Non-Reinforced)

The EMSL of concrete pipe can be predicted using several methods; however, much controversy exists over which method should be used for service life prediction in a particular jurisdiction. Ohio DOT and Florida DOT have developed statistical regression equations based on the historical experiences that reflect local conditions in those states.

The Ohio DOT equations for predicting the EMSL of concrete pipe were developed from data collected from over 500 sites by the Ohio DOT (see Ohio DOT model below). Hurd (1985) and Hadipriono (1986) used the Ohio data set to develop
different predictive equations based on different criteria and regression analyses. The U.S. Army Corps of Engineers subsequently reviewed these methods, applied a consistent rating system, and developed service life predictive equations; hereafter referred to as the Hurd (1985) Model and Hadipriono (1986) Model.

Four models: a) Ohio Model, b) Hurd Model, c) Hadipriono Model, and d) Florida Model can be used to predict the EMSL of concrete pipe. The designer may choose the model most appropriate to the site conditions based on the criteria used to develop each model.

Potter (1988) reviewed the Ohio data and describes the Ohio DOT model as the most complete data set which included pipe diameters ranging between 610 mm (24 inches) and 2,740 mm (108 inches), pipe gradients (slopes) between 0.01 percent and 58 percent, and pH values between 2.4 and 9.0.

Potter (1988) describes the Hurd Model as being developed on a subset of the Ohio data which used only data from pipes with diameters greater than about 1,070 mm (42 inches) to improve the condition rating and increase the probability of dry weather flow. Also, Hurd used only data with a pH of less than 7.0 on the assumption that acid attack is the principal deterioration mechanism. The total subset used included 59 cases and a nonlinear regression equation was developed.

Potter (1988) describes the Hadipriono Model as also being developed on a subset of the Ohio data and used the complete data set. It was assumed that factors such as weathering, velocity abrasion and sulphate disruption contributed to pipe deterioration regardless of pH. Thus, data from the entire pH range were included. Hadipriono also included pipe sizes less than about 1,070 mm (42 inches) in diameter. The pipes were grouped by rise (diameter) and linear, additive regression equations were used.

\[ a) \text{ ODOT Model – Concrete pipe} \]

For \( 2.5 < \text{pH} < 7 \), use the following equation

\[
\text{EMSL} = \left( \frac{0.349(\text{pH})^{0.204}}{(\text{Slope})^{0.824}} \right)^{7.758} \left( 1 - \frac{\text{sed}}{\text{rise}} \right)^{-5.912}
\]

For \( \text{pH} \geq 7 \),
\[ EMSL = \left( \frac{3.5}{K} \right)^{5.9} \left( \frac{\text{flow}^{0.52}}{\text{Slope}^{0.31}} \right) \]

where:  
EMSL = estimated material service life (years)  
pH = water pH  
Slope = pipe invert slope (%)  
Sed = sediment depth in pipe invert (inches, conversion needed for mm)  
rise = pipe vertical diameter (inches, conversion needed for mm)  
flow = velocity rating number (1 = rapid, 2 = moderate, 3 = slow, 4 = negligible, 5 = none)  
K = abrasive constant (0.90 without abrasive flow, 1.19 with abrasive flow)

Figures B2 and B3a portray the ODOT Model equations using a sediment depth equal to zero (for conservative design) for a range of typical pH and pipe slope values.

**b) Hurd Model – Concrete pipe**

For pH < 7 (for acidic sites)

\[ EMSL = \left( \frac{123.5(pH)^{5.55}}{(Slope)^{0.42} \left( \frac{\text{rise}^{0.94}}{\text{rise}} \right)^{2.64}} \right) \]

Figure B3b portrays the Hurd Model equation for the average pipe diameter (about 1,500 mm) used in the Ohio data set, using a sediment depth equal to zero (for conservative design) for a range of typical pH and pipe slope values.

Table C10 provides minimum pH values required to attain EMSL’s for a range of pipe diameters (i.e. pipe rise) and pipe slopes using the Hurd Model, based on the Ohio DOT Drainage Manual.

**c) Hadipriono Model – Concrete pipe**

For 2.5 < pH < 9

\[ EMSL = -33.23 + 160.92(\log pH) - 4.16\sqrt{\text{Slope}} - 0.28(\text{rise}) \]

Figure B3c. portrays the Hadipriono Model equation for the average pipe diameter (about 1,500 mm) used in the Ohio data set, using a sediment depth equal to zero (for conservative design) for a range of typical pH and pipe slope values.
The EMSL of concrete pipe can also be predicted using equations developed by the Florida DOT from data collected from sites within that State. Florida DOT (2003) developed a regression equation for concrete pipe that takes into account the corrosion (including the steel reinforcing) as the only distress mechanism (excludes velocity and abrasive flow). Although this predictive model may have limited applicability to the typical pre-cast concrete pipe used in Ontario, it is included since it uses depth of steel cover, chloride and sulphate concentration and concrete mix as factors in the equation. These factors are not included in the above models (a, b and c).

Based on Florida experience and analysis, the EMSL may be predicted by the following equation (i.e. Florida Model):

**d) Florida Model – Concrete pipe**

\[
EMSL = (SL - F1)F2
\]

where:

\[
SL = 1,000 \left(1.107^C \cdot D^{1.22} \cdot K^{-0.37} \cdot W^{-0.631}\right) - 4.22 \times 10^{10} (pH)^{14.1} - 2.94 \times 10^{13} (S) + 4.41
\]

SL = service life (years)

\( C \) = sacks of cement per cubic yard of concrete (e.g. Type V cement is equal to 7 sacks = 390 kg cement/m\(^3\) of concrete (TRB, 1998)),

D = steel depth in concrete (inches),

K = environmental chloride concentration in ppm,

W = total percent water in the mix, and

S = environmental sulphate content in ppm

pH = anticipated value

F1 = service life reduction factor for sulphate content (n/a if sulphate resistant cement is used)

F2 = conversion factor for different size pipe diameters

Figure B4 portrays an example of the Florida Model equation for a pipe diameter equal to about 1,500 mm (60 inches), C = 7 sacks (to represent Type V cement or Type 50 equivalent), D = 1.5 inches, W = 45 %. The EMSL can be estimated using the conversion factors provided within the figure, if the other variables are consistent for a given project.

The designer should understand the basis for the different predictive models (a, b, c, and d) and choose an EMSL that is appropriate for the specific site conditions encountered.

On Federal Lands Highway projects in the United States (FHWA, 1996a), it is recommended that reinforced concrete pipe should not be specified for extremely
corrosive condition where the pH is less than 3 and the resistivity is less than 300 ohm-cm (Ω⋅cm). Where the pH is less than 4, or the pipe is exposed to wetting and drying in a salt or brackish water environment, protective coatings should be used. When the sulphate concentration is greater than 0.2 percent in the soil or 2000 parts per million (ppm) in the water, Type 50 cement should be specified. When the sulphate concentration is greater than 1.5 percent in the soil or 15,000 ppm in the water, Type 50 cement should be used with a sulphate resistant pozzolan or equivalent, or a higher cement ratio may be used. FHWA (1996a) and AASHTO (2000) suggest that where severe abrasion is anticipated, additional concrete cover over the reinforcing steel or increasing the cement content of the concrete is recommended. AASHTO (2000) suggests if the soil or water pH is 5.5 or less, concrete pipe should be required to have extra cover over the reinforcing steel (i.e. greater wall thickness) and cast-in-place concrete pipe should not be used.

The designer, having determined an EMSL based on the appropriate predictive model for the specific site conditions encountered, must compare the predicted EMSL to the DSL for the highway project. Refer to Table C5 for recommended DSL for various highway projects.

Should the predicted EMSL be equal to or greater than the DSL, the concrete pipe material is deemed to meet the durability requirements of the project.

Should the predicted EMSL be less than the DSL, the designer has two options. The first option is elimination of the concrete pipe material based on a decision to not include pipe materials with EMSL’s less than the DSL. The second option is continued consideration of the concrete pipe material based on a decision to include pipe materials with EMSL’s less than the DSL. This requires the designer to undertake a LCCA (Refer to Chapter 8 for more details), complete with required replacement, construction, road user and other related costs, to determine total present value cost for comparison with other pipe material options and to be able to meet the durability requirements of the project.

7.3.2 Steel Pipe (Polymer Laminated, Aluminized Type 2 and Galvanized Coated)

The EMSL of steel pipe can be predicted using several methods; however, much controversy exists over which method should be used for service life prediction. California DOT (i.e. California Method) has developed statistical regression equations for plain galvanized CSP (see Figure B5), based on the historical experience that
reflects a wide range of conditions in that state. The U.S. Army Corps of Engineers (1998) modified the California Method (shown graphically in Figure B6) to incorporate using a base steel thickness of 1.6 mm (16-gauge) versus 1.3 mm (18-gauge) which was used in Figure B5, and not typically used in modern day practice. Service life prediction for polymer laminated galvanized steel pipe is estimated by using add-on years to the estimated base service life obtained from the California method (TRB, 1998); whereas service life prediction for Aluminized Type 2 steel pipe is estimated from limited studies performed by the FHWA and research from several U.S. DOT’s.

Based on experience in Ontario, the CSPI states that the prevalence of soft water (i.e. stormwater that is low in dissolved calcium and magnesium salt content, i.e. less than 70 ppm), typical in Northeastern, Northwestern and in some areas of Eastern Regions of Ontario may lead to over-estimates of EMSL, based on the California Method. Alternatively, in areas where there is intermittent flow (mainly dry conditions) or hard water conditions which promote the scaling effect which are typical in Southern Ontario, the California Method tends to under-estimate actual service life for plain galvanized CSP. These predictive methods will need to be improved as more documented case studies become available.

Based on the CSPI industry experience and to minimize the number of steel pipe options for the design process, the CSPI recommends the following steel pipe types be used for design in the specific environmental ranges in Ontario:

Table 7.4 Recommended Environmental Range for Steel Pipe Options in Ontario (CSPI, 2004)

<table>
<thead>
<tr>
<th>Steel Pipe Type</th>
<th>pH</th>
<th>Resistivity (R) (ohm-cm)</th>
<th>Abrasion Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer Laminated</td>
<td>3.0 to 12.0</td>
<td>&gt;100</td>
<td>Level 1, 2, or 3</td>
</tr>
<tr>
<td>Aluminized Type 2</td>
<td>5.0 to 9.0</td>
<td>&gt;1500</td>
<td>Level 1 or 2</td>
</tr>
<tr>
<td>Plain Galvanized</td>
<td>6.0 to 12.0</td>
<td>2,000 &lt; R &lt; 10,000</td>
<td>Level 1 or 2</td>
</tr>
</tbody>
</table>

Notes:
1. For higher abrasion levels, special invert protection design is required;
2. For steel pipe applications that fall outside of the environmental ranges given above, pipes with increased wall thickness may need to be considered to try and achieve an EMSL $\geq$ DSL.

Polymer Laminated Steel Pipe (CSP/SRP)

Polymer laminated CSP/SRP provides the longest service life predictions compared to the other steel products (i.e. Aluminized Type 2 and plain galvanized coated steel pipe). The Estimated Material Service Life of polymer laminated steel pipe is calculated by add-on years to the service life obtained from Figure B6 for plain galvanized steel pipe as shown below:
EMSL = (EMSL_s) + X2

where: EMSL_s = estimated material service life for base steel component

= Years \times X1 (must be a minimum 10 years for MTO projects)

For pH < 7.3, \( Years = 17.24 \times [\log_{10}R - \log_{10}(2160 - 2490\log_{10}pH)] \)

For pH > 7.3, \( Years = 1.84R^{0.41} \)

X1 = factor for various steel gauges/thicknesses (see Figure B6)
X2 = factor for anticipated service life added by abrasive or corrosion resistant protective polymer lamination (years), see Table C9.
R = minimum anticipated resistivity of soil and water (ohm-cm)
pH = anticipated value of soil and water

Typical values for the factor (X2) used in the above EMSL calculation for polymer laminations are shown in Table C9 in Appendix C. The add-on years reported in Table 9 vary based on the referenced jurisdictions quality of bonding (which may be lower quality than CSA standards), abrasive conditions and thickness of lamination. It should be adjusted based on local experience. On Federal Lands Highway projects in the United States (FHWA, 1996a), an additional 30 years (X2 = 30 years) is used (with a minimum 0.25 mm polymer thickness on both sides of the steel pipe) at sites with a maximum abrasion Level of 3 (i.e. moderate abrasive sites). The “Best Practice Selection of Culvert Types” used in Alberta Transportation (1997) for roadways in Alberta uses a higher add-on value, backcalculated to be about 40 years for polymer coatings, and Ohio and Oregon D.O.T.’s specify an additional 50 years for polymer coatings. Research and testing performed by The Dow Chemical Company suggests that the add-on value for polymer laminated steel pipe is as follows: in a pH range from 3 to 12 and resistivity > 100 ohm-cm, add-on value is 50 years; in a pH range from 4 to 9 and resistivity > 750 ohm-cm, add-on value is 75 years; and in a pH range from 5 to 9 and resistivity > 1500 ohm-cm, add-on value is 100 years.

These guidelines need to be periodically reviewed and updated as more local Ontario experience is obtained. Until research or documented case studies indicate otherwise, MTO, will accept an additional 50 years to the EMSL based on the use of polymer laminated steel pipe.

Aluminized Type 2 Coated Steel Pipe (CSP/SRP)

It is generally accepted that Aluminized Type 2 coated steel pipe should only be used within the environmental range of 5 < pH < 9 and resistivity equal or greater than 1500 \( \Omega \cdot \text{cm} \). The results of a study performed by the U.S. DOT Federal Highway Administration in a report entitled “Durability Analysis of Aluminized Type 2 Corrugated Metal Pipe” (FHWA, 2000) indicated that at non-abrasive sites, the service-life multiplier for Aluminized Type 2 coated pipe can be up to eight (8) times
the service life estimated using the California Method predictions for plain galvanized pipe. The report states that if only waterside corrosion is considered, the ratio becomes 3.5. Under extreme conditions, it is possible that galvanized and Aluminized Type 2 could perform in a relatively similar manner.

Florida DOT has developed statistical regression equations to predict the EMSL for Aluminized Type 2 coated CSP as shown graphically on Figure B7. The figure is based on anticipated soil/water pH and resistivity and calculated as follows.

**Florida DOT method - Aluminized Type 2 Corrugated Steel Pipe**

EMSL = (Years × Y1)

where: For 5.0 < pH < 7.0, \[\text{Years} = 50\left(10^{\frac{\text{Log}_{10} R - \text{Log}_{10} \left[2160 - 2490\text{Log}_{10}(pH)\right]}{10}}\right)\]

For pH 7.0 < pH < 8.5, \[\text{Years} = 50\left(10^{\frac{\text{Log}_{10} R - 1.746}{10}}\right)\]

For 8.5 < pH < 9,

\[\text{Years} = 50\left(10^{\frac{\text{Log}_{10} R - \text{Log}_{10} \left(2160 - 2490\text{Log}_{10}(7 - 4(pH - 8.5))\right]}{10}}\right)\]

Y1 = factor for various metal gauges/thicknesses available with Aluminized Type 2 coating (see Figure B7)

**Other methods – Aluminized Type 2 Coated Steel Pipe**

Aluminized Type 2 coated steel pipes have not been used widely in Ontario but they have been used extensively in other jurisdictions within the United States. To our knowledge, no long term monitored trial projects or instrumented test installations of Aluminized Type 2 steel pipes have been undertaken in Ontario conditions.

On Federal Lands Highway projects in the United States (FHWA, 1996a), at sites with the same environmental restrictions (i.e. non-abrasive to low abrasive conditions, 5 < pH < 9, and resistivity equal to or greater than 1500 Ω·cm), Aluminized Type 2 coated steel can be expected to give an EMSL of twice that of plain galvanized pipe. On installations in moderate to abrasive conditions where protective coatings are not required for corrosion protection, the design thickness of the steel should be increased by at least one standard pipe thickness from that determined using the California method. In severe abrasive conditions where protective coatings are not required for corrosion protection, the thickness of the metal should be increased by one standard steel pipe thickness from that determined using the California method and invert protection should be provided. Invert protection may involve additional steel protection or velocity reduction structures.

These guidelines need to be periodically reviewed and updated as more local Ontario experience is obtained. Until research or documented case studies indicate otherwise, MTO, will accept an EMSL using Figure B7 based on the use of Aluminized Type 2 coated steel pipe.
Plain Galvanized Steel Pipe

California Method – Plain Galvanized Steel Pipe (CSP, SRP, and SPCSP)

California DOT (CALTRANS, 2001) has developed statistical regression equations (the California Method) for plain galvanized CSP, based on historical experiences that reflect a wide range of soil and water conditions at over 7,000 sites. The California Method is the most widely accepted method to estimate culvert durability (FHWA, 2000). Many other agencies (including the CSPI) have used the California Method as a basis for the development of their own site-specific analyses and methods for predicting CSP service life.

The California Method has proven to be both conservative (under-estimates) and liberal (over-estimates) for different environments and includes the combined effects of soil corrosion, water corrosion and abrasion (CSPI, 2002). Where possible, local experience should be used to validate or calibrate the predictions. The California Method equations are based on anticipated soil and water pH and resistivity parameters for predicting EMSL to first perforation and are shown graphically in Figure B5. It is recognized that pipe can have useful serviceable life beyond development of first perforation. The U.S. Army Corps of Engineers modified the equations to incorporate a minimum 1.6 mm steel thickness (as used in Ontario) as shown on Figure B6 and below.

\[ \text{EMSL} = (\text{Years} \times X1) \]

where: For pH < 7.3, \( Y_{\text{ears}} = 17.24\left[\log_{10} R - \log_{10}(2160 - 2490\log_{10}pH)\right] \)

For pH > 7.3, \( Y_{\text{ears}} = 1.84R^{0.41} \)

\( X1 \) = factor for various steel gauges/thickness’ (see Figure B6)
\( R \) = minimum anticipated resistivity of soil and water (ohm-cm)
\( pH \) = anticipated value of soil and water

On Federal Lands Highway projects in the United States (FHWA, 1996a), at sites with nonabrasive to low abrasive conditions, the EMSL of plain galvanized steel pipe may be determined based upon corrosion conditions (pH and resistivity) using the California method. Under moderate abrasive conditions where protective coatings/laminations are not required for corrosion protection, the design thickness of the steel should be increased by at least one standard pipe thickness from that determined using the California method. In severe abrasive conditions where protective coatings/laminations are not required for corrosion protection, the thickness of the metal should be increased by one standard steel pipe thickness from that determined using the California method and invert protection should be provided.
Invert protection may involve site specific design protection or velocity reduction structures.

These guidelines need to be periodically reviewed and updated as more local Ontario experience is obtained. Until research or documented case studies indicate otherwise, MTO, will accept an EMSL using Figure B6 based on the use of plain galvanized steel pipe.

In all cases the designer should utilize the steel pipe with the coating/lamination that is most appropriate to the environment in which the pipe is to be installed (i.e. Polymer Laminated, Aluminized Type 2 or Plain Galvanized Coated).

The designer, having determined an EMSL based on the appropriate predictive model for the specific site conditions encountered, must compare the predicted EMSL to the DSL for the highway project. Refer to Table C5 for recommended DSL for various highway projects.

Should the predicted EMSL be equal to or greater than the DSL, the steel pipe material is deemed to be able to meet the durability requirements of the project.

Should the predicted EMSL be less than the DSL, the designer has two options. The first option is elimination of the steel pipe material based on a decision to not include pipe materials with EMSL’s less than the DSL. The second option is continued consideration of the steel pipe material based on a decision to include pipe materials with EMSL’s less than the DSL. This requires the designer to undertake a LCCA (Refer to Chapter 8 for more details), complete with the required replacement, construction, road user and other related costs, to determine total present value cost for comparison with other pipe material options and to be able to meet the durability requirements of the project.

7.3.3 HDPE (High Density Polyethylene)

The availability of empirical data to assist the designer in predicting EMSL is limited for HDPE when compared to concrete and CSP. No statistical regression equations were found in the technical literature to predict the EMSL for HDPE pipe. The example of the use of HDPE liners in landfills is used to support the acceptance of an EMSL value for HDPE pipe, since these applications have been the subject of extensive research. However, the component materials are not identical and the service conditions are quite different. There is a substantial amount of research work and case studies in progress to identify the primary distress modes of HDPE pipe, and to attempt to relate such distresses to environmental or in-service conditions. To date, however, no such predictive methods (equations) are available.

In the absence of reliable predictive models and a means to quantify the influence of unfavourable service conditions or risk factors, most agencies have elected to use one
constant value for EMSL for all HDPE pipe products for all applications and environments. Since this base value is not related to risk factors, the estimate for EMSL needs to be conservative. The U.S. Army Corps of Engineers (1998) and FHWA (1996a) recommend that an EMSL of 50 years be used for HDPE with no restrictions on pH or resistivity values.

Florida DOT has commissioned a study by Drexel University to establish criteria needed to allow corrugated HDPE pipe to last for 100 years, which is their standard for freeway applications. This study is still in progress; however, a draft report issued for comment in August 2003 (McGrath and Hsuan, 2003) defined the following requirements with respect to controlling pipe stresses for long term durability:

- Minimum pipe tensile strength should be about 3.5 MPa (500 p.s.i.) at 2.5% strain;
- Backfill should be limited to well graded, coarse grained soils with maximum of 12% fines (i.e. passing the No. 200 sieve according ASTM D2487-92);
- Increased inspection during construction is recommended;
- Backfill should be compacted to at least 95% of Standard Proctor maximum dry density;
- Pipe must be inspected after installation to verify that the total reduction in vertical diameter is less than 5%;
- Minimum cover for applications subjected to live loads should be 600 mm (2 ft.) or one-half the pipe diameter, whichever is greater.

It should be noted that the United States (i.e. ASTM) production and installation standards for HDPE are different from Canadian Standards. No similar research has been undertaken to establish criteria for establishing the EMSL for HDPE pipe for highway applications in Ontario.

On Federal Lands Highway projects in the United States (FHWA, 1996a), HDPE pipe may be specified without regard to the resistivity and pH of the site and under nonabrasive and low abrasive conditions. HDPE is not used under moderate and severe abrasive conditions without invert protection.

Until research or documented case studies indicate otherwise, MTO, will accept an assumed EMSL of at least 75 years based on the use of certified CSA B182.6, CSA B182.8, or ASTM F894 HDPE pipe (minimum 320 kPa pipe stiffness as per CSA requirements or equivalent). This value for the EMSL of HDPE is equal to or greater than the DSL for all categories of highways. Where the application requires a DSL of 75 years, post installation verification of the pipe integrity should be undertaken, such as by mandrel pull or video inspection and it should be verified that there are no unusual risk factors associated with the application. For a 75 year EMSL, the structural design (i.e. fill height tables) must incorporate long-term material properties in the
design procedure. An increased factor of safety may be used with the current OPSD fill height tables.

Further research is required before MTO is in a position to accept 210 kPa, CSA 182.8 certified HDPE pipe on MTO highway projects. A designer, through justification, could consider using 210 kPa CSA 182.8 certified HDPE pipe for special circumstances (i.e. temporary or short-term requirements).

Under these conditions, HDPE pipe material is deemed to be able to meet the durability requirements of the project.

### 7.3.4 PVC (Polyvinyl Chloride)

The availability of empirical data to assist the designer in predicting EMSL is also limited for PVC pipe when compared to concrete and steel. As for HDPE, no statistical regression equations were found in the technical literature to predict the EMSL for PVC pipe. The first production of PVC pipes for industrial use began in Germany in the 1930’s (Hulsmann and Nowack, 2004). Documented case studies are available that indicate that PVC material used in pipe systems installed in Europe in the 1960’s have not deteriorated significantly over that period, with respect to material stiffness and other physical properties (Alferink et al., 1995).

In the absence of reliable predictive models and a means to quantify the influence of unfavourable service conditions or risk factors, most agencies have elected to use one constant value for EMSL for all PVC pipe products for all applications and environments. Since this base value is not related to risk factors, the EMSL value needs to be conservative. The U.S. Army Corps of Engineers (1998) and FHWA (1996a) recommend that an EMSL of 50 years be used for PVC with no restrictions on pH or resistivity values. However, no portion of the pipe (ends) should be exposed to ultraviolet light (sunlight).

Following an evaluation of available technical information on the performance of PVC pipe in 2003, with diameters up to about 910 mm (36 inches), the Florida DOT allows a 100 year service life for PVC pipe subject to the following requirements:

- Meets all the requirements of ASTM F 949;
- Will only be used in installations where the pipe is not exposed to direct sunlight (e.g. above ground applications or installations with mitered end sections are excluded);
- The pipe is manufactured from PVC compound having no less than 1.0 part of titanium dioxide per 100 parts resin, by weight; and
- Pipe shall be installed within two years from the date of manufacture (this is to avoid the possibility that PVC pipe has been stored for long periods with exposure to sunlight prior to delivery to site).
It should be noted that the United States (i.e. ASTM) production and installation standards for PVC are different from Canadian Standards.

On Federal Lands Highway projects in the United States (FHWA, 1996a), PVC pipe may be specified without regard to the resistivity and pH of the site and under nonabrasive and low abrasive conditions. PVC is not used under moderate and severe abrasive conditions without invert protection.

Until research or documented case studies indicate otherwise, MTO, will accept an assumed EMSL of at least 75 years based on the use of CSA B182.2-02 or B182.4-02 certified PVC pipe (minimum 320 kPa pipe stiffness). This value for the EMSL of PVC is equal to or greater than the DSL for all categories of highways. Where the application requires a DSL of 75 years, post installation verification of the pipe integrity should be undertaken, such as by mandrel pull or video inspection. In addition, an increased factor of safety on the structural design should be considered and it should be verified that there are no unusual risk factors associated with the application. Under these conditions, PVC pipe material is deemed to be able to meet the durability requirements of the project.
Chapter 8.0 Life Cycle Cost Analysis (LCCA)

8.1 LCCA Methodology

Life Cycle Costing Analysis (LCCA) is an accepted procedure in infrastructure design to compare alternative strategies for providing a specific product over a relatively long period of time. The comparison is based on the total cost over the designated analysis period, including initial construction costs, maintenance costs, and disposal costs at the end of the analysis period, if applicable. Since the analysis periods are usually relatively long and since expenditures can be incurred at any point within that analysis period, all expenditures are adjusted to present costs using a discount rate. In more complete analyses, traffic disruption/user delay costs, re-lining costs and credits for salvage/residual value can be included. The overall objective of LCCA is to identify the best long term value alternative to the owning agency.

To compute the Life Cycle Costing (LCC) for a drainage system, all relevant costs incurred in constructing and maintaining the system over the design life of the project are discounted back to the present value and summed. The basic method used in these guidelines is in accordance with ASTM Standards (i.e. ASTM F1675-96 and ASTM C1131-95) as follows:

\[ PVLCC = PVIC + \sum (PVM + PVN + PVR) - PVT \]

where:
- \( PVLCC \) = present value life cycle cost
- \( PVIC \) = present value initial cost
- \( PVM \) = present value operating and maintenance cost
- \( PVN \) = present value rehabilitation cost
- \( PVR \) = present value replacement cost
- \( PVT \) = present value terminal value (i.e. residual or salvage value)

*Initial costs* may be assumed to occur in the base year (year zero) and no discounting is required.
Operating or Maintenance Costs (i.e. Recurring Annual Costs): Future costs such as inspection, cleaning, etc. (i.e. operating or maintenance costs) that are expected to occur in about the same amount (in constant dollars) from year to year may be discounted to present value as follows.

\[
P_{VM} = \frac{M_r (1 + d_r)^n - 1}{d_r (1 + d_r)^n} \quad \text{(for annual costs)}
\]

where
- \( M_r \) = recurring annual amount,
- \( d_r \) = real discount rate, and
- \( n \) = number of years

From a comparative point of view, these costs need NOT be included if they are expected to be the same for each pipe material alternative.

Replacement/Rehabilitation Costs: Future costs expected to occur at a single point in time (e.g. replacement/rehabilitation costs) may be discounted to present value by multiplying the estimated current cost of the item by the single present value factor as follows:

\[
P_{VN} \text{ or } P_{VR} = \left( N_s \left( \frac{1}{1 + d_r} \right) \right)^n
\]

where:
- \( N_s \) = single amount,
- \( d_r \) = real discount rate, and
- \( n \) = number of years from year zero to time of future single amount expenditure.

The need to include the PVR (present value replacement cost) parameter will only occur when the analysis period exceeds the estimated material service life. Where PVR is required, it will automatically be assumed that the pipe will be replaced with a pipe of similar type. Costs associated with the replacement actions include the construction and material costs for the work and any other direct or indirect related costs. These may include additional easements, engineering design and supervision, safety, temporary detours, and traffic disruption costs. Specifically, traffic costs associated with vehicle deterioration, passenger time, and construction-related accidents should be included. The calculations for traffic costs are derived from the US Federal Highway Administration (FHWA, 1981). There are basically three subcategories of traffic-related losses which might occur:

1. Increased running cost due to the detour \( (N_{\text{SRC}}) \)

\[
N_{\text{SRC}} = \frac{(\text{Time})(\text{ADTE})(\text{Length})(\text{UnitCost})}{(24)}
\]
where:

\[ Time = \text{time (duration of detour) in hours} \]
\[ ADTE = \text{equivalent average daily traffic (vehicles/day)} \]
\[ Length = \text{additional length of detour (km)} \]
\[ Unit \ Cost = \text{vehicle running cost ($/km)} \]

2. Lost time of vehicle occupants \( N_{LT} \)

\[
N_{LT} = \frac{(Time)(ADTE)(Length)(OccupancyRate)(UnitCost)}{(Speed)(24)}
\]

where:

\[ Time = \text{time (duration of detour) in hours} \]
\[ ADTE = \text{equivalent average daily traffic (vehicles/day)} \]
\[ Length = \text{additional length of detour (km)} \]
\[ Occupancy \ Rate = \text{no. of people per vehicle} \]
\[ Speed = \text{speed of vehicle (km/hr)} \]

3. Increased accidents on the detour \( N_{AC} \)

\[
N_{AC} = \frac{1}{3.84 \times 10^9} \left[ (Time)(ADTE)(Length)(DeathRate)(Accident \& \ Injury Factor) \right]
\]

where:

\[ Time = \text{time (duration of detour) in hours} \]
\[ ADTE = \text{equivalent average daily traffic (vehicles/day)} \]
\[ Length = \text{additional length of detour (km)} \]
\[ Death \ Rate = \text{Death rate is in people per 160 million vehicle kilometres} \]
\[ Accident \& \ Injury Factor = [(Cost per Death)+(Injury Ratio)(Unit Cost of Injury) + (Damage Ratio)(Unit Cost of Damage)] \]
\[ Injury \ Ratio = \text{injuries per death} \]
\[ Damage \ Ratio = \text{damage per death} \]
\[ Unit \ Cost \ of \ Death = \text{cost of death in dollars} \]
\[ Unit \ Cost \ of \ Injury = \text{dollars per injury claim} \]
\[ Unit \ Cost \ of \ Damage = \text{dollars per damage claim} \]
If detours are required, vehicle deterioration costs reflect additional wear on vehicles from the extra traveling distance. Cost of passengers’ time is based on the additional time to travel through the construction zone and/or detour. Costs associated with construction/detour related accidents (including property damage, injuries, and fatalities) reflect the number and cost of vehicle accidents through the construction zone/detour.

If re-lining is considered a viable option, the associated re-lining costs can be included as a PVR.

Discount Rates and Inflation: Discount rates vary for all owners. Rate selection should be guided by the value of money to the owner. Use of the borrowing rate (i.e. interest rate) is incorrect. The interest rate represents a “cost” to the project and does not reflect the “value” of money used on the project.

Inflation: Several approaches can be used. If it is assumed that inflation will affect all cost and/or benefits in a uniform manner over the life of the project, then a straightforward approach can be used. All costs, both present and future, can be estimated in base year or current year dollars and discounted back to the present value using a “real” discount rate (excluding inflation). The real discount rate ($d_r$) and its corresponding nominal discount rate ($d_n$) are related as follows:

$$d_r = \frac{(1 + d_n)}{(1 + I)} - 1 \quad \text{or} \quad d_n = (1 + d_r)(1 + I) - 1$$

where: $I =$ the rate of general price inflation

8.2 Life Cycle Cost Analysis Parameters

Recommendations for several parameters used in the Life Cycle Cost Analysis (LCCA) of gravity pipes are provided as follows:

- **Analysis Period ($n =$ number of years).** It is recommended that the following LCC minimum analysis periods be used:
  - Freeways: $n = 75$ years
  - Arterials and Collectors: $n = 50$ years
  - Local roads: $n = 25$ years

- Where the Design Service Life exceeds the above recommended analysis periods, the higher of the two values should be used.

- The capital costs should be estimated using current MTO contract values, and should include all associated costs listed in Section 4.2, such as excavation, bedding, backfill, etc. and any recommended quality assurance
or inspection requirements which are unique to a specific pipe type. Items that will be common to all pipe options, such as groundwater control and shoring, will be excluded for simplicity.

- The Discount Rate should be set by MTO - 6% is recommended as a default value.

- Where the Estimated Material Service Life is less than the Analysis Period, the cost of replacement of a similar pipe type should be assumed. This cost should include traffic control costs, and possibly user-delay costs during installation.

- Where a replacement pipe is allowed, a minimum EMSL of 25 years must be achieved for each for each option.

- For significant detours or construction traffic, accident costs are based on death rate statistics. For each death, there are assumed a certain number of personal injuries and property damage accidents. The personal injuries and property damage losses are obtained by applying property damage and personal injury rates to the costs of damage and injury. The rate and cost data may be site specific or based on national statistics. One problem with considering loss of life is arriving at a reasonable value to use in the analysis.

- Re-lining should not be used as an automatic design method for extending the initial pipe life, since it is not suitable in all cases. However, it can be included at the designer's discretion.

- Disposal Costs: Salvage, Disposal, and Residual value beyond the Analysis Period shall not be used in the LCCA.

- The output from the LCCA should include a list of all acceptable pipe alternatives. For each pipe alternative, the estimated unit capital cost and Life Cycle Cost should be listed. The final pipe selection(s) should be made by the designer from the identified alternatives.
Chapter 9.0  Pipe Alternatives

9.1 Feasible Pipe Alternatives

The use of these guidelines will, for most applications, allow a range of pipe alternatives to be assessed, designed and specified. Each one of these alternatives will meet the hydraulic, structural and durability requirements for the application and provide a viable gravity pipe solution. Thus they can be included as equal alternatives in the contract documents. A Life Cycle Cost Analysis can be undertaken for each feasible alternative, but in practice, provided the DSL is exceeded for each alternative, and since routine maintenance interventions for all pipe types are essentially similar, the outcome of the LCCA will be determined by the initial construction costs.

Where it is desired to increase the number of pipe options by allowing pipes that have EMSL’s less than the project DSL, LCCA should be used to compare options. If a strategy involving programmed pipe replacement within the DSL is determined to be the most cost-effective option, then this option should be specified in the contract documents. However, given the wide range of pipe products available in Ontario, it is unlikely that this latter strategy would be justified, except in exceptional circumstances.

The design approach described in these guidelines is based on a consideration of pipe hydraulic and structural strength, as well as durability. However, there may be other factors that need to be considered in selecting pipe alternatives for a particular application. Other, indirect design considerations and risk factors are discussed in the following sections.

9.2 Other Design Considerations

Culverts and storm sewers are connected by appurtenant structures such as inlets, outlets, access holes, junction boxes, etc. Occasionally, there may be a need for specially designed components, such as for high velocity transitions, for division of flows between two or more systems, for pipe extensions, and for any special combined storm/sanitary sewer facilities. The need to accommodate fish passage may also
require special culvert characteristics or modifications for a particular site application. In some applications, aesthetics or the need to apply a particular end or head wall treatment may be an additional consideration. These examples have been provided to assist the designer in identifying special design considerations needed on the drainage system. There are potentially many other design considerations too numerous to mention here that a designer may encounter on a highway project.

All pipe material types should still be considered when dealing with special design considerations, such as those listed above, and any additional costs (related to the special design requirements for each pipe material type) should be included in the total cost analysis. In some cases, certain pipe materials may have to be eliminated as options based on their inability to satisfy other design considerations identified, as discussed above.

9.3 Summary of Risk Factors for Alternative Pipe Types

There are risk factors that cannot be easily quantified that may be relevant in the selection of the most suitable pipes for a particular application. Although the pipe design process outlined in these guidelines incorporates the main environmental and loading conditions that establish a pipe’s suitability, random events can occur that could cause a pipe to fail prematurely. While the risks of such events may be negligible for an individual pipe, these events should be considered on a network or regional basis. The appropriate weight to be placed on such risk factors in the pipe selection process will depend on the nature of the risk, the probability of occurrence, and on the consequences of premature failure for the particular pipe application. The risk factors may need to be considered both on a regional basis and on an individual project basis. However, it is cautioned that since the process outlined in these guidelines is aimed at achieving appropriate, unbiased, cost-effective and competitive gravity pipe solutions, the standard design process should only be over-ridden with justification and with the concurrence of the MTO Regional Planning and Design Section. A wider range of viable pipe alternatives in the contract documents will encourage a higher level of competition within the industry.

The risk factors that may need to be considered include:

- ability of contractors to install pipes properly;
- repair costs and mitigation measures as a result of improper installation or premature failure;
- risk of differential foundation settlement and the impact on joint integrity;
- highly corrosive environments and environmental changes with time;
- product manufacturing defects;
• the use of the route as a construction haul road;
• flotation/buoyancy issues related to flooding or variable water levels;
• exposure to chemical or fuel spills, and associated risk of fire and combustion damage;
• exposure to UV radiation;
• seismic risk; and
• vandalism.

The mode of failure may also be important in assessing the effects of premature failure as a result of a particular risk factor.

9.4 Specifying Pipe Materials in Contract Package

The MTO current practice for specifying gravity pipe is provided in the “Contract Design Estimating and Documentation manual, Volume I” (Ministry of Transportation, August 25, 1995), Section 421.1.2. Pipe is specified as either smooth interior wall (sometimes designated as ‘rigid’ pipe) or corrugated interior wall (sometimes designated as ‘flexible’ pipe). The current practice is to then allow the Contractor to choose from a product list currently provided under each heading. The following table provides an updated list of available pipe material types, categorized traditionally as to whether they are smooth or corrugated wall:

Table 9.1 Former MTO Practice of Specifying Pipe Materials

<table>
<thead>
<tr>
<th>Pipe Type</th>
<th>Smooth Inside Wall / Rigid</th>
<th>Corrugated Inside Wall / Flexible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>Smooth inside wall</td>
<td>N/A</td>
</tr>
<tr>
<td>Steel</td>
<td>Spiral Rib smooth wall</td>
<td>Corrugated inside and outside wall</td>
</tr>
<tr>
<td>HDPE</td>
<td>Smooth inside wall (Corrugated or Smooth outside wall)</td>
<td>Corrugated inside and outside wall</td>
</tr>
<tr>
<td>PVC</td>
<td>Smooth inside wall (Solid or Profile smooth wall)</td>
<td>N/A</td>
</tr>
</tbody>
</table>

It is recommended that gravity pipe should not be specified in terms of “corrugated” or “smooth” wall, or in terms of “flexible” or “rigid”. The main limitation with this traditional approach is that it may suggest to the contractor, for example, that all “rigid” or “flexible” pipes are similar in terms of quality, installation procedure, quality control, etc. This is not the case. Another limitation would be if “smooth” wall pipe is
specified, the contractor may view this statement as traditionally only allowing plastic or concrete pipe for a project when, in fact, all material types have specific products that would have hydraulically “smooth” wall characteristics. With the use of these guidelines, one or more equivalent pipe products can be specified, together with the appropriate installation and quality control requirements.

It is recommended that the designer specify a list of allowable pipe material types (with applicable minimum material specifications) and allow contractors bidding on the work to include whichever one of these products they prefer.

Each pipe type would have an associated, appropriate material specification, and installation and bedding requirements. Where a number of alternative pipe products are specified, it is assumed that any of these products, if correctly installed, will provide an acceptable level of service.
References and Bibliography


Alberta Transportation – Infrastructure. 1997. “Best Practice Selection of Culvert Types (Guidelines for Culvert Material Selection)”.


ASTM. 1996. “ASTM F1675-96 Standard Practice for Life-Cycle cost Analysis of Plastic Pipe Used for Culverts, Storm Sewers, and Other Buried Conduits”.

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Hulsmann, Thomas and Nowack, Reinhard E. 2004 “70 Years of experience with PVC pipes”, Plastics Pipes XII World Symposium on Plastic Pipes, Milan, Italy, April 19th - 22


APPENDIX A

EXAMPLES

All costs used in the following examples are hypothetical and used only to aid the designer in the design procedure. The prices used for pipe materials and life cycle costing may not accurately reflect current market costs for each Region.
EXAMPLE 1

Assume a cross culvert is scheduled to be replaced along Highway 7 within Central Region in Ontario in two years. The existing soil data taken from the culvert geotechnical investigation suggest that the site is swampy, consisting predominantly of peat soils, underlain by silty clay. Soils data were fairly consistent in the area. The lowest pH value taken on samples of the soil and water was 6.2, and the minimum resistivity value was 2400 ohm-cm. The results of the hydrology analysis performed using the MTO Drainage Manual indicated a Culvert Design Flow = 6 m³/s and Design Slope = 0.6 %. The design inside diameter of a pipe with Manning roughness coefficient of 0.012 was calculated to be 1500 mm using the Manning Equation. Proposed road grades indicate a maximum fill height of about 1.2 m over the top of the pipe, and a minimum fill height of 900 mm above the pipe. Replacement costs are considered to be similar to initial construction costs, and no significant user costs are expected from delays or detours.

Solution: Using Step-by-Step Pipe Selection Procedure

Step 1 - Define Design Parameters

Pipe Location: N 4862370.9; E 260408.1

Design Service Life (DSL) = 50 years (see Table C5)

For this example, it is determined that pipe materials with an EMSL < DSL will be considered, thus Life Cycle Costing Analysis is required.

Step 2 – Size Availability

Given: Design inside diameter ≥ 1500 mm (assuming Manning ‘n’ ≥ 0.012).

Referring to the maximum pipe diameter sizes listed on the Material Availability Tables in Appendix C (Tables C1, C2.0 – C2.2, C3.0 – C3.2, C4.0 – C4.1); we can eliminate the following pipe material types for the remainder of the analysis.

- Non-reinforced Concrete pipe not available above 900 mm diameter,
- PVC pipe not available above 1200 mm diameter,
- HDPE-CIO pipe not available above 900 mm diameter, and
- HDPE-SICO pipe not available above 900 mm diameter
Step 3 - Durability

Concrete
Given: Slope = 0.6%, Pipe Inside Diameter=1,500 mm, pH=6.2;
Referring to Table C10, Reinforced Concrete EMSL > 50 yrs. > DSL

HDPE
HDPE-CPSIO EMSL > 50 yrs (Pipe Stiffness > Class 210) > DSL

PVC
Not required. PVC eliminated in Step 2

Steel
Given: pH = 6.2, Resistivity = 2400 ohm-cm;

1. Using Figure B6, Base Life Years for plain galvanized 1.6 mm thick steel = 19 yrs.
Using Figure B7, Base Life Years for ALT2 1.6 mm thick steel = 55 yrs.

2. X1 Factor = EMSL./(Base Life Years)

   Steel-P (Check 4<pH<10 ✓ and R >100 ohm-cm ✓)
   Assuming the EMSL for Steel-P is at least 50 years, EMSL = (EMSL - 50)
   X1 Factor = (EMSL-50)/(Base Life Years) = (50-50)/(19) = 0

   Steel – ALT2 (Check 5<pH<9 ✓ and R > 1,500 ohm-cm ✓)
   EMSL = 55 yrs. > DSL, therefore Y1 Factor does not need to be calculated

   Steel-PG (Check 6<pH<12 ✓ and 2,000 < R < 10,000 ohm-cm ✓)
   For the EMSL < DSL option, EMSL for Steel-PG must be ≥ 25 years to be considered for replacement.
   X1 Factor = EMSL./(Base Life Years) = (25 years)/(19 years) = 1.3

3. Steel-P
   Because X1 Factor is less than 1 and Base Life Years is 19 years (i.e. greater than the required 10 year minimum), 1.6 mm thick Steel-P is sufficient for durability design (EMSL ≥ DSL for Steel-P).

   Steel-ALT2
   Because Base Life Years is 55 years (i.e. greater than the required 25 year minimum), 1.6 mm thick Steel-ALT2 is sufficient for durability design (EMSL ≥ DSL for Steel-ALT2).
Steel-PG
From insert table in Figure B6, the closest Factor $\geq X_1$ Factor (equal to 1.3) is 1.8 for 2.8 mm steel thickness (i.e. Gauge 12). Therefore, a minimum steel thickness of 2.8 mm is sufficient for durability design for an EMSL = 25 years (EMSL < DSL for Steel-PG and must be replaced after 25 years).

Step 4 – Short List

List of pipe products still eligible for consideration after Steps 1 to 3, and after checking the Pipe Availability Tables in Appendix C:

- HDPE – CPSIO
- Concrete - Reinforced
- Steel – P, 2.0 mm thick (1.6 mm thickness not available in this size)
- Steel – ALT2, 2.0 mm thick (1.6 mm thickness not available in this size)
- Steel - PG, 2.8 mm thick (requires replacement after 25 years)

Step 5 – Hydraulic Evaluation

Upon direction from the Drainage Design Engineer, in this case, the geometrics and physical characteristics of the site make it practical to use the Manning Equation and Design Chart method for sizing pipe based on hydraulic capacity equivalency. It should be noted that this is not always the case. The hydrology and hydraulic analysis for the entire water “system” should be evaluated or re-evaluated using the new diameters and pipe material types (i.e. using the different Manning roughness coefficients).

- Concrete – Reinforced
  Manning “n” = 0.012 (Table C1).
  From Figure B1, $n_2/n_1 = 1$, therefore $D_2 = D_1 = 1500$ mm.
  Minimum Inside Design Diameter = 1500 mm.

- HDPE – CPSIO
  Manning “n” = 0.012 (Table C3.2)
  From Figure B1, $n_2/n_1 = 1$, therefore $D_2 = D_1 = 1500$ mm
  Minimum Inside Design Diameter = 1520 mm (closest nominal diameter available)

- Steel – P or ALT2, 2.0 mm thick or Steel-PG, 2.8 mm thick
  19x19x190 Spiral Rib Profile
  Manning “n” = 0.012 for 19x19x190 Spiral Rib Profile (Table C2.2, C2.1, and C2.0)
  From Figure B1, $n_2/n_1 = 1$, therefore $D_2 = D_1 = 1500$ mm
  Minimum Inside Design Diameter = 1500 mm

Example 1 - Appendix A
Steel – P or ALT2, 2.0 mm thick or Steel – PG, 2.8 mm thick

125x25 Helical Profile

Assume Manning “n” ≈ 0.024 (Table C2.2, C2.1, and C2.0) for 125x25 Helical profile, From Figure B1, \( n_2/n_1 = 0.024/0.012 = 2 \), therefore \( D_2 = 1950 \) mm

Check actual Manning “n” for \( D_2 = 1950 = 2000 \) mm (see Table C2.1), \( n = 0.025 \)

Therefore, assumed Manning “n” is within +/-0.01 of actual “n”, and is acceptable

Minimum Inside Design Diameter = 2000 mm

Referring to Table C7, Minimum Inside Design Diameter for all remaining pipe types is greater than the minimum serviceability design diameter.

Step 6 – Structural Evaluation

Concrete – Reinforced

From OPSD 807.03 (given an embankment construction, a maximum fill height of 1.2 m, and nominal diameter of 1500 mm), a minimum Class 50-D, Bedding type B or C is sufficient for structural requirements.

HDPE – CPSIO

There are currently no OPSDs for maximum or minimum fill heights for Closed Profile Wall HDPE pipe and values should be checked with the manufacturer, and approved by MTO. For the purpose of this example, first principles were used (given an embankment construction, a maximum fill height of 1.2 m, and nominal diameter of 1520 mm) and it was calculated that a minimum Ring Stiffness Constant (RSC) value of 160 is sufficient for structural requirements. However, an RSC 160 pipe is equivalent to a pipe stiffness of about 110 kPa for this diameter (refer to Appendix X1 in ASTM Standard F894). Considering MTO will not accept a pipe stiffness less than or equal to 210 kPa for permanent highway applications, and this pipe is only available up to a pipe stiffness of about 170 kPa at this diameter, the HDPE-CPSIO pipe will be eliminated from the remainder of the analysis.

Steel – P or ALT2, 2.0 mm thick or Steel-PG, 2.8 mm thick

19x19x190 Spiral Rib Profile

From OPSD 805.030 (given an embankment construction, a maximum fill height of 1.2 m, and nominal diameter of 1500 mm), a minimum steel thickness of 2.8 mm is required. It should be noted that if the pipe were installed in trench-like conditions, the steel thickness could be reduced. Therefore, the Steel-P, Steel-ALT2, and Steel-PG options require a minimum 2.8 mm steel thickness (greater than the previous 2.0 mm thickness calculated for the EMSL (from Step 3) for Steel-P and Steel-ALT2).

Steel – P or ALT2, 2.0 mm thick or Steel – PG, 2.8 mm thick

125x25 Helical Profile

From OPSD 805.010, (given an embankment construction, a maximum fill height of 1.2 m, and nominal diameter of 2000 mm), a minimum steel thickness of 2.0 mm is
required. Therefore, the 2.0 mm thick Steel-P, Steel-ALT2 and 2.8 mm thick Steel-PG required for the EMSL (from Step 3) are adequate.

**Step 7 - LCCA**

The following pipe material types meet the durability, hydraulic, and structural requirements for an EMSL ranging between 25 years and 50 years.

For EMSL ≥ 50 years ≥ DSL; the following pipe material types are available,

1. 1500 mm diameter, Reinforced Concrete Pipe, Class 50-D, Bedding Type B/C
2. 2000 mm diameter, Steel CSP-P, 2.0 mm thick, 125x25 Helical profile
3. 2000 mm diameter, Steel CSP-ALT2, 2.0 mm thick, 125x25 Helical profile
4. 1500 mm diameter, Steel SR-P, 2.8 mm thick, 19x19x190 profile
5. 1500 mm diameter, Steel SR-ALT2, 2.8 mm thick, 19x19x190 profile

For EMSL = 25 years < DSL; pipe replacement is required and the following pipe material types are available,

6. 2000 mm diameter, Steel CSP-PG, 2.8 mm thick, 125x25 Helical profile
7. 1500 mm diameter, Steel SR-PG, 2.8 mm thick, 19x19x190 profile

Due to the fact that the EMSL < DSL for some pipe material types listed above, a Life Cycle Costing Analysis is performed and summarized below:

<table>
<thead>
<tr>
<th>Description of Costs</th>
<th>Option No. 1 Reinforced Concrete</th>
<th>Option No. 2 CSP-P</th>
<th>Option No. 3 CSP-ALT2</th>
<th>Option No. 4 SR-P</th>
<th>Option No. 5 SR-ALT2</th>
<th>Option No. 6 CSP-PG</th>
<th>Option No. 7 SR-PG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Costs</td>
<td>115,692.00</td>
<td>99,673.00</td>
<td>89,883.00</td>
<td>104,122.00</td>
<td>93,433.00</td>
<td>71,195.00</td>
<td>74,755.00</td>
</tr>
<tr>
<td>Maintenance Costs</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Repair Costs</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Replacement Costs</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>23,280.00</td>
<td>24,211.00</td>
</tr>
<tr>
<td><strong>Total life cycle cost</strong></td>
<td><strong>115,692.00</strong></td>
<td><strong>99,673.00</strong></td>
<td><strong>89,883.00</strong></td>
<td><strong>104,122.00</strong></td>
<td><strong>93,433.00</strong></td>
<td><strong>94,475.00</strong></td>
<td><strong>98,965.00</strong></td>
</tr>
</tbody>
</table>

Assumptions:

1. Maintenance and Repair costs are considered to be negligible for comparison purposes;
2. Analysis Period = DSL = 50 years
3. Discount Rate (real) = 6 %
The details of the life cycle cost analysis for each option are provided in the LCCA tables following this example.

**Step 8 - Acceptable Pipes for Tender Documents**

Based on the results of the LCCA, the Steel-PG Option Nos. 6 and 7 including pipe replacement are more expensive than Steel-ALT2 Option Nos. 3 and 5, that do not require pipe replacement. As a result, Option Nos. 6 and 7 will not be specified in the tender documents. The following pipe material types may be included in the tender documents as equal alternatives.

1. 2000 mm diameter, CSP-ALT2, 2.0 mm thick, 125x25 Helical profile;
2. 1500 mm diameter, Steel SR-ALT2, 2.8 mm thick, 19x19x190 profile;
3. 2000 mm diameter, CSP-P, 2.0 mm thick, 125x25 Helical profile;
4. 1500 mm diameter, Steel SR-P, 2.8 mm thick, 19x19x190 profile;
5. 1500 mm diameter, Reinforced Concrete Pipe, Class 50-D; Bedding Type B or C.
**LIFE CYCLE COST ANALYSIS TABLE**

**Project Description:**
- **Project Title:** EXAMPLE 1 - OPTION NO. 1
- **Description:** Reinforced Concrete Pipe, Nom Diam. = 1500 mm, Class 50-D, EMSL >= 50 yrs.

**Work Project Number:** 9015-A-00191
- **Region:** Central
- **District:** Highway 7
- **Closest Intersection:** N 4862370.9; E 260408.1
- **Application:** Culvert ☒ Storm Sewer ☐
- **Material Type / Option:** Reinforced concrete pipe

**Consultant:** Company Corp.
- **Analyzed By:** Joe Pipe

**Date:** 2-Apr-05

**Economic Factors:**
- **Discount rate (nominal):** 10.0% (dn)
- **Inflation rate:** 3.8% (I)
- **Discount rate (real):** 6.00% (dr)

**Assumptions:**
- **Design Service Life (years):** 50 (DSL)
- **Analysis Period (years):** 50

**Methodology:**
- **Estimated Material Service Life (years):** 50 (EMSL)

<table>
<thead>
<tr>
<th>Description of Costs</th>
<th>Number of years until cost expended (n)</th>
<th>Actual Cost in Base Year dollars ($)</th>
<th>Present Value of Cost ($)</th>
<th>Present Value of Cost ($ Sub-total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Initial Costs:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1 Design Costs</td>
<td>0 $</td>
<td></td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>1.2 Bid price for Material:</td>
<td>2 $ 125,000</td>
<td>$111,242</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3 Bid price for Installation:</td>
<td>0 $</td>
<td>$0</td>
<td></td>
<td>$0</td>
</tr>
<tr>
<td>1.4 Bid price for Installation Inspection:</td>
<td>2 $ 5,000</td>
<td>$4,450</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5 Traffic Disruption Cost:</td>
<td>0 $</td>
<td>$0</td>
<td></td>
<td>$0</td>
</tr>
<tr>
<td>1.6 Detour Cost:</td>
<td>0 $</td>
<td>$0</td>
<td></td>
<td>$0</td>
</tr>
<tr>
<td>1.7 Other:</td>
<td>0 $</td>
<td>$0</td>
<td></td>
<td>$0</td>
</tr>
<tr>
<td><strong>Total Initial Costs:</strong></td>
<td><strong>$115,692</strong></td>
<td><strong>$115,692</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Maintenance Costs (Annual costs):</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1 Annual inspection and maintenance:</td>
<td>50 $</td>
<td>$</td>
<td>$</td>
<td>$</td>
</tr>
<tr>
<td>2.2 Traffic Delay:</td>
<td>50 $</td>
<td>$</td>
<td>$</td>
<td>$0</td>
</tr>
<tr>
<td>2.3 Other:</td>
<td>50 $</td>
<td>$</td>
<td>$</td>
<td>$0</td>
</tr>
<tr>
<td><strong>Total Maintenance Costs:</strong></td>
<td><strong>$0</strong></td>
<td><strong>$0</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Rehabilitation / Repair Costs:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1 Capital Cost:</td>
<td>NOT APPLICABLE $</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>3.2 Traffic Disruption Cost:</td>
<td>NOT APPLICABLE $</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>3.3 Detour Cost:</td>
<td>NOT APPLICABLE $</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>3.4 Other Cost (minor repairs):</td>
<td>NOT APPLICABLE $</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td><strong>Total Rehabilitation / Repair Costs:</strong></td>
<td><strong>$0</strong></td>
<td><strong>$0</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Replacement Costs:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1 Capital Cost:</td>
<td>0 $</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>4.2 Traffic Disruption Cost:</td>
<td>0 $</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>4.3 Detour Cost:</td>
<td>0 $</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>4.4 Other Cost:</td>
<td>0 $</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td><strong>Total Replacement Costs:</strong></td>
<td><strong>$0</strong></td>
<td><strong>$0</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Total life cycle cost (present value):</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>$115,692</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### LCCA Table September 2005

**LIFE CYCLE COST ANALYSIS TABLE**

**Project Description:**
- **Project Title:** EXAMPLE 1 - OPTION NO. 2
- **Description:** CSP-P, Nominal Diam. = 2,000 mm, EMSL = 50 years

**Work Project Number:** 9015-A-000191
- **Region:** Central
- **Consultant:** Company Corp.
- **Contractor:**
- **Closest Intersection:** N 4862370.9; E 260408.1
- **District:**
- **Analyzed By:** Joe Pipe
- **Road:** Highway 7
- **Date:** 2-Apr-05
- **Location:** N 4862370.9; E 260408.1
- **Application:** Culvert □ Storm Sewer
- **Material Type / Option:** CSP-Polymer Coated

**Economic Factors:**
- **Discount rate (nominal):** 10.0% (d)
- **Inflation rate:** 3.8% (I)
- **Discount rate (real):** 6.00% (d)

**Assumptions:**
- **Design Service Life (years):** 50 (DSL)
- **Analysis Period (years):** 50

**Methodology:**
- **Estimated Material Service Life (years):** 50 (EMSL)

### Description of Costs

<table>
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<tr>
<th>Description of Costs</th>
<th>Number of years until cost expended</th>
<th>Actual Cost in Base Year dollars ($)</th>
<th>Present Value of Cost ($)</th>
<th>Present Value of Cost ($ Sub-total)</th>
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</thead>
<tbody>
<tr>
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<td>5 Total life cycle cost (present value):</td>
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</table>
### LIFE CYCLE COST ANALYSIS TABLE

**Project Description:**
**Project Title:** EXAMPLE 1 - OPTION NO. 3  
**Description:** CSP-ALT2, Nominal Diam. = 2,000 mm, EMSL = 50 years

**Work Project Number:** 9015-A-000191  
**Consultant:** Company Corp.  
**Region:** Central  
**Contractor:** -  
**District:** Highway 7  
**Analyzed By:** Joe Pipe  
**Road:** Highway 7  
**Closest Intersection:** N 4862370.9; E 260408.1  
**Location:** N 4862370.9; E 260408.1  
**Application:** Culvert ☑ Storm Sewer □

**Material Type / Option:** Corrugated Steel Pipe - Aluminized Type 2 Coated

**Economic Factors:**
- Discount rate (nominal): 10.0% (d)
- Inflation rate: 3.8% (I)
- Discount rate (real): 6.00% (d)

**Assumptions:**
- Design Service Life (years): 50 (DSL)
- Analysis Period (years): 50

**Methodology:**
- Estimated Material Service Life (years): 50 (EMSL)

#### Description of Costs

<table>
<thead>
<tr>
<th>Description of Costs</th>
<th>Number of years until cost expended (n)</th>
<th>Actual Cost in Base Year dollars ($)</th>
<th>Present Value of Cost ($)</th>
<th>Present Value of Cost ($ Sub-total)</th>
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<tbody>
<tr>
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<td>1.3 Bid price for Installation:</td>
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<td>$0</td>
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<td>$0</td>
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<tr>
<td>1.4 Bid price for Installation Inspection:</td>
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<td>1.6 Detour Cost:</td>
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<td><strong>Total Initial Costs:</strong></td>
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<td>$0</td>
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<td>3.4 Other Cost (repairs):</td>
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<td><strong>Note: Minimum Life of Rehab Years (yrs):</strong></td>
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<tr>
<td><strong>Total Rehabilitation / Repair Costs:</strong></td>
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<td><strong>$0</strong></td>
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<td>4 Replacement Costs:</td>
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<td>4.4 Other:</td>
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<td>N/A</td>
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<td><strong>Total Replacement Costs:</strong></td>
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<td>5 Total life cycle cost (present value):</td>
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<td><strong>$89,883</strong></td>
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</table>
**LIFE CYCLE COST ANALYSIS TABLE**

**Project Description:**
Project Title: EXAMPLE 1 - OPTION NO. 4
Description: Steel SR-P Pipe, Nominal Diam.= 1,500 mm, EMSL = 50 years

**Work Project Number:** 0015-A-000191
**Consultant:** Company Corp.
Region: Central
**Contractor:**
District: Highway 7
**Analyzed By:** Joe Pipe
**Date:** 2-Apr-05
Closest Intersection: N 4862370.9; E 260408.1
Location: Highway 7
**Road:** Highway 7
**Date:** 2-Apr-05
**Region:** Central

**Application:** Culvert ☒ Storm Sewer ☐
**Material Type / Option:** Steel Spiral Rib - Polymer Laminated

**Economic Factors:**
Discount rate (nominal): 10.0% (dn)
Inflation rate: 3.8% (I)
Discount rate (real): 6.00% (dr)

**Assumptions:**
Design Service Life (years): 50 (DSL)
Analysis Period (years): 50

**Methodology:**
Estimated Material Service Life (years): 50 (EMSL)

<table>
<thead>
<tr>
<th>Description of Costs</th>
<th>Number of years until cost expended (n)</th>
<th>Actual Cost in Base Year dollars ($)</th>
<th>Present Value of Cost ($)</th>
<th>Present Value of Cost ($ Sub-total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Initial Costs:</td>
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<td>$0</td>
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<td>1.4 Bid price for Installation Inspection:</td>
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<td>1.5 Traffic Disruption Cost:</td>
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<td>2.2 Traffic Delay:</td>
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<td>3 Rehabilitation / Repair Costs:</td>
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<td>4 Replacement Costs:</td>
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<td>4.3 Detour Cost:</td>
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<td>4.4 Other Cost:</td>
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<td>5 Total life cycle cost (present value):</td>
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</table>
## LIFE CYCLE COST ANALYSIS TABLE

### Project Description:

**Project Title:** EXAMPLE 1 - OPTION NO. 5  
**Description:** Steel SR-ALT2, Nominal Diam.= 1,500 mm, EMSL = 50 years

**Work Project Number:** 9015-A-000191  
**Region:** Central  
**Contractor:** Company Corp.  
**District:** Highway 7  
**Analyzed By:** Joe Pipe  
**Date:** 2-Apr-05  
**Closest Intersection:** N 4862370.9; E 260408.1  
**Application:** Culvert  
**Material Type / Option:** Spiral Rib Steel Pipe - Aluminized Type 2 Coating

### Economic Factors:

- **Discount rate (nominal):** 10.0%  
- **Inflation rate:** 3.8%  
- **Discount rate (real):** 6.00%

### Assumptions:

- **Design Service Life (years):** 50  
- **Analysis Period (years):** 50

### Methodology:

- **Estimated Material Service Life (years):** 50

<table>
<thead>
<tr>
<th>Description of Costs</th>
<th>Number of years until cost expended (n)</th>
<th>Actual Cost in Base Year dollars ($)</th>
<th>Present Value of Cost ($)</th>
<th>Present Value of Cost ($ Sub-total)</th>
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<tr>
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<tr>
<td>1.1 Design Costs</td>
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<td>1.6 Detour Cost:</td>
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<td>1.7 Other:</td>
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<tr>
<td>2.1 Annual inspection and maintenance:</td>
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<tr>
<td>2.2 Traffic Delay:</td>
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<td>2.3 Other:</td>
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<td><strong>Total Maintenance Costs:</strong></td>
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<tr>
<td>3.4 Other Cost (repairs):</td>
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<td><strong>Total Rehabilitation / Repair Costs:</strong></td>
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</tr>
<tr>
<td>4 Replacement Costs:</td>
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</tr>
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<td>$</td>
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<tr>
<td>4.2 Traffic Disruption Cost:</td>
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<td>4.3 Detour Cost:</td>
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<td>4.4 Other Cost:</td>
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<tr>
<td><strong>Total Replacement Costs:</strong></td>
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<td><strong>$0</strong></td>
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<td>5 Total life cycle cost (present value):</td>
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<td><strong>$93,443</strong></td>
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</table>
## LIFE CYCLE COST ANALYSIS TABLE

**Project Description:**

**Project Title:** EXAMPLE 1 - OPTION NO. 6  
**Description:** CSP-PG, Nominal Diam. = 2,000 mm, EMSL = 25 years

**Work Project Number:** 9015-A-000191  
**Consultant:** Company Corp.  
**Region:** Central  
**Contractor:** -  
**District:** Highway 7  
**Analyzed By:** Joe Pipe  
**Road:** Highway 7  
**Date:** 2-Apr-05  
**Closest Intersection:** -  
**Location:** N 4862370.9; E 260408.1  
**Application:** Culvert  
**Material Type / Option:** Corrugated Steel Pipe - Plain Galvanized

### Economic Factors:

- **Discount rate (nominal):** 10.0%  
- **Inflation rate:** 3.8%  
- **Discount rate (real):** 6.00%

### Assumptions:

- **Design Service Life (years):** 50  
- **Analysis Period (years):** 50

### Methodology:

- **Estimated Material Service Life (years):** 25

### Description of Costs

<table>
<thead>
<tr>
<th>Description of Costs</th>
<th>Number of years until cost expended (n)</th>
<th>Actual Cost in Base Year dollars ($)</th>
<th>Present Value of Cost ($)</th>
</tr>
</thead>
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<td>1.6 Detour Cost:</td>
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<td>1.7 Other</td>
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<td>3.4 Other Cost (repairs):</td>
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</tr>
<tr>
<td><strong>5 Total life cycle cost (present value):</strong></td>
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<td>$94,475</td>
</tr>
</tbody>
</table>

Total life cycle cost (present value): $94,475
**LIFE CYCLE COST ANALYSIS TABLE**

**Project Description:**
- **Project Title:** EXAMPLE 1 - OPTION NO. 7
- **Description:** Steel SR-PG, Nominal Diam. = 1,500 mm, EMSL = 25 years

**Work Project Number:** 9015-A-000191
- **Region:** Central
- **District:** Highway 7
- **Consultant:** Company Corp.
- **Contractor:** -
- **Analyzed By:** Joe Pipe
- **Date:** 2-Apr-05
- **Road:** Highway 7
- **Location:** N 4862370.9; E 260408.1
- **Application:** Culvert □ Storm Sewer □
- **Material Type / Option:** Spiral Rib Steel Pipe - Plain Galvanized

**Economic Factors:**
- Discount rate (nominal): 10.0%
- Inflation rate: 3.8%
- Discount rate (real): 6.00%

**Assumptions:**
- Design Service Life (years): 50
- Analysis Period (years): 50

**Methodology:**
- Estimated Material Service Life (years): 25

<table>
<thead>
<tr>
<th>Description of Costs</th>
<th>Number of years until cost expended (n)</th>
<th>Actual Cost in Base Year dollars ($)</th>
<th>Present Value of Cost ($)</th>
<th>Present Value of Cost ($ Sub-total)</th>
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<tr>
<td>4.4 Other Cost:</td>
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</table>
EXAMPLE 2

Assume a series of side storm sewers are to be designed for a new road extension along a collector road. The sewers are to be constructed using open trench excavation in a dense to very dense sand. The lowest anticipated pH value taken on samples of the soil and water was 8.0, and minimum anticipated resistivity values were 1,400 ohm-cm. The design inside diameter of a pipe with Manning roughness coefficient ‘n’ = 0.012 was calculated to be 600 mm using the Manning Equation, which is considered an acceptable hydraulic design procedure in this case. The slope of the sewers is considered to range between 2% and 3%. Proposed road grades indicate a maximum fill height of about 5 m over the top of the pipes, and a minimum fill height of 600 mm in anticipated.

Solution: Using Step-by-Step Pipe Selection Procedure

Step 1 - Define Design Parameters

Pipe Location: Highway 101, Station 10+000 to Station 10+500

Design Service Life (DSL) = 50 years (see Table C5)

For this example, pipe replacement is considered an option and EMSL < DSL will be acceptable. As a result, Life Cycle Costing Analysis may be required.

Step 2 - Size Availability

Given: Design inside diameter ≥ 600 mm (assuming Manning ‘n’ ≥ 0.012)

Referring to the maximum pipe diameter sizes listed on the Material Availability Tables in Appendix C (Tables C1, C2.0 – C2.2, C3.0 – C3.2, C4.0 – C4.1); all pipe material options are available for the analysis.

Step 3 - Durability

Concrete
Given: Slope = 2-3%, Pipe Inside Diameter=600 mm (i.e. pipe rise), pH=8;
Referring to Hadipriono Model described in Section 7.3.1 of the guidelines,
For 2.5 < pH < 9, \[ H_{EMSL} = -33.23 + 160.92 \log(pH) - 4.16 \sqrt{Slope} - 0.28 \text{ (rise)} \]
Concrete EMSL > 75 yrs ≥ DSL

HDPE
HDPE EMSL = 75 yrs (Class 320) ≥ DSL
PVC
PVC EMSL = 75 yrs (Class 320) ≥ DSL

Steel
Given: $pH = 8.0$, Resistivity = 1,400 ohm-cm;

1. Using Figure B6, Base Life Years for plain galvanized 1.6 mm thick steel = 36 yrs.
Using Figure B7, Base Life Years for ALT2 1.6 mm thick steel = 68 yrs.

2. Steel-P (Check $4 < pH < 10$ ✓ and $R > 100$ ohm-cm ✓)
   Assuming the EMSL for Steel-P is at least 50 years, \( \text{EMSL} = (\text{EMSL} - 50) \)
   \( X1 \text{ Factor} = (\text{EMSL} - 50)/(\text{Base Life Years}) = (50 - 50)/(36) = 0 \)

   Steel – ALT2 (Check $5 < pH < 9$ ✓ and $R > 1,500$ ohm-cm ☻)
   Because the Resistivity is 1400 ohm-cm (i.e. outside of the specified range), Steel-
   ALT2 will not be considered further in the analysis.

   Steel-PG (Check $6 < pH < 12$ ✓ and $2,000 < R < 10,000$ ohm-cm ☻)
   Because the Resistivity is 1400 ohm-cm (i.e. outside of the specified range), Steel-
   PG can still be considered (unlike Steel-ALT2); however, the EMSL must be
   designed to be greater than or equal to the DSL.

   \( X1 \text{ Factor} = \frac{\text{EMSL}}{\text{Base Life Years}} = \frac{50}{36} = 1.39 \)

3. Steel-P
   Because $X1 \text{ Factor} < 1$ and Base Life Years is 36 years (i.e. greater than the
   required 10 year minimum), 1.6 mm thick Steel-P is sufficient for durability design
   (EMSL ≥ DSL for Steel-P).

   Steel-PG
   From insert table on Figure B6, the closest Factor ≥ $X1 \text{ Factor}$ (equal to 1.39) is 1.8
   for 2.8 mm steel thickness (i.e. Gauge 12).
   Therefore, a minimum steel thickness equal to 2.8 mm is sufficient for durability
   design (EMSL ≥ DSL for Steel-PG).

Step 4 - Short List

List of pipe products still eligible for consideration after Steps 1 to 3, and after checking
the Pipe Availability Tables in Appendix C:

✓ Concrete - Reinforced (Non-reinforced concrete pipe is not available in Ontario)
✓ HDPE - SICO
Step 5 - Hydraulic Evaluation

Upon direction from the Drainage Design Engineer, in this case, the geometrics and physical characteristics of the site make it practical to use the Manning Equation and Design Chart method for sizing pipe based on hydraulic capacity equivalency. It should be noted that this is not always the case.

Concrete – Reinforced
Manning “n” = 0.012 (Table C1)
From Figure B1, \(\frac{n_2}{n_1} = 1\), therefore \(D_2 = D_1 = 600\) mm
Minimum Inside Design Diameter = 600 mm

HDPE – SICO
Manning “n” = 0.012 (Table C3.1)
From Figure B1, \(\frac{n_2}{n_1} = 1\), therefore \(D_2 = D_1 = 600\) mm
Minimum Inside Design Diameter = 600 mm

PVC – SWSI
Manning “n” = 0.012 (Table C4.1)
From Figure B1, \(\frac{n_2}{n_1} = 1\), therefore \(D_2 = D_1 = 600\) mm
Minimum Inside Design Diameter = 600 mm

PVC – SIRO
Manning “n” = 0.012 (Table C4.0)
From Figure B1, \(\frac{n_2}{n_1} = 1\), therefore \(D_2 = D_1 = 600\) mm
Minimum Inside Design Diameter = 600 mm

Steel – P, 1.6 mm thick or Steel-PG, 2.8 mm thick
19x19x190 Spiral Rib Profile
Manning “n” = 0.012 for 19x19x190 Spiral Rib Profile (Table C2.2 and C2.0)
From Figure B1, \(\frac{n_2}{n_1} = 1\), therefore \(D_2 = D_1 = 600\) mm
Minimum Inside Design Diameter = 600 mm

Steel – P, 1.6 mm thick or Steel-PG, 2.8 mm thick
68x13 Helical Profile
Assume Manning “n” ≈ 0.017 (Table C2.2 and C2.0),
From Figure B1, using \(\frac{n_2}{n_1} = 0.017/0.012 = 1.4\), Figure B1 gives \(D_2 \approx 682\) mm
Check actual Manning “n” for \(D_2 \approx 680 = 700\) mm (see Table C2.2, C2.0), \(n=0.017\)
Therefore, assumed Manning “n” = actual “n”,
Minimum Inside Design Diameter = 700 mm
Step 6 - Structural Evaluation

☑️ Concrete – Reinforced
From OPSD 807.03, (given shallow trench construction, a maximum fill height of 5 m, and nominal diameter of 600 mm), use minimum Class 65-D, Bedding type B or Class 100-D with no restriction to bedding type.

☑️ HDPE – SICO
From OPSD 806.02, (given confined trench construction, a maximum fill height of 5 m, and nominal diameter of 600 mm), Class 320 pipe can be used with no restrictions on trench width.

☑️ PVC – SWSI
From OPSD 806.06, (given confined trench construction in Type 1 or 2 soil, a maximum fill height of 5 m, and nominal diameter of 600 mm), SDR 41 pipe can be used with no restrictions on cover material type.

☑️ PVC – SIRO
From OPSD 806.040, (given confined trench construction in Type 1 or 2 soil, a maximum fill height of 5 m, and nominal diameter of 600 mm), Class 320 pipe can be used with no restrictions on trench width.

☑️ Steel – P, 1.6 mm thick or Steel-PG, 2.8 mm thick 19x19x190 Spiral Rib Profile
From OPSD 805.030 (given trench construction, a maximum fill height of 5 m, and nominal diameter of 600 mm), a minimum steel thickness of 1.6 mm is required. Therefore, the 1.6 mm thick Steel-P option and 2.8 mm thick Steel-PG option required for the EMSL (from Step 3) is adequate.

☑️ Steel – P, 1.6 mm thick or Steel-PG, 2.8 mm thick 68x13 Helical Profile
From OPSD 805.010, (given a maximum fill height of 5 m, and nominal diameter of 700 mm), a minimum steel thickness of 1.6 mm is required. Therefore, the 1.6 mm thick Steel-P option and 2.8 mm thick Steel-PG option required for the EMSL (from Step 3) is adequate.

Step 7 - LCCA

The EMSL ≥ DSL for all of the pipe material types listed above; therefore, no LCCA will be performed.
Step 8 - Acceptable Pipes for Tender Documents

The following pipe material types meet the durability, hydraulic, and structural requirements and may be included in the tender documents as equal alternatives:

1. 600 mm diameter, Reinforced Concrete Pipe, Class 65-D, Class B bedding, no restriction to wall type;
2. 600 mm diameter, Reinforced Concrete Pipe, Class 100-D, no restrictions to Bedding Type;
3. 600 mm diameter, HDPE, Smooth inside and corrugated outside, Pipe Stiffness ≥ 320 kPa;
4. 600 mm diameter, PVC, Closed profile - smooth inside and outside, Maximum SDR = 41;
5. 600 mm diameter, PVC, Smooth inside and ribbed outside, Pipe Stiffness ≥ 320 kPa;
6. 700 mm diameter, Steel CSP-P (Polymer Laminated), 1.6 mm thick, 68x13 Helical profile;
7. 600 mm diameter, Steel SR-P (Polymer Laminated), 1.6 mm thick, 19x19x190 profile.
8. 700 mm diameter, Steel CSP-PG, 2.8 mm thick, 68x13 Helical profile;
9. 600 mm diameter, Steel SR-PG, 2.8 mm thick, 19x19x190 profile.
EXAMPLE 3

Assume a drainage structure is being selected for construction one year after the analysis base date. The new drainage structure is a side storm sewer for a collector road. The side storm sewer passes under several other local roads and commercial entrances. No pH or resistivity data for the soil or water were available at the time of this analysis. The geotechnical investigation and culvert investigation at the site suggest near surface soils consist of silt, and the water table is at or above the proposed pipe invert at some locations (Type 2 soil according to OHSA). Given a slope of 1%, a 600 mm and 700 mm inside diameter pipe were calculated for the same storm sewer run using Manning roughness coefficients of 0.012 and 0.017 respectively. The hydraulic analysis was performed as part of the drainage study using methods outlined in the MTO Drainage Management Manual. The typical drainage conditions in the sewer consist of nonabrasive flow with water velocities expected to be 1.5 m/s.

Solution: Using Step-by-Step Pipe Selection Procedure and referencing applicable chapters where sufficient information is not provided.

Step 1 - Define Design Parameters

Pipe Location: Highway 108, Station 20+000 to Station 21+000, Offset 40 m Left

Design Service Life (DSL) = 50 years (see Table C5)

Note: The highway facility is classified as a collector road, side storm sewer; however, due to the fact that the storm sewer crosses under several local roads and entrances, the more stringent design service life of the two applications is used.

Referring to Note 4 on Table C5, due to the fact that groundwater is anticipated to be at or near the pipe invert, gasketed or leak-free joint options will only be considered in this example.

For this example, pipe replacement is not considered an option and EMSL ≥ DSL will only be acceptable. As a result, Life Cycle Costing Analysis is not required.

Step 2 - Size Availability

Given: Design inside diameter
= 600 mm (Manning “n” = 0.012)
= 700 mm (Manning “n” = 0.017)
= 750 mm (Manning “n” = 0.021)
Referring to the maximum pipe diameter sizes listed on the Material Availability Tables in Appendix C (Tables C1, C2.0 – C2.2, C3.0 – C3.2, C4.0 – C4.1); all pipe material options are available for the analysis.

**Step 3 - Durability**

Considering no soil or water pH, resistivity or chemical testing was performed during the investigation, preliminary estimates need to be made that should be checked with actual field conditions prior to detailed design. Referring to Chapters 3, 4, and 7 and using Figures D1 and D2 (assuming that the site is in the Greater Toronto Area), a rainfall pH value of about 4.5 is estimated to increase based on the moderate acidity reducing potential of the apparent soils. Experience indicates that surface and subsurface water in Ontario is generally in the pH range of 6 to 8 (see pg. 55 in Guidelines); thus, a pH value of 6.0 is estimated. However, it should be noted that in urban areas, the pH can also decrease depending on specific site conditions and the predicted values should be verified with actual measurements. The geotechnical investigation indicates that the near surface soil consists predominantly of silt and the invert elevation will be near the water table. Referring to Table 3.3, the soil is considered to be moderately corrosive. Using Tables 3.1 and 3.2, the resistivity of the soil/water is estimated to be about 4500 ohm-cm. Referring to Table C8, the storm sewer is anticipated to have an abrasion level 2 or less.

**Concrete**

Given: Nonabrasive Flow (slope = 1%), Pipe Inside Diameter=600 mm, pH=6;
Referring to Table C10, Reinforced Concrete EMSL \( \geq \) DSL

Due to high water table, it is assumed that CSA Type HS/HSb cement will be used and should be specified; thus, no sulphate reduction factor will be applied.

**HDPE**

HDPE EMSL = 75 yrs (Class 320, CSA certified) \( \geq \) DSL

**PVC**

PVC EMSL = 75 yrs (Class 320, CSA certified) \( \geq \) DSL

**Steel**

Given: pH = 6, Resistivity = 4,500 ohm-cm;

1. Using Figure B6, Base Life Years for plain galvanized 1.6 mm thick steel = 23 yrs.

2. Steel-P (Check 4<pH<10 \( \checkmark \) and R >100 ohm-cm \( \checkmark \))

   X1 Factor = EMSL

   Assuming the EMSL for Steel-P is at least 50 years, EMSL\(_{s} = (\text{EMSL-50})

---

**Example 3 - Appendix A**
X1 Factor = \((\text{EMSL}-50)/(\text{Base Life Years}) = (50-50)/(23) = 0\)

Steel – ALT2 (Check \(5<pH<9\) \(\checkmark\) and \(R > 1,500 \text{ ohm-cm} \(\checkmark\)\)

For the EMSL = DSL, determine Y1 as follows,
Y1 Factor = \((\text{EMSL})/(\text{Base Life Years}) = (50)/(65) = 0.77\)

Steel-PG (Check \(6<pH<12\) \(\times\) and \(2,000 < R < 10,000 \text{ ohm-cm}\) \(\checkmark\)\)

Because the pH is not within the specified range, Steel-PG can still be considered; however, the EMSL must be designed to be greater than or equal to the DSL.

X1 Factor = \(\text{EMSL}/(\text{Base Life Years}) = (50 \text{ years})/(23 \text{ years}) = 2.17\)

### 3. Steel-P

Because X1 Factor is less than 1 and Base Life Years is 23 years (i.e. greater than the required 10 year minimum), 1.6 mm thick Steel-P is sufficient for durability design (EMSL \(\geq\) DSL for Steel-P).

### Steel-ALT2

Because Y1 Factor is less than 1 and Base Life Years is 65 years (i.e. greater than the DSL), 1.6 mm thick Steel-ALT2 is sufficient for durability design (EMSL \(\geq\) DSL for Steel-ALT2).

### Steel-PG

From insert table on Figure B6, the closest Factor \(\geq\) X1 Factor (equal to 2.17) is 2.3 for 3.5 mm steel thickness (i.e. Gauge 10).

Therefore, 3.5 mm thick steel is sufficient for durability design (EMSL \(\geq\) DSL for Steel-PG).

### Step 4 - Short List

List of pipe products still eligible for consideration after Steps 1 to 3, and after checking the Pipe Availability Tables in Appendix C for available diameters and gasketed (or leak-free) joints:

- Concrete - Reinforced (Non-reinforced concrete pipe is not available in Ontario)
- HDPE - SICO
- PVC – SIRO & SWSI
- Steel – P and ALT 2, 1.6 mm thick (68x13 Helical and 19x19x190 SR types)
- Steel – PG, 3.5 mm thick (not available in 3.5 mm thickness until minimum diameter of 900 mm; thus, this option is eliminated)
Step 5 - Hydraulic Evaluation

For this example, a separate hydraulic analysis was carried out for a range of diameters and Manning roughness coefficients. The given internal diameters (600 mm and 700 mm) and corresponding Manning roughness coefficients (0.012 and 0.017) should be checked with the values assumed in this manual.

☑ Concrete – Reinforced
  Manning “n” = 0.012 (Table C1)
  Minimum Inside Design Diameter = 600 mm

☑ HDPE – SICO
  Manning “n” = 0.012 (Table C3.1)
  Minimum Inside Design Diameter = 600 mm

☑ PVC – SWSI
  Manning “n” = 0.012 (Table C4.1)
  Minimum Inside Design Diameter = 600 mm

☑ PVC – SIRO
  Manning “n” = 0.012 (Table C4.0)
  Minimum Inside Design Diameter = 600 mm

☑ Steel – P and Steel-ALT2
  19x19x190 Spiral Rib Profile
  Manning “n” = 0.012 for 19x19x190 Spiral Rib Profile (Table C2.2 and C2.1)
  Minimum Inside Design Diameter = 600 mm

☑ Steel – P and Steel-ALT2
  68x13 Helical Profile
  Assume Manning “n” = 0.017 (Table C2.2 and C2.1),
  Minimum Inside Design Diameter = 700 mm

For this case, there is no need to perform the hydraulic equivalency check since the Manning roughness coefficients used in the original hydraulic analysis are applicable for all pipe types under consideration.

Step 6 - Structural Evaluation

☑ Concrete – Reinforced
  From OPSD 807.01, (given confined trench construction, a maximum fill height of 3 m, and nominal diameter of 600 mm), a minimum Class 50-D, Bedding type B is sufficient for structural requirements.
☑ HDPE – SICO
From OPSD 806.02, (given confined trench construction in Type 2 soil, a maximum fill height of 3 m, and nominal diameter of 600 mm), Class 320 pipe can be used with no restrictions on trench width.

☑ PVC – SWSI
From OPSD 806.06, (given confined trench construction in Type 2 soil, a maximum fill height of 3 m, and nominal diameter of 600 mm), SDR 41 pipe can be used with no restrictions on cover material type.

☑ PVC – SIRO
From OPSD 806.040, (given confined trench construction in Type 2 soil, a maximum fill height of 3 m, and nominal diameter of 600 mm), Class 320 pipe can be used with no restrictions on trench width.

☑ Steel – P and ALT2, 1.6 mm thick
19x19x190 Spiral Rib Profile
From OPSD 805.030 (given a confined trench construction, a maximum fill height of 3 m, and nominal diameter of 600 mm), a minimum steel thickness of 1.6 mm is required. Therefore, the 1.6 mm thick Steel-P option calculated for the EMSL (from Step 3) is adequate.

☑ Steel – P and ALT2, 1.6 mm thick
68x13 Helical Profile
From OPSD 805.010, (given a confined trench construction, a maximum fill height of 3 m, and nominal diameter of 700 mm), a minimum steel thickness of 1.6 mm is required. Therefore, the 1.6 mm thickness of steel required for the EMSL (from Step 3) is adequate.

Step 7 - LCCA
The EMSL ≥ DSL for all of the pipe material types listed above; therefore, no LCCA will be performed.

Step 8 - Acceptable Pipes for Tender Documents
The final step for selecting the appropriate pipe material type is to assess the risk factors outlined in the manual. In this example, considering that the water table is at or above the invert level and due to the fact that several of the local road crossings are to be upgraded to collector roads in the near future, the risk of leaky joints in the high water table with horizontal gradient is considered significant and gasketed joints are to be specified to reduce the risk of water and soil infiltration at the joints. Refer to Chapter 4 (Sections 4.1.4 and 4.1.5) for more details.
Of the remaining pipe material types that meet the durability, hydraulic, and structural requirements, concrete, HDPE, and PVC have pre-qualified leak testing capabilities; whereas steel pipe will need post installation leak testing specified (refer to OPSS 410).

The following pipe material types meet the durability, hydraulic, and structural requirements and may be included in the tender documents as equal alternatives:

1. 600 mm diameter, PVC Profile Wall (ribbed outside, smooth inside), CSA182.4, Class 320, leak-free joints;
2. 600 mm diameter, PVC Solid Wall (smooth inside and outside), CSA 182.6, SDR 41, leak-free joints;
3. 600 mm diameter, HDPE Open Profile (corrugated outside and smooth inside), CSA182.6/Sewer, Class 320, leak-free joints;
4. 600 mm diameter, Reinforced Concrete, Class50-D, Bedding Type B, Type HS/HSb cement, leak-free joints;
5. 700 mm diameter, CSP-P, 1.6 mm thick, 68x13 Helical profile, leak-free joints;
6. 700 mm diameter, CSP-ALT2, 1.6 mm thick, 68x13 Helical profile, leak-free joints;
7. 600 mm diameter, Steel SR-P, 1.6 mm thick, 19x19x190 profile, leak-free joints;
8. 600 mm diameter, Steel SR-ALT2, 1.6 mm thick, 19x19x190 profile; leak-free joints.
EXAMPLE 4

Assume several cross culverts are being constructed as part of a freeway expansion in Northern Ontario. The geotechnical investigation and drainage investigation at the site indicate a typical pH value of 7.0 and a resistivity of 14,000 ohm-cm. The culvert is anticipated to be constructed within an earthfill embankment, up to 10 m in height, over bedrock. The drainage analysis performed using the MTO Drainage Management Manual indicates that the culverts will be inlet control (with specific inlet geometrics given in the drainage report) corresponding to culverts with a minimum inside diameter of 1800 mm. The design flow water velocity is 0.5 m/s on an anticipated grade of 0.25%. The freeway is the main route to several large towns and potential detour routes are estimated to be over 100 km additional length.

Solution: Using Step-by-Step Pipe Selection Procedure

Step 1 - Define Design Parameters

Pipe Location: Highway 412, Station 20+000

Design Service Life (DSL) = 75 years (see Table C5)

Note: Referring to Note 4 on Table C5, it is considered that only pipe materials with leak-free joints be specified due to the risk of infiltration/exfiltration of water and soils beneath the freeway which could cause settlement or collapse of the overlying road surface.

For this example, pipe replacement is not considered an option and EMSL ≥ DSL will only be acceptable. As a result, Life Cycle Costing Analysis is not required.

Step 2 - Size Availability

Given: Design inside diameter = 1800 mm

Referring to the maximum pipe diameter sizes listed on the Material Availability Tables in Appendix C (Tables C1, C2.0 – C2.2, C3.0 – C3.2, C4.0 – C4.1); we can eliminate the following pipe material types for the remainder of the analysis.

- Non-reinforced Concrete pipe not available above 900 mm diameter,
- PVC pipe not available above 1200 mm diameter,
- HDPE-CIO pipe not available above 900 mm diameter, and
- HDPE-SICO pipe not available above 900 mm diameter
**Step 3 - Durability**

**Concrete**
Given: Slope = 0.25%, Pipe Inside Diameter=1,800 mm, pH=7.0;
Referring to Table C10, Reinforced Concrete EMSL ≥ 75 yrs ≥ DSL.

**HDPE**
HDPE-CPSIO EMSL ≥ 75 yrs (Class 320, CSA certified) ≥ DSL.

**PVC**
Not required. PVC eliminated in Step 2

**Steel**
Given: pH = 7.0, Resistivity = 14,000 ohm-cm;

1. Using Figure B6, Base Life Years for plain galvanized 1.6 mm thick steel = 41 yrs.
Using Figure B7, Base Life Years for ALT2 1.6 mm thick steel > 75 yrs

2. Steel-P (Check 4<pH<10 ✓ and R >100 ohm-cm ✓)
   X1 Factor = EMSL/(Base Life Years)
   Assuming the EMSL for Steel-P is at least 50 years, EMSL = (EMSL-50)
   X1 Factor = (EMSL-50)/(Base Life Years) = (75-50)/(41) = 0.6

Steel – ALT2 (Check 5<pH<9 ✓ and R > 1,500 ohm-cm ✓)
EMSL > 75 yrs. > DSL, therefore Y1 Factor does not need to be calculated

Steel-PG (Check 6<pH<12 ✓ and 2,000 < R < 10,000 ohm-cm ✗)
Because the Resistivity (R) is not within the specified range, Steel-PG can still be considered; however, the EMSL must be designed to be greater than or equal to the DSL.

   X1 Factor = EMSL/(Base Life Years) = (75 years)/(41 years) = 1.83

3. Steel-P
Because X1 Factor is less than 1 and Base Life Years is 41 years (i.e. greater than the required 10 year minimum), 1.6 mm thick Steel-P is sufficient for durability design (EMSL ≥ DSL for Steel-P).

Steel-ALT2
Because Base Life Years > 75 years (i.e. greater than the required 25 year minimum), 1.6 mm thick Steel-ALT2 is sufficient for durability design (EMSL ≥ DSL for Steel-ALT2).
Steel-PG

From insert table on Figure B6, the closest Factor ≥ X1 Factor (equal to 1.83) is 2.3 for 3.5 mm steel thickness (i.e. Gauge 10). Therefore, the minimum steel thickness of 3.5 mm is sufficient for durability design (EMSL ≥ DSL for Steel-PG).

Step 4 - Short List

List of pipe products still eligible for consideration after Steps 1 to 3, and after checking the Pipe Availability Tables in Appendix C:

- HDPE – CPSIO
- Concrete - Reinforced
- Steel–P, 2.0 mm thick (1.6 mm thickness not available for 1800 mm diameter)
- Steel–ALT2, 2.0 mm thick (1.6 mm thickness not available for 1800 mm diameter)
- Steel-PG, 3.5 mm thick (68x13 and 125x25 Helical profile only)

Step 5 - Hydraulic Evaluation

The drainage analysis performed using the MTO Drainage Management Manual indicates that the culverts will be inlet control (with specific inlet geometrics given in the drainage report) corresponding to culverts with a minimum inside diameter of 1800 mm. Checking the Pipe Availability Tables in Appendix C, the following minimum internal diameters are available for each pipe type:

- Concrete – Reinforced
  (Table C1)
  Minimum Inside Design Diameter = 1829 mm (nominal diameter 1800 mm)

- HDPE – CPSIO
  (Table C3.2)
  Minimum Inside Design Diameter = 1830 mm (nominal diameter 1830 mm)

- Steel – P or ALT2, 2.8 mm thick (2.0 mm thick not available)
  19x19x190 Spiral Rib Profile
  (Table C2.2 and C2.1)
  Minimum Inside Design Diameter = 1800 mm (nominal diameter 1800 mm)

- Steel – P or ALT2, 2.0 mm thick
  125x25 Helical Profile
  (Table C2.2 and C2.1)
  Minimum Inside Design Diameter = 1800 mm (nominal diameter 1800 mm)
Steel – PG, 3.5 mm thick
125x25 and 68x13 Helical Profile
(Table C2.0)
Minimum Inside Design Diameter = 1800 mm (nominal diameter 1800 mm)

Referring to Table C7, Minimum Inside Design Diameter for all remaining pipe types is greater than the minimum serviceability design diameter.

Step 6 – Structural Evaluation

Concrete – Reinforced
From OPSD 807.03, (given embankment construction, zero projecting embankment, a maximum fill height of 10 m, and nominal diameter of 1800 mm), a minimum Class 140-D, Bedding type B or C is sufficient for structural requirements.

HDPE – CPSIO
There are currently no OPSDs for maximum or minimum fill heights for Closed Profile Wall HDPE pipe and values should be checked with the manufacturer, and approved by MTO. For the purpose of this example, first principles were used (given an embankment construction, a maximum fill height of 10 m, and nominal diameter of 1830 mm), and it was calculated that the maximum Ring Stiffness Constant manufactured (RSC 250) is not sufficient for structural requirements (i.e. the fill height is greater than the maximum cover allowed). As a result, this pipe product will be eliminated from the remainder of the analysis.

Steel – P or ALT2, 2.8 mm thick
19x19x190 Spiral Rib Profile
From OPSD 805.030 (given an embankment construction, a maximum fill height of 10 m, and nominal diameter of 1800 mm), a minimum steel thickness of 2.8 mm is required (greater than the previous 1.6 mm thickness calculated from Step 3 for the EMSL durability) for Steel-P and Steel-ALT2; in this case, 2.8 mm is the only steel thickness currently available for this manufacture type.

Steel – P or ALT2, 2.0 mm thick and Steel-PG, 3.5 mm thick
125x25 Helical Profile
From OPSD 805.010, (given an embankment construction, a maximum fill height of 10 m, and nominal diameter of 1800 mm), a minimum steel thickness of 2.0 mm is required. Therefore, the 2.0 mm thick Steel-P and Steel-ALT2, and 3.5 mm thick Steel-PG required for the EMSL (from Step 3) is adequate.

Steel – PG, 3.5 mm thick
68x13 Helical Profile
From OPSD 805.010, (given an embankment construction, a maximum fill height of 10 m, and nominal diameter of 1800 mm), a minimum steel thickness of 2.0 mm is
required. Therefore, the 3.5 mm thick Steel-PG option required for the EMSL (from Step 3) is adequate.

Step 7 - LCCA

The EMSL $\geq$ DSL for all of the pipe material types listed above; therefore, no LCCA will be performed.

Step 8 - Acceptable Pipes for Tender Documents

The final step for selecting the appropriate pipe material type is to assess the risk factors outlined in the manual. In this example, considering that the series of cross culverts have been specified to be leak-free, either pre-qualified leak-tested joints or field testing of joints is required. Referring to OPSS 410, it states “leakage tests shall only be carried out on complete pipe sewers 1200 mm in diameter and there shall be no visible leakage for pipe sewers larger than 1200 mm diameter”. In addition, considering the Design Service Life is 75 years and the anticipated high cost for unanticipated replacement/repair (i.e. due to high fill and lengthy detour route, traffic control, etc.), a designer may specify quality verification during construction.

For this case, considering the pipe diameter is larger than 1200 mm, it is suggested that a Special Provision for visual or video inspection be included in the tender documents to verify less than 5% pipe deflection by measurement and pipe/joint integrity during and after construction, as referenced in OPSS 514.

The following pipe material types meet the durability, hydraulic, and structural requirements and may be included in the tender documents as equal alternatives:

1. 1800 mm diameter, Reinforced Concrete, Class140-D, Bedding Type B or C, Type HS/HSb cement, leak-free joints;
2. 1800 mm diameter, Steel CSP-P, 2.0 mm thick, 125x25 Helical profile, leak-free joints;
3. 1800 mm diameter, Steel CSP-ALT2, 2.0 mm thick, 125x25 Helical profile, leak-free joints;
4. 1800 mm diameter, Steel SR-P, 2.8 mm thick, 19x19x190 profile, leak-free joints;
5. 1800 mm diameter, Steel SR-ALT2, 2.8 mm thick, 19x19x190 profile, leak-free joints;
6. 1800 mm diameter, Steel CSP-PG, 3.5 mm thick, 125x25 Helical profile, leak-free joints;
7. 1800 mm diameter, Steel CSP-PG, 3.5 mm thick, 68x13 Helical profile, leak-free joints.
Known Pipe Diameter, $D_1$ (mm) versus Unknown Pipe Diameter, $D_2$ (mm)

$$D_2 = D_1 \times (n_2/n_1)^{3/8}$$

Notes:
1. Figure based on Manning Equation assuming circular pipe, full flow conditions, constant slope, and constant total flow.
2. Actual flow conditions may vary and warrant a more detailed analysis.

Figure B1 - Determination Of Equivalent Pipe Diameters Step-by-Step Design Procedure
Figure B2 - Concrete Pipe Estimated Material Service Life Model
(after Ohio Department of Transportation Study, 1982)

Figure B3 - Comparison of 1500 mm diameter Concrete Pipe Estimated Material Service Life using: a. ODOT model, b. Hurd’s Model, and c. Hadipriono Model

Figure B4 - Concrete Pipe Estimated Material Service Life using Florida Model (Assume: diameter = 1500 mm, C = 7 sacks (Type 50 cement, assume S = 0), D = 1.5 inches, W = 45 %)

pH OF ENVIRONMENT NORMALLY
GREATER THAN 7.3
YEARS = 1.47 R^{0.41}
R = MINIMUM RESISTIVITY

pH OF ENVIRONMENT NORMALLY
LESS THAN 7.3
YEARS = 13.79[Log_{10}R-Log_{10}(2160-2490Log_{10}pH)]

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<tr>
<th>Thickness (mm)</th>
<th>1.3</th>
<th>1.6</th>
<th>2.0</th>
<th>2.8</th>
<th>3.5</th>
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<td>Gage</td>
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<td>16</td>
<td>14</td>
<td>12</td>
<td>10</td>
<td>8</td>
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<td>Factor (X1)</td>
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<td>1.6</td>
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<td>2.8</td>
<td>3.4</td>
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</table>

Multiply Years To Perforation
By Factor For The Various Metal Gages

Figure B5 - Galvanized Corrugated Steel Pipe Estimated Material Service Life - California Method

Reference: California Department of Transportation (CALTRANS), 2001 “Highway Design Manual”
Note: This figure is to be used as a general guide, the accuracy can be improved if the practical experience of the design agency is drawn on to ‘calibrate’ this method to their specific applications and specific environments
YEARS = 17.24[Log_{10}R - Log_{10}(2160 - 2490Log_{10}pH)]

(pH of environment normally less than 7.3)

YEARS = 1.84R^{0.41}

(pH of environment normally greater than 7.3)

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<tr>
<th>Thickness (mm)</th>
<th>1.6</th>
<th>2.0</th>
<th>2.8</th>
<th>3.5</th>
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<td>1.8</td>
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</table>

Multiply Years to Perforation by Factor for the various metal Gauges to calculate the EMSL of the base metal.


Note: This figure is to be used as a general guide, the accuracy can be improved if the practical experience of the design agency is drawn on to 'calibrate' this method to their specific applications and specific environments.
Figure B7 - Aluminized Type II Corrugated Steel Pipe Estimated Material Service Life - Florida DOT Model

References: i) U.S. DOT, Federal Highway Administration, 1996, "Durability Analysis of Aluminized Type II Corrugated Metal Pipe", December;
## Table C1
Concrete Pipe Material Availability List

<table>
<thead>
<tr>
<th>Nominal Diameter (mm)</th>
<th>Actual Inside Diameter (Avg.) (mm)</th>
<th>Actual Inside Diameter (Avg.) (inches)</th>
<th>CSA-A257.1-M92 Non-Reinforced</th>
<th>CSA-A257.2-M92 Reinforced</th>
<th>Joint Type Available</th>
<th>Manning Roughness Coefficient ( n ) (OPSS1820)</th>
<th>Outside Diameter (OPSS1820)</th>
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<td>Nominal Diameter (mm)</td>
<td>Actual Inside Diameter (Avg.) (mm)</td>
<td>Actual Inside Diameter (Avg.) (inches)</td>
<td>CSA-A257.1-M92 Non-Reinforced</td>
<td>CSA-A257.2-M92 Reinforced</td>
<td>Joint Type Available (OPSS1820)</td>
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</table>

Notes:
1. Outside Pipe Diameter is dependent on class of pipe and wall thickness A, B, or C according to CSA A257.1 and CSA A257.2
2. Joints for Bell and Spigot or Tongue and Groove include: COR = Confined ‘O’ Ring gasket, ROG = Roll-on Gasket, SOS= Single Off-Set
3. Materials and sizes listed in the table above were available at the time this manual was produced (April 2005). Designers should verify that the information and standards referenced in the table are still applicable, and the pipe types still available.
* Denotes concrete pipe not manufactured in Ontario

Reference: Ontario Concrete Pipe Association, 2005
### Table C2.0
Plain Galvanized Steel Pipe Material Availability List

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<tr>
<th>Nominal &amp; Actual Inside Diameter (Avg.) (mm)</th>
<th>Corrugation (Pitch x Depth)/Profile</th>
<th>Manufacture Type</th>
<th>Joint Type Available</th>
<th>Manning ‘n’ Value</th>
<th>Available Thickness (mm)</th>
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### Table C2.0
Plain Galvanized Steel Pipe Material Availability List

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<th>Nominal &amp; Actual Inside Diameter (mm)</th>
<th>Corrugation (Pitch x Depth) Profile</th>
<th>Manufacture Type</th>
<th>Joint Type Available</th>
<th>Manning ‘n’ Value</th>
<th>Available Thickness (mm)</th>
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<td>CC, UC, G, F</td>
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<td>2.0 – 3.5</td>
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### Notes:
1. Outside Diameter Calculated to be Inside Diameter + Wall thickness + Corrugation Depth Wall Thickness
2. Custom diameters are available for relining of existing pipes.
3. Wall thickness Specified as 1.3, 1.6, 2.0, 2.8, 3.5 and 4.2 mm for CSP. For actual dimensions, wall thickness should be taken as 1.12, 1.40, 1.82, 2.64, 3.35, and 4.08 mm, respectively for CSP (CSPI, 2003). For SPP, wall thickness’ for dimensioning should be taken to be 3, 4, 5, 6, and 7 mm.
4. Corrugation Profile Types: H = Helical, SR = Spiral Rib, SPP = Structural Plate Pipe
5. Joint Types (CSA G401-01): CC = Corrugated Coupler; UC = Universal Coupler, SCC = Semi Corrugated Coupler, BS = Bolted Seam, G = Gaskets, F = Filter Cloth. Special Couplers available for severe or unusual site conditions and relining.
6. Annular (Riveted) manufacture type may be supplied provided higher Manning ‘n’ value of 0.024 is used.
7. Materials and sizes listed in the table above were available at the time this manual was produced (April 2005). Designers should verify that the information and standards referenced in the table are still applicable, and the pipe types still available.

Reference: Corrugated Steel Pipe Institute, 2005 and CSA G401-01
### Table C2.1
Aluminized Type 2 Coated Steel Pipe Material Availability List

<table>
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<tr>
<th>Nominal &amp; Actual Inside Diameter (mm)</th>
<th>Corrugation (Pitch x Depth) /Profile</th>
<th>Manufacture Type</th>
<th>Joint Type Available</th>
<th>Manning 'n' Value</th>
<th>Available Thickness (mm)</th>
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Table C2.1
Aluminized Type 2 Coated Steel Pipe Material Availability List

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<th>Nominal &amp; Actual Inside Diameter(^2)(Avg.)</th>
<th>Corrugation (PitchxDepth)/Profile</th>
<th>Manufacture Type(^4)</th>
<th>Joint Type Available(^5)</th>
<th>Manning ‘n’ Value</th>
<th>Available Thickness (^1,3) (mm)</th>
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<tr>
<td>(mm)</td>
<td>(mm)</td>
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<td></td>
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</tr>
<tr>
<td>19 x 19 x 190</td>
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<td>SCC,G</td>
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<td>2.0, 2.8</td>
</tr>
<tr>
<td>1800</td>
<td>125 x 25</td>
<td>H</td>
<td>CC,UC G,F</td>
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<td>2.0 – 3.5</td>
</tr>
<tr>
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<td>SCC,G</td>
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<td>2.8</td>
</tr>
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<td>H</td>
<td>CC,UC G,F</td>
<td>0.025</td>
<td>2.0 – 3.5</td>
</tr>
<tr>
<td>19 x 19 x 190</td>
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<td>2200</td>
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<td>H</td>
<td>CC, G,F</td>
<td>0.025</td>
<td>2.0 – 3.5</td>
</tr>
<tr>
<td>19 x 19 x 190</td>
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<td>2.8</td>
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<td>H</td>
<td>CC, G,F</td>
<td>0.025</td>
<td>2.0 – 3.5</td>
</tr>
<tr>
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<td>SR</td>
<td>SCC,G</td>
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<td>2.8</td>
</tr>
<tr>
<td>2600</td>
<td>19 x 19 x 190</td>
<td>SR</td>
<td>SCC,G</td>
<td>0.012</td>
<td>2.8</td>
</tr>
<tr>
<td>2700</td>
<td>125 x 25</td>
<td>H</td>
<td>CC, G,F</td>
<td>0.025</td>
<td>2.0 – 3.5</td>
</tr>
<tr>
<td>3000</td>
<td>125 x 25</td>
<td>H</td>
<td>CC, G,F</td>
<td>0.025</td>
<td>2.8 – 3.5</td>
</tr>
</tbody>
</table>

Notes:
1. Outside Diameter Calculated to be Inside Diameter + Wall thickness + Corrugation Depth Wall Thickness
2. Custom diameters are available for relining of existing pipes.
3. Wall thickness Specified as 1.3, 1.6, 2.0, 2.8, 3.5 and 4.2 mm for CSP. For actual dimensions, wall thickness should be taken as 1.12, 1.40, 1.82, 2.64, 3.35, and 4.08 mm, respectively for CSP (CSPI, 2003). For SPP, wall thickness’ for dimensioning should be taken to be 3, 4, 5, 6, and 7 mm.
4. Corrugation Profile Types: H = Helical, SR=Spiral Rib, SPP = Structural Plate Pipe
5. Joint Types (CSA G401-01): CC = Corrugated Coupler; UC = Universal Coupler, SCC = Semi Corrugated Coupler, BS = Bolted Seam, G = Gaskets, F = Filter Cloth. Special Couplers available for severe or unusual site conditions and relining.
6. Annular (Riveted) manufacture type may be supplied provided higher Manning ‘n’ value of 0.024 is used.
7. Materials and sizes listed in the table above were available at the time this manual was produced (April 2005). Designers should verify that the information and standards referenced in the table are still applicable, and the pipe types still available.

Reference: Corrugated Steel Pipe Institute, 2005 and CSA G401-01
### Table C2.2
Polymer Laminated Steel Pipe Material Availability List

<table>
<thead>
<tr>
<th>Nominal &amp; Actual Inside Diameter (Avg.)</th>
<th>Corrugation (Pitch x Depth) Profile</th>
<th>Manufacture Type</th>
<th>Joint Type Available</th>
<th>Manning ‘n’ Value</th>
<th>Available Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(mm)</td>
<td>(mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>68 x 13</td>
<td>H</td>
<td>CC, UC, G, F</td>
<td>0.013</td>
<td>1.6, 2.0</td>
</tr>
<tr>
<td>400</td>
<td>68 x 13</td>
<td>H</td>
<td>CC, UC, G, F</td>
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<td></td>
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<td>68 x 13</td>
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<td>1.6 – 2.8</td>
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<td>SCC, G</td>
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<td>600</td>
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<td>H</td>
<td>CC, UC, G, F</td>
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<td>SCC, G</td>
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<tr>
<td>700</td>
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<td>CC, UC, G, F</td>
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<tr>
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<tr>
<td>800</td>
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<td>H</td>
<td>CC, UC, G, F</td>
<td>0.017</td>
<td>1.6 – 2.8</td>
</tr>
<tr>
<td></td>
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<td>SCC, G</td>
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<tr>
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<td>SCC, G</td>
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<tr>
<td>900</td>
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<td>CC, UC, G, F</td>
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<td>SCC, G</td>
<td>0.012</td>
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</tr>
<tr>
<td>1000</td>
<td>68 x 13</td>
<td>H</td>
<td>CC, UC, G, F</td>
<td>0.019</td>
<td>1.6 – 3.5</td>
</tr>
<tr>
<td></td>
<td>19 x 19 x 190</td>
<td>SR</td>
<td>SCC, G</td>
<td>0.012</td>
<td>1.6 – 2.8</td>
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<tr>
<td>1050</td>
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<td>SR</td>
<td>SCC, G</td>
<td>0.012</td>
<td>1.6 – 2.8</td>
</tr>
<tr>
<td>1200</td>
<td>68 x 13</td>
<td>H</td>
<td>CC, UC, G, F</td>
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<td>2.0 – 3.5</td>
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<tr>
<td></td>
<td>125 x 25</td>
<td>H</td>
<td>CC, UC, G, F</td>
<td>0.021</td>
<td>2.0 – 3.5</td>
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<tr>
<td></td>
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<td>2.0, 2.8</td>
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<tr>
<td>1350</td>
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<tr>
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<td>68 x 13</td>
<td>H</td>
<td>CC, UC, G, F</td>
<td>0.021</td>
<td>2.8 – 3.5</td>
</tr>
<tr>
<td></td>
<td>125 x 25</td>
<td>H</td>
<td>CC, UC, G, F</td>
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<td>2.0 – 3.5</td>
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<tr>
<td></td>
<td>19 x 19 x 190</td>
<td>SR</td>
<td>SCC, G</td>
<td>0.012</td>
<td>2.0, 2.8</td>
</tr>
<tr>
<td>1500</td>
<td>125 x 25</td>
<td>H</td>
<td>CC, UC, G, F</td>
<td>0.022</td>
<td>2.0 – 3.5</td>
</tr>
<tr>
<td></td>
<td>19 x 19 x 190</td>
<td>SR</td>
<td>SCC, G</td>
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<td>2.0, 2.8</td>
</tr>
<tr>
<td>1600</td>
<td>68 x 13</td>
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<td>CC, UC, G, F</td>
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<tr>
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<td>H</td>
<td>CC, UC, G, F</td>
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<tr>
<td></td>
<td>19 x 19 x 190</td>
<td>SR</td>
<td>SCC, G</td>
<td>0.012</td>
<td>2.0, 2.8</td>
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</table>
### Table C2.2
Polymer Laminated Steel Pipe Material Availability List

<table>
<thead>
<tr>
<th>Nominal &amp; Actual Inside Diameter (^{2})(Avg.) (mm)</th>
<th>Corrugation (PitchxDepth)/Profile</th>
<th>Manufacture Type (^{4})</th>
<th>Joint Type Available (^{5})</th>
<th>Manning ‘n’ Value</th>
<th>Available Thickness (^{1,3}) (mm)</th>
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<td>1800</td>
<td>125 x 25 H</td>
<td>CC,UC,G,F</td>
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<td>2.0 – 3.5</td>
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</tr>
<tr>
<td>19 x 19 x 190 SR</td>
<td>SCC,G</td>
<td>0.012</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>125 x 25 H</td>
<td>CC,UC,G,F</td>
<td>0.025</td>
<td>2.0 – 3.5</td>
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</tr>
<tr>
<td>19 x 19 x 190 SR</td>
<td>SCC,G</td>
<td>0.012</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2200</td>
<td>125 x 25 H</td>
<td>CC,G,F</td>
<td>0.025</td>
<td>2.0 – 3.5</td>
<td></td>
</tr>
<tr>
<td>19 x 19 x 190 SR</td>
<td>SCC,G</td>
<td>0.012</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2400</td>
<td>125 x 25 H</td>
<td>CC,G,F</td>
<td>0.025</td>
<td>2.0 – 3.5</td>
<td></td>
</tr>
<tr>
<td>19 x 19 x 190 SR</td>
<td>SCC,G</td>
<td>0.012</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2600</td>
<td>19 x 19 x 190 SR</td>
<td>SCC,G</td>
<td>0.012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2700</td>
<td>125 x 25 H</td>
<td>CC,G,F</td>
<td>0.025</td>
<td>2.0 – 3.5</td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td>125 x 25 H</td>
<td>CC,G,F</td>
<td>0.025</td>
<td>2.8 – 3.5</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**

1. Outside Diameter Calculated to be Inside Diameter + Wall thickness + Corrugation Depth Wall Thickness
2. Custom diameters are available for relining of existing pipes.
3. Wall thickness Specified as 1.3, 1.6, 2.0, 2.8, 3.5 and 4.2 mm for CSP. For actual dimensions, wall thickness should be taken as 1.12, 1.40, 1.82, 2.64, 3.35, and 4.08 mm, respectively for CSP (CSPI, 2003). For SPP, wall thickness’ for dimensioning should be taken to be 3, 4, 5, 6, and 7 mm.
4. Corrugation Profile Types: H = Helical, SR=Spiral Rib, SPP = Structural Plate Pipe
5. Joint Types (CSA G401-01): CC = Corrugated Coupler; UC = Universal Coupler, SCC = Semi Corrugated Coupler, BS = Bolted Seam, G = Gaskets, F = Filter Cloth. Special Couplers available for severe or unusual site conditions and relining.
6. Annular (Riveted) manufacture type may be supplied providing higher Manning ‘n’ value of 0.0024.
7. Materials and sizes listed in the table above were available at the time this manual was produced (April 2005). Designers should verify that the information and standards referenced in the table are still applicable, and the pipe types still available.

Reference: Corrugated Steel Pipe Institute, 2005 and CSA G401-01
# Table C3.0

High Density Polyethylene (HDPE – corrugated inside and outside wall) Pipe Availability List

<table>
<thead>
<tr>
<th>Nominal Diameter (mm)</th>
<th>Class 210</th>
<th>Class 320</th>
<th>Joint type Available (ISC, ESC, ESOC)</th>
<th>Manning ‘n’ Value</th>
<th>Outside Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>✓</td>
<td>✓</td>
<td>ISC, ESOC</td>
<td>0.016</td>
<td>120</td>
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<tr>
<td>150</td>
<td>✓</td>
<td>✓</td>
<td>ISC, ESOC</td>
<td>0.017</td>
<td>180</td>
</tr>
<tr>
<td>200</td>
<td>✓</td>
<td>✓</td>
<td>ISC, ESOC</td>
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</tr>
<tr>
<td>250</td>
<td>✓</td>
<td>✓</td>
<td>ESC, ESOC</td>
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</tr>
<tr>
<td>300</td>
<td>✓</td>
<td>✓</td>
<td>ESC, ESOC</td>
<td>0.020</td>
<td>375</td>
</tr>
<tr>
<td>400</td>
<td>✓</td>
<td>✓</td>
<td>ESC</td>
<td>0.021</td>
<td>470</td>
</tr>
<tr>
<td>450</td>
<td>✓</td>
<td>✓</td>
<td>ESC</td>
<td>0.021</td>
<td>530</td>
</tr>
<tr>
<td>500</td>
<td>✓</td>
<td>✓</td>
<td>ESC</td>
<td>0.021</td>
<td>580</td>
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<tr>
<td>600</td>
<td>✓</td>
<td>✓</td>
<td>ESC</td>
<td>0.021</td>
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<tr>
<td>750</td>
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<td>✓</td>
<td>ESC</td>
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<td>✓</td>
<td>✓</td>
<td>ESC</td>
<td>0.022</td>
<td>1087</td>
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</table>

**Notes:**

1. Need to update OPSD 806.02 to include class 320 and separate corrugated and smooth interior pipe sizes.
2. Applicable Standards: OPSS 1840, OPSS421, OPSD 806.02
3. No third party certification for corrugated interior & exterior HDPE pipe.
4. Joint types: ISC = Snap Coupler (no gasket), ESC – External Split Coupler (no gasket), ESOC: External screw-on Coupler (no gasket)
5. Materials and sizes listed in the table above were available at the time this manual was produced (April 2005). Designers should verify that the information and standards referenced in the table are still applicable, and the pipe types still available

Reference: Armtec Limited, 2005
Table C3.1
High Density Polyethylene Pipe
(Open Profile Wall – smooth inside and corrugated outside)
Availability List

<table>
<thead>
<tr>
<th>Nominal/Inside Diameter (Avg.)</th>
<th>Class 210²</th>
<th>Class 320²³</th>
<th>Joint Type Available¹</th>
<th>Manning ‘n’ Value</th>
<th>Outside Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>(mm) (inch)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(mm) (inches)</td>
</tr>
<tr>
<td>100 4</td>
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<td>✓</td>
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<td>120 4.7</td>
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<tr>
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<td>POS²,³, EDBSC²</td>
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<td>✓</td>
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<td>✓</td>
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<td>✓</td>
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<td>✓</td>
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<td>✓</td>
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<td>✓</td>
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<td>✓</td>
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<tr>
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<td>✓</td>
<td>✓</td>
<td>POS²,³, ESC²</td>
<td>&quot;</td>
<td>1087 42.8</td>
</tr>
</tbody>
</table>

Notes:
1 Joint Types Available: POS = “positive” gasketed joints, EDBSC = External double bell snap coupler (no gasket), ESC = External split coupler (no gasket).
² Certified by CSA B182.8-02
³ Certified by CSA B182.6-02
⁴ Materials and sizes listed in the table above were available at the time this manual was produced (April 2005).
Designers should verify that the information and standards referenced in the table are still applicable, and the pipe types still available.

### Table C3.2

**High Density Polyethylene Pipe (Closed Profile Wall – smooth inside and outside)**

**Availability List**

<table>
<thead>
<tr>
<th>Nominal/Inside Diameter (Avg.)</th>
<th>Ring Stiffness Constant (RSC)$^{1,4}$</th>
<th>Joint Type Available$^{2}$</th>
<th>Manning ‘n’ Value</th>
<th>Outside Diameter</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>40 63 100 160 250 400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(mm) (inch)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>840 33</td>
<td>X X</td>
<td>Wld, Thd</td>
<td>0.012</td>
<td>960 960</td>
</tr>
<tr>
<td>910 36</td>
<td>X X X</td>
<td>Wld, Thd</td>
<td>&quot;</td>
<td>1010 1030 1030</td>
</tr>
<tr>
<td>1020 40</td>
<td>X X X</td>
<td>Wld, Thd</td>
<td>&quot;</td>
<td>1150 1180 1200 1210</td>
</tr>
<tr>
<td>1070 42</td>
<td>X X X X</td>
<td>Wld, Thd</td>
<td>&quot;</td>
<td>1310 1340 1500 1530</td>
</tr>
<tr>
<td>1220 48</td>
<td>X X X X</td>
<td>Wld, Thd</td>
<td>&quot;</td>
<td>1460 1490 1500 1520 1530</td>
</tr>
<tr>
<td>1370 54</td>
<td>X X X X X</td>
<td>Wld, Thd</td>
<td>&quot;</td>
<td>1620 1640 1650 1690 1700</td>
</tr>
<tr>
<td>1520 60</td>
<td>X X X X X</td>
<td>Wld, Thd</td>
<td>&quot;</td>
<td>1790 1820 1840 1870</td>
</tr>
<tr>
<td>1680 66</td>
<td>X X X X</td>
<td>Wld, Thd</td>
<td>&quot;</td>
<td>1960 1990 2010 2040</td>
</tr>
<tr>
<td>1830 72</td>
<td>X X X X</td>
<td>Wld, Thd</td>
<td>&quot;</td>
<td>2120 2140 2180 2200</td>
</tr>
<tr>
<td>1980 78</td>
<td>X X X X</td>
<td>Wld, Thd</td>
<td>&quot;</td>
<td>2280 2290 2330 2370</td>
</tr>
<tr>
<td>2130 84</td>
<td>X X X X</td>
<td>Wld, Thd</td>
<td>&quot;</td>
<td>2450 2470 2480 2520 2560</td>
</tr>
<tr>
<td>2290 90</td>
<td>X X X X X X</td>
<td>Wld, Thd</td>
<td>&quot;</td>
<td>2450 2470 2480 2520 2560</td>
</tr>
<tr>
<td>2440 96</td>
<td>X X X X</td>
<td>Wld, Thd</td>
<td>&quot;</td>
<td>2620 2650 2690 2730</td>
</tr>
<tr>
<td>2740 108</td>
<td>X X X X</td>
<td>Wld, Thd</td>
<td>&quot;</td>
<td>2940 2980 3010 3070</td>
</tr>
<tr>
<td>3050 120</td>
<td>X X X X</td>
<td>Wld, Thd</td>
<td>&quot;</td>
<td>3260 3300 2240 3410</td>
</tr>
</tbody>
</table>

**Notes:**

1. Pipe is manufactured to ASTM F894 and is available in 2 stiffness classes higher than included in Standard.
3. Materials and sizes listed in the table above were available at the time this manual was produced (April 2005). Designers should verify that the information and standards referenced in the table are still applicable, and the pipe types still available.
4. Refer to Appendix X1 in ASTM F894 for minimum equivalent pipe stiffness (i.e. Class) for specified RSC’s.

Reference: KWH Pipe Canada, 2005
### Table C4.0

Polyvinyl Chloride (PVC) Pipe  
(Profile Wall - smooth inside and ribbed outside)  
**Availability List**

<table>
<thead>
<tr>
<th>Nominal Diameter</th>
<th>Inside Diameter (Avg.)</th>
<th>Class 320&lt;sup&gt;Note 1&lt;/sup&gt;</th>
<th>Manning ‘n’ Value</th>
<th>Avg. Outside Diameter Over Ribs</th>
<th>Joint Type&lt;sup&gt;Note 2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>(mm)</td>
<td>(inches)</td>
<td>(m)</td>
<td>(inches)</td>
<td>(m)</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>8</td>
<td>200</td>
<td>7.89</td>
<td>✓</td>
<td>0.012</td>
</tr>
<tr>
<td>250</td>
<td>10</td>
<td>251</td>
<td>9.86</td>
<td>✓</td>
<td>0.012</td>
</tr>
<tr>
<td>300</td>
<td>12</td>
<td>298</td>
<td>11.74</td>
<td>✓</td>
<td>0.012</td>
</tr>
<tr>
<td>375</td>
<td>15</td>
<td>365</td>
<td>14.37</td>
<td>✓</td>
<td>0.012</td>
</tr>
<tr>
<td>450</td>
<td>18</td>
<td>448</td>
<td>17.65</td>
<td>✓</td>
<td>0.012</td>
</tr>
<tr>
<td>525</td>
<td>21</td>
<td>527</td>
<td>20.75</td>
<td>✓</td>
<td>0.012</td>
</tr>
<tr>
<td>600</td>
<td>24</td>
<td>597</td>
<td>23.50</td>
<td>✓</td>
<td>0.012</td>
</tr>
</tbody>
</table>

**Notes:**
1. Meets CSA B182.4.
2. Joint Types: POS = “Positive” (gasketed) joints available.
3. Applicable Standards OPSS 421, OPSS1841, OPSD 806.040.
4. Materials and sizes listed in the table above were available at the time this manual was produced (April 2005). Designers should verify that the information and standards referenced in the table are still applicable, and the pipe types still available.

Reference: IPEX Inc., 2005
Table C4.1
Polyvinyl Chloride (PVC) Pipe
(Solid Wall - DR smooth inside)
Availability List

<table>
<thead>
<tr>
<th>Nominal Diameter</th>
<th>SDR</th>
<th>Actual Inside Diameter (Avg)</th>
<th>Availability</th>
<th>Joint Type Available&lt;sup&gt;Note 1&lt;/sup&gt;</th>
<th>Manning 'n' Value</th>
<th>Avg. Outside Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>(mm)</td>
<td>(inch)</td>
<td>(mm) (inch)</td>
<td>CSA-B182.2</td>
<td></td>
<td></td>
<td>(mm) (inch)</td>
</tr>
<tr>
<td>100</td>
<td>4</td>
<td>35</td>
<td>100.94</td>
<td>3.97</td>
<td>✓ POS</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>99.42</td>
<td></td>
<td></td>
<td>✓ POS</td>
<td></td>
</tr>
<tr>
<td>135</td>
<td>5</td>
<td>35</td>
<td>135.08</td>
<td>5.32</td>
<td>✓ POS</td>
<td>&quot;</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>133.02</td>
<td></td>
<td></td>
<td>✓ POS</td>
<td>&quot;</td>
</tr>
<tr>
<td>150</td>
<td>6</td>
<td>35</td>
<td>150.29</td>
<td>5.92</td>
<td>✓ POS</td>
<td>&quot;</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>148.01</td>
<td></td>
<td></td>
<td>✓ POS</td>
<td>&quot;</td>
</tr>
<tr>
<td>200</td>
<td>8</td>
<td>35</td>
<td>201.16</td>
<td>7.92</td>
<td>✓ POS</td>
<td>&quot;</td>
</tr>
<tr>
<td>250</td>
<td>10</td>
<td>35</td>
<td>251.46</td>
<td>9.90</td>
<td>✓ POS</td>
<td>&quot;</td>
</tr>
<tr>
<td>300</td>
<td>12</td>
<td>35</td>
<td>299.36</td>
<td>11.79</td>
<td>✓ POS</td>
<td>&quot;</td>
</tr>
<tr>
<td>375</td>
<td>15</td>
<td>35</td>
<td>366.42</td>
<td>14.43</td>
<td>✓ POS</td>
<td>&quot;</td>
</tr>
<tr>
<td>450</td>
<td>18</td>
<td>35</td>
<td>447.87</td>
<td>17.63</td>
<td>✓ POS</td>
<td>&quot;</td>
</tr>
<tr>
<td>525</td>
<td>21</td>
<td>35</td>
<td>527.99</td>
<td>20.79</td>
<td>✓ POS</td>
<td>&quot;</td>
</tr>
<tr>
<td>600</td>
<td>24</td>
<td>35</td>
<td>594.00</td>
<td>23.39</td>
<td>✓ POS</td>
<td>&quot;</td>
</tr>
<tr>
<td>675</td>
<td>27</td>
<td>35</td>
<td>669.42</td>
<td>26.36</td>
<td>✓ POS</td>
<td>&quot;</td>
</tr>
<tr>
<td>750</td>
<td>30</td>
<td>35</td>
<td>766.36</td>
<td>30.17</td>
<td>✓ POS</td>
<td>&quot;</td>
</tr>
<tr>
<td>900</td>
<td>36</td>
<td>35</td>
<td>917.22</td>
<td>36.11</td>
<td>✓ POS</td>
<td>&quot;</td>
</tr>
<tr>
<td>1050</td>
<td>42</td>
<td>35</td>
<td>1065.72</td>
<td>41.95</td>
<td>✓ POS</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

Notes:
1. Joint Types: POS = “positive” (gasketed).
2. Materials and sizes listed in the table above were available at the time this manual was produced (April 2005). Designers should verify that the information and standards referenced in the table are still applicable, and the pipe types still available.

Reference: IPEX Inc., 2005
## Table C5
Determining Design Service Life (DSL)
(i.e. Minimum Design Material Service Life)

<table>
<thead>
<tr>
<th>Highway Facility</th>
<th>Median Storm Sewer</th>
<th>Side Storm Sewer</th>
<th>Cross Culvert</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Service Life (DSL), years</td>
<td>Freeway or Arterial</td>
<td>Freeway or Arterial</td>
<td>Collector</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>75</td>
<td>50</td>
</tr>
</tbody>
</table>

### Notes:

1. For cross culverts beneath greater than 4 m of fill and where road is vital link with no practical detour routes, minimum design lives may be increased at discretion of design engineer. This may be appropriate for Northwestern and Northeastern Regions.
2. For sites where culvert access is difficult and/or traffic disruption is a concern for future rehabilitation/replacement, consideration should be given to using a longer design service life.
3. Although culverts under intersecting roads function as sidedrains for the project under consideration, these culverts are cross culvert drains and should be designed using appropriate cross culvert criteria.
4. The Design Service Lives given above are directly related to the ability of the pipe joints to perform satisfactory depending on the specific site conditions. Refer to Chapters 2 and 4 for more details on pipe joints.
5. In the rare event in which the Estimated Material Service Life of all pipe material types under consideration does not meet the Design Service Life, the Design Service Life will be reduced accordingly from either 75 years to 50 years or from 50 years to 25 years.
### Table C6

**Manning Roughness Coefficients (‘n’) for Circular Pipe**

<table>
<thead>
<tr>
<th>Pipe Material Type</th>
<th>Manning Roughness Coefficients (Range)</th>
<th>Manning Roughness Coefficients (Default)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precast pipe</td>
<td>0.011–0.013</td>
<td>0.012</td>
</tr>
<tr>
<td>Wood forms, rough</td>
<td>0.015 – 0.017</td>
<td>0.016</td>
</tr>
<tr>
<td>Wood forms, smooth</td>
<td>0.012 – 0.014</td>
<td>0.013</td>
</tr>
<tr>
<td>Steel forms</td>
<td>0.012 – 0.013</td>
<td>0.012</td>
</tr>
<tr>
<td><strong>Steel Pipe</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Corrugated Steel Pipe</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>68x13 mm helical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unpaved: 600 to 2000 mm diameter</td>
<td>0.016 – 0.021</td>
<td>Refer to Table C2</td>
</tr>
<tr>
<td>125x25 mm helical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unpaved: 1200 to 3000 mm diameter</td>
<td>0.021 – 0.025</td>
<td>Refer to Table C2</td>
</tr>
<tr>
<td><strong>Structural Steel Plate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>152x51 mm corrugation (annular)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unpaved: 1500 - 3000 mm diameter</td>
<td>0.032 – 0.033</td>
<td>Refer to Table C2</td>
</tr>
<tr>
<td><strong>Spiral Rib Steel Pipe</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19x19x190 mm spiral rib</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unpaved</td>
<td>0.012</td>
<td>0.012</td>
</tr>
<tr>
<td><strong>High Density Polyethylene Pipe</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smooth Inside Wall</td>
<td>0.011 – 0.013</td>
<td>0.012</td>
</tr>
<tr>
<td>Corrugated Inside Wall</td>
<td>0.017 – 0.024</td>
<td>Refer to Table C3</td>
</tr>
<tr>
<td><strong>Polyvinyl Chloride – Smooth Inside Wall</strong></td>
<td>0.011 – 0.013</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Table C7
Minimum Culvert Serviceability Design Diameters

<table>
<thead>
<tr>
<th>Application</th>
<th>Culvert Minimum Inside Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highway</td>
<td>800 mm</td>
</tr>
<tr>
<td>Sideroad</td>
<td>600 mm</td>
</tr>
<tr>
<td>Private Entrances</td>
<td>500 mm (if more than 10 m length)</td>
</tr>
<tr>
<td>Private Entrances</td>
<td>400 mm (if length 10 m or less)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Abrasion Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Non-abrasive – No bedload</td>
</tr>
<tr>
<td>2</td>
<td>Low abrasion – Minor bedloads of sand &amp; gravel and velocities of 1.5 m/s or less or storm sewer applications</td>
</tr>
<tr>
<td>3</td>
<td>Moderate abrasion – bedloads of sand and gravel with velocities between 1.5 and 4.5 m/s.</td>
</tr>
<tr>
<td>4</td>
<td>Severe abrasion – Heavy bedloads of gravel and rock with velocities exceeding 4.5 m/s.</td>
</tr>
</tbody>
</table>

### Table C9
**EMSL for Steel Pipe Coatings / Laminations**

<table>
<thead>
<tr>
<th>Coating(^\text{Note 3})</th>
<th>Water Side</th>
<th>Max. Abrasion Level(^\text{Note 2}) (See Table C8)</th>
<th>Soil Side Add-On Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminized Type 2 (Sizes 1.3 to 3.5 mm)</td>
<td>EMSL</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Lamination(^\text{Note 3})</td>
<td>Add-On Years to Plain Galvanized EMSL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polymer Coated(^\text{Note 1}) (sizes 1.3 to 3.5 mm)</td>
<td>10 – 40 (Reference 1)</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>20 – 70 (Reference 2)</td>
<td>3</td>
<td>50 -75</td>
</tr>
<tr>
<td></td>
<td>50 (Reference 3)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>30 (Reference 4)</td>
<td>3</td>
<td>-</td>
</tr>
</tbody>
</table>

**Notes:**
1. Polymeric sheet coating provides adequate abrasion resistance to meet or exceed 50 year design service life for Abrasion Level 2 or below (see Reference 1)
2. No abrasive resistant protective coatings are recommended above Abrasion Level 3 (see Reference 1.)
3. Specific add-on values should be selected based on environmental conditions (abrasion, pH, resistivity, and low soil moisture content) and experience in comparable environments. Upper limits should be considered for the most favourable environmental conditions, (non-abrasive, high pH and resistivity) while low limits should be considered for the maximum abrasion level and most corrosive environments. (See reference 2).

**References:**
2. CSPI, 2002, pg 353
3. Ohio DOT
4. FHWA, 2000
# Table C10

**Concrete EMSL Requirements**  
**Step-by-Step Design Procedure**

<table>
<thead>
<tr>
<th>Pipe Slope (%)</th>
<th>Pipe Rise (mm)</th>
<th>Minimum pH to attain EMSL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>25 Year EMSL</td>
</tr>
<tr>
<td>&lt; 1 %</td>
<td>&lt; 1050</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>1050 – 1800</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>&gt; 1800</td>
<td>3.7</td>
</tr>
<tr>
<td>1 % to 3 %</td>
<td>&lt; 1050</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>1050 – 1800</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>&gt; 1800</td>
<td>4.0</td>
</tr>
<tr>
<td>3 % to 10 %</td>
<td>&lt; 1050</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>1050 – 1800</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>&gt; 1800</td>
<td>4.4</td>
</tr>
<tr>
<td>&gt; 10 %</td>
<td>&lt; 1050</td>
<td>Note 1</td>
</tr>
<tr>
<td></td>
<td>1050 – 1800</td>
<td>Note 1</td>
</tr>
<tr>
<td></td>
<td>&gt; 1800</td>
<td>Note 1</td>
</tr>
</tbody>
</table>

Notes:
1. If slope is greater than 10%, a more detailed analysis is required.

Reference: Table based on Figure B3, b. Hurd’s Model
FIGURE D1 – Water (Rainfall) pH Levels Based on Average pH for Regions in Ontario (1998)

Abbreviations and Definitions

ABBREVIATIONS

AASHTO – American Association of State Highway and Transportation Officials

ACPA – American Concrete Pipe Association

ADTE – Average Daily Traffic Equivalent

ALT2 – Aluminized Type 2 coated steel pipe

ASCE – American Society of Civil Engineers

ASTM – American Society of Testing and Materials

CCTV – Closed-circuit television

CDED – MTO Contract Design Estimating and Documentation manual

CHBDC – Canadian Highway Bridge Design Code

CIO – Corrugated Inside and Outside HDPE pipe

CIPP – Cured-In-Place Pipe

CLSM – Controlled Low-Strength Material (i.e. Unshrinkable Fill)

CPPA – Corrugated Polyethylene Pipe Association

CPSIO – Closed Profile Smooth Inside and Outside HDPE pipe

CSA – Canadian Standards Association

CSP – Corrugated Steel Pipe

CSPI – Corrugated Steel Pipe Institute

DOT – Department of Transportation

DSL – Design Service Life

EMSL – Estimated Material Service Life

FCM – Federation of Canadian Municipalities
F DOT – Florida Department of Transportation
GPS – Global Positioning System
HDPE – High Density Polyethylene
LCC – Life Cycle Costing
LCCA – Life Cycle Costing Analysis
LHRS – Linear Highway Reference System
MEA – Municipal Engineers Association
MIC – Microbially Induced Corrosion
MTO – Ministry of Transportation Ontario
NRCC – National Research Council Canada
OCPA – Ontario Concrete Pipe Association
OHSA – Occupational Health and Safety Act
OPS – Ontario Provincial Standards
OPSD – Ontario Provincial Standard Drawings
OPSS – Ontario Provincial Standard Specifications
P – Polymer laminated steel pipe
PG – Plain Galvanized coated steel pipe
PPI – Plastic Pipe Institute
PVC – Polyvinyl Chloride
PVIC – Present Value Initial Cost
PVLCC – Present Value Life Cycle Cost
PVM – Present Value Operating and Maintenance Cost
PVN – Present Value Rehabilitation Cost

PVR – Present Value Replacement Cost

PVT – Present Value Terminal Value

R – Electrical Resistivity

RSC – Ring Stiffness Constant

SDR – Standard Dimension Ratio

SICO – Smooth Inside and Corrugated Outside pipe

SIDD – Standard Installation Direct Design

SIRO – Smooth Inside and Ribbed Outside pipe

SPCSP – Structural Plate Corrugated Steel Pipe

SR – Spiral Rib steel pipe

SSM – Select Subgrade Material

SWSI – Solid Wall Smooth Inside pipe

TDS – Total Dissolved Solids

USACE – United States Army Corps of Engineers
DEFINITIONS

**Arching** – the transfer of pressure or load between the soil masses adjacent to and above the conduit that move relative to one another. Positive arching is that which results in the transfer of load away from the conduit; negative arching produces the opposite effect (CSA 2000).

**Common Costs** – costs that are common to all alternatives in nature and amount, such as initial planning fees or future annual inspection costs (ASTM 1996).

**Discount Rate** – the investor’s time value of money, expressed as a percent, used to convert costs occurring at different times, to equivalent costs at a common point in time (ASTM 1996).

**Drainage Project** – a project having a definable, functional drainage requirement that can be satisfied by two or more design or construction alternatives, or both (ASTM 1996).

**Fold and form sliplining** – method of pipeline rehabilitation in which a liner is folded to reduce its size before insertion and reversion to its original shape by the application of pressure and/or heat.

**Future Costs** – costs required to keep the system operating that are incurred after the project is placed in service, such as operation, maintenance, rehabilitation, or replacement costs (ASTM 1996).

**Gravity Flow** – refers to piping systems limited to applications where internal hydrostatic heads will not exceed 7.6 m (25 feet) of water (USACE 1998).

**Inflation** – the general trend or rising prices that, over time, result in the reduction of the purchasing power of the dollar from year to year (ASTM 1996).

**Initial Cost** – the total of all costs such as design costs, material purchase costs, and construction/installation costs, that are specific to each alternative and are incurred to bring each alternative to a point of functional readiness (ASTM 1996).

**Maintenance Cost** – the annual or periodic costs, such as inspection and cleaning to keep a drainage structure functioning for the project design life, but do not extend the material service life (ASTM 1996).

**Material Service Life (Estimated Material Service Life)** – the number of years of service a particular material, system, or structure will provide before rehabilitation or replacement is necessary (ASTM, 1996). This parameter can be estimated using calculations/empirical correlations (Estimated Material Service Life).
Design Service Life (Minimum Design Material Service Life) – The minimum number of years of relatively maintenance-free performance that a material has to meet or exceed for a particular storm sewer / culvert application and corresponding roadway type to be included in the design of a project. According to this definition, design service life does not necessarily equal the number of years to failure (NRCC 1998b), which may occur many more years after the design service life is reached.

Maintenance Free Service Life: (from NRCC, 1998b and CALTRANS, 2001)

Steel Pipe - maintenance free service life, with respect to corrosion, abrasion, and/or durability, is the number of years from installation until the deterioration reaches the point of perforation at any location on the pipe.

Reinforced Concrete Pipe – is the number of years from installation until the deterioration reaches the point of exposed reinforcement at any point on the culvert or development of cracks with soil loss at any point on the pipe.

Non-reinforced Concrete Pipe – is the number of years from installation until the deterioration reaches the point of perforation or major cracking with soil loss at any point on the pipe.

HDPE Pipe – with respect to corrosion, abrasion, and long term structural performance, is the number of years from installation until the deterioration reaches the point of perforation at any location on the pipe or until the pipe material has lost structural load carrying capacity.

PVC Pipe - with respect to abrasion, degradation and long term structural performance, is the number of years from installation until the deterioration reaches the point of perforation at any location on the pipe or until the pipe material has lost structural load carrying capacity.

Pipe Bursting – is a trenchless technology that replaces a sewer by breaking and displacing the existing pipe and installing a replacement pipe in the void created.

Projecting Embankment – Positive projecting embankment is an embankment where the top of the pipe is located above the top of the in-situ (natural) ground level; Zero Projecting Embankment is an embankment where the top of the pipe is located at the in-situ (natural) ground level (ACPA 1993).

Project Design Life (Analysis Period) – the planning horizon for the project, expressed as the number of years of useful life required of the drainage structure (ASTM 1996). This value will be determined by the MTO (i.e. the user).

Rehabilitation Cost – the total of all costs incurred to extend the material service life of a specific alternative (ASTM 1996).
**Replacement Cost** – the total of all costs incurred to replace a material before the end of the project design life (ASTM 1996).

**Terminal Value** – the remaining value of the drainage structure in place at the end of the project design life (ASTM 1996).