Reinforced Concrete Pipe

How to Assess the Transition from Indirect to Direct Design Methods in Deep Cover Installations

Adam Braun, P.Eng.
Winnipeg, Manitoba
Canada
• Introduction, Background, and History
• Indirect Design
• SIDD Installations and Direct Design
• Transition from Indirect to Direct Design
• Conclusion
Introduction, Background & History
Introduction

• Reinforced Concrete Pipe (RCP)
• First produced in 1896 in France
• Brought to North America in 1905
Introduction

- **Indirect Design (Marston/Spangler Analysis)**
  - Developed in the 1920’s and 30’s
  - Empirically derived
  - Excellent performance record in low to moderate soil covers

- **Direct Design (Heger/Selig)**
  - Developed in the 1970’s and 80’s
  - Reinforced concrete design theory
  - Limit states design principals
  - Applicable for large diameter and high external load conditions

While direct design has been formally adopted by industry it does not see widespread use.
Iowa Experiment Station

- Anson Marston began research into the behavior of buried rigid pipe in 1910
- Born out of the increased use of clay and non-reinforced concrete pipe in sizes up to 36” as both drain tile and sewer pipe
- The “large diameter” pipe was prone to failure shortly after installation
- Began with investigation into failures

At the time there was no quantifiable design method for buried pipe!
Original Soil Load and Pipe Strength Experiments

Evaluating Trench Loads

12" Pipe Test

36" Pipe Test
Original Soil Load and Pipe Strength Experiments

• Testing of pipe up to 42” diameter
• Homebuilt sand bedding testing machines
• Evaluation of test results to actual supporting strength for various installation types
Evaluation of Testing Methods

Fig. 16. "Sand" bearings

Bearings recommended for use in tests of the "ordinary supporting strength" of sewer pipe

Fig. 17. "Two-point" bearings

Fig. 18. "Three-point" bearings
The Theory of Loads on Pipes in Ditches and Tests of Cement and Clay Drain Tile and Sewer Pipe

- Published in 1913 by the Iowa State College of Agriculture and Mechanical Arts
- Authors:
  - Anson Marston
  - A. O. Anderson
- New theories for calculating soil loads on buried pipes in narrow trenches
The Supportive Strength of Sewer Pipe in Ditches and Methods of Testing Sewer Pipe in Laboratories to Determine Their Ordinary Supportive Strength

- Published in 1917 by the Iowa State College of Agriculture and Mechanical Arts
- New theories for quantifying the external load capacity of buried rigid pipe
- Authors:
  - Anson Marston
  - W. J. Schillick
  - H. F. Clemmer
Continued Research...

- Further development was undertaken in the 1920’s and 30’s by:
  - W. J. Schillick
  - M. G. Spangler
- Resulted in numerous papers on an ever expanding knowledge of soil loads and pipe strengths
- Developed calculations for determining earth loads from embankment (projection) and tunnel installations
- Load calculations were all empirically derived from experiments undertaken at the Iowa Experiment Station
Indirect Design

AND PLAIN END PIPE

- Upper Bearing Wood Block
- Rigid Steel Member
- Lower Bearing Strips
- Rigid Base

(See Fig. 5)
Indirect Design

- Matches estimated trench loads to the estimated supporting strength of the installed pipe
- Installed pipe strengths estimated through the use of empirically derived factors
- Pipe strengths assessed using three edge bearing (3EB) tests
Three Edge Bearing Tests

- **Standards:**
  - ASTM C497 - Standard Test Methods for Concrete Pipe, Manhole Sections, or Tile
  - CSA A257
- Quantifiable means of determining a pipe ability to support externally applied loads
Three Edge Bearing Tests

- RCP is typically tested with the intent of determining the following loads:
  - Hairline Crack
  - Service Cracking (0.01” or 0.3 mm)
  - Ultimate Failure

- Typical QA/QC procedures only require testing up to servicing cracking limit with the rare test taken to ultimate failure

- It should be noted that standard three edge bearing tests do not check for diagonal tension (shear) or radial tension failure modes.

- Both are governing failure modes in high soil cover conditions.
Traditional Installation Types and Bedding Factors

- Bedding types developed to reflect pipe installation methods at the beginning of the 1900’s
- Reflect installation efforts involving hand vs. machine excavation
- Bedding factors were developed for each installation type reflect the increase in load a pipe can support when installed vs. in the three edge bearing test
- The bedding factor each installation type reflects the level of load distribution provided
- Better soil support equals a higher bedding factor!
Traditional Installation Types and Bedding Factors
Indirect Design Method

- Calculate live and dead loads
- Determine a bedding factor
- Determine the equivalent three edge bearing load (divide the soil load by the bedding factor)
- Convert to equivalent D-Load (Divide by the diameter of the pipe)
- Select appropriate pipe from the ASTM or CSA specification or specify required load

<table>
<thead>
<tr>
<th>ASTM C76 Pipe Class</th>
<th>Service Cracking D-Load (N/m/mm)</th>
<th>Ultimate Failure D-Load (N/m/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Class II</td>
<td>50</td>
<td>75</td>
</tr>
<tr>
<td>Class III</td>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>Class IV</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Class V</td>
<td>140</td>
<td>175</td>
</tr>
</tbody>
</table>
Indirect Design Method

• Reinforcement requirements are stipulated in ASTM C76 or CSA A257
• Empirically derived in order to meet required D-Loads
• Single factor of safety applied against ultimate failure, ranging from 1.25 and 1.5
• No differentiation between live and dead loads and their respective levels of uncertainty
• Adequate for low to moderate soil covers consistent with those used to develop the empirical design method
SIDD Installations and Direct Design
New Design Approach

- American Concrete Pipe Association (ACPA) undertook a long term research project in the 1970’s and 80’s to develop a new design approach for reinforced concrete pipe
- Dr. Frank Heger was engaged to develop this new design method based on his knowledge of reinforced concrete design
- Continuation of Heger’s post graduate work at MIT
- Dr. Ernest Selig was engaged to provide geotechnical expertise in development of the pipe-soil interaction models
- Heger’s other work included...

Rigid Rugged Resilient
New Design Theory

• Heger’s 1962 PhD thesis “A Theory for the Structural Behavior of Reinforced Concrete Pipe” strove to develop a rational procedure for predicting the structural behavior of reinforced concrete pipe

• Adapted reinforced concrete beam theory to the circular pipe wall
New Design Theory

- Proposed design procedures considered the following:
  - Flexural strength
  - Diagonal tension (shear) capacity
  - Predicting and limiting in service crack widths
  - Use of stirrups in controlling diagonal tension
  - Combined internal and external loading conditions
- Assessed the development of internal wall forces under test (3EB) and in service conditions

(Heger 1962)
Imparted Wall Forces

- Max bending moments develop at:
  - Obvert
  - Invert
  - Springline
- Max wall thrust:
  - Springline
- Max diagonal tension:
  - $\approx 12^\circ$ to $13^\circ$ from invert

Flexure Design Locations:
1, 5 Maximum Positive Moment Locations at Invert and Crown.
3 Maximum Negative Moment Location Near Springline.

Shear Design Locations:
2, 4 Locations Near Invert and Crown Where $M_{nu}/(V_{ud}) = 3.0$
Bending Moments

Soil Load

Compression

Tension

Crown

Outer Cage

Inner Cage

C

T

M

N

90°

Spring Line

Tension

Compression

M

C_1

C_2

x

y
Development of Bending Moments during 3EB Test

(Heger 1962)
Diagonal and Radial Tension

Radial Tension Failure:
- Cause by tension forces within the radial reinforcement
- These tension forces act to straighten out curved steel, causing it to pull away from the pipe wall
Soil Pressures and Wall Forces

• The interaction between buried pipe, the embedment material, and native soils is complex and dependent on many factors.

• Heger and Selig developed the computerized finite element program SPIDA (Soil-Pipe Interaction Design and Analysis) to determine the distribution of soil pressures around the pipe and wall forces developed.

• This lead to the development of four new installation types to reflect modern pipe installation techniques...
Standard Installations Direct Design (SIDD)

Type 1 Installation

Quantitative vs. Qualitative Installation Procedure

Most Intensive Installation Requirements

Least Intensive Installation Requirements

<table>
<thead>
<tr>
<th>Installation Type</th>
<th>Bedding Thickness</th>
<th>Haunch and Outer Bedding</th>
<th>Lower Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>$D_{h}/24$ minimum, not less than 3 in. (75 mm). If rock foundation, use $D_{h}/12$ minimum, not less than 6 in. (150 mm).</td>
<td>95% SW</td>
<td>90% SW, 95% ML, or 100% CL</td>
</tr>
<tr>
<td>Type 2</td>
<td>$D_{h}/24$ minimum, not less than 3 in. (75 mm). If rock foundation, use $D_{h}/12$ minimum, not less than 6 in. (150 mm).</td>
<td>90% SW or 95% ML</td>
<td>85% SW, 90% ML, or 95% CL</td>
</tr>
<tr>
<td>Type 3</td>
<td>$D_{h}/24$ minimum, not less than 3 in. (75 mm). If rock foundation, use $D_{h}/12$ minimum, not less than 6 in. (150 mm).</td>
<td>85% SW, 90% ML, or 95% CL</td>
<td>85% SW, 90% ML, or 95% CL</td>
</tr>
<tr>
<td>Type 4</td>
<td>No bedding required, except if rock foundation, use $D_{h}/12$ minimum, not less than 6 in. (150 mm).</td>
<td>No compaction required, except if CL, use 85% CL</td>
<td>No compaction required, except if CL, use 85% CL</td>
</tr>
</tbody>
</table>
Standard Installations Direct Design (SIDD)

Visual Representation of Applied Soil Pressures
**Heger Positive Projection Load**

- Heger and Selig developed a simplified load calculation method based on the new SIDD installation types.
- Only positive projection conditions considered.
- Load coefficients developed with SPIDA.
- Applied load = Prism load x Vertical Arching Factor (VAF).

Trench Widths are Difficult to Control in the Field.
Estimating Wall Forces

- Heger and Selig utilized SPIDA to assess and develop load coefficients for the new SIDD installations types

```
<table>
<thead>
<tr>
<th>Location</th>
<th>Load Type</th>
<th>C_H</th>
<th>C_V</th>
<th>C_W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invert</td>
<td>W_x</td>
<td>.225</td>
<td>.077</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W_y</td>
<td>.091</td>
<td>.188</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W_z</td>
<td>.088</td>
<td>-.445</td>
<td>.250</td>
</tr>
<tr>
<td></td>
<td>W_d</td>
<td>.075</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>W_z2</td>
<td>.165</td>
<td>-.046</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W_x1</td>
<td>.079</td>
<td></td>
<td>.077</td>
</tr>
<tr>
<td></td>
<td>W_x2</td>
<td>.083</td>
<td>.157</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W_d1</td>
<td>.057</td>
<td></td>
<td>-.187</td>
</tr>
<tr>
<td></td>
<td>W_d2</td>
<td>.068</td>
<td>.200</td>
<td></td>
</tr>
<tr>
<td>Crown</td>
<td>W_x</td>
<td></td>
<td></td>
<td>.236</td>
</tr>
<tr>
<td></td>
<td>W_y</td>
<td>-.091</td>
<td>.249</td>
<td>.046</td>
</tr>
<tr>
<td></td>
<td>W_z</td>
<td>-.077</td>
<td>.500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W_z1</td>
<td>-.064</td>
<td>-.068</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W_z2</td>
<td>-.065</td>
<td>.500</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>W_d</td>
<td>-.154</td>
<td></td>
<td>.500</td>
</tr>
<tr>
<td>Springline 90°</td>
<td>W_x</td>
<td></td>
<td></td>
<td>.174</td>
</tr>
<tr>
<td></td>
<td>W_y</td>
<td>.219</td>
<td>.143</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W_d</td>
<td>-.408</td>
<td>.141</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W_d1</td>
<td>.270</td>
<td>.150</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W_d2</td>
<td>.055</td>
<td>.083</td>
<td>.205</td>
</tr>
<tr>
<td></td>
<td>W_d3</td>
<td>.167</td>
<td>.117</td>
<td>.062</td>
</tr>
<tr>
<td></td>
<td>W_d4</td>
<td>.250</td>
<td>.100</td>
<td></td>
</tr>
</tbody>
</table>

Critical Shear Invert θ_s = 12°

<table>
<thead>
<tr>
<th>Location</th>
<th>Load Type</th>
<th>C_H</th>
<th>C_V</th>
<th>C_W</th>
</tr>
</thead>
</table>
| Critical Shear Crown θ_s = 159°
```
Direct Design

• Proposed in Heger’s 1988 paper “New Installation Designs for Buried Concrete Pipe”
• Incorporates SIDD Installations and SPIDA developed load coefficients
• Incorporates limit states design methodology
• Proposed steel reinforcement design methods to counteract the following applied wall forces:
  • Bending moments
  • Wall thrust
  • Diagonal tension (shear)
  • Radial tension
ASCE 15 and PIPECAR

- ASCE 15 – Standard Practice for Direct Design of Buried Precast Concrete Pipe Using Standard Installations (SIDD)
  - Originally published in 1993 subsequently updated in 1998 and 2017
  - Outlines SIDD installation requirements and direct design methodology

- Computerized design program PIPECAR™
  - Developed by Frank Heger for the ACPA
  - Direct design of RCP for a myriad of design and installation conditions

- Direct design and SIDD installations have now been adopted by both AASTHO and CSA
Transition from Indirect to Direct Design

![Graph showing transitions from indirect to direct design](image-url)
Limits of Indirect Design

• Indirect design was developed based on empirical testing on small to intermediate diameter pipe (<36") under loading conditions typical of the time (<15’)

• Failure modes recognized at the time were limited to flexural failure
  • Testing of unreinforced clay tile and concrete pipe

• 3EB tests do not directly assess diagonal or radial tension failure modes which govern under large external loading conditions
Diagonal and Radial Tension

- Pipes designed to withstand applied flexural stresses may not contain sufficient reinforcing to withstand imparted diagonal tension forces.
- If not confirmed, mobilization of tensile steel under high loads may result in radial tension failure.

Under 3EB test conditions large diameter pipes can fail under diagonal or radial tension prior to experiencing flexural failure.
Reinforcing for Diagonal Tension

- Diagonal tension is resisted by:
  - Placement of additional radial reinforcing steel (to a point)
  - Placement of stirrups

(Stirrups placed to intercept the shear plane)

(Heavily reinforced 10’ diameter concrete pipe, designed using direct design methods)

(Brzev et al 2006)
Reinforcing for Radial Tension

- Stirrups must be employed to overcome radial tension forces

Stirrups used to anchor the inner reinforcement into the pipe wall
Transitioning from Indirect to Direct Design

- Determine the transition from a flexural controlled failure to diagonal and/or radial tension controlled failure
- Requires the direct design methodologies (i.e. hand calcs or PIPECAR™)
Inner Reinforcing Steel vs. Soil Cover
1650 mm ASTM C76 CL V Pipe
Type 2 SIDD Installation

Loading Criteria:
Soil Unit Weight: 20.42 kN/m³
Live Load: AASHTO HS25
Verification

- Governing failure modes
- Bending moment capacity
- Diagonal tension capacity

<table>
<thead>
<tr>
<th>Pipe Diameter (mm)</th>
<th>3\textsubscript{EB} Testing</th>
<th>Pipecar Analysis @ at Soil Cover Limit (Type 2)</th>
<th>Pipecar Analysis @ at Soil Cover Limit (Type 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bending Moment (kN*m/m)</td>
<td>Bending Moment (kN*m/m)</td>
<td>Bending Moment (kN*m/m)</td>
</tr>
<tr>
<td></td>
<td>Shear (kN/m)</td>
<td>Shear (kN/m)</td>
<td>Shear (kN/m)</td>
</tr>
<tr>
<td>1050</td>
<td>42.79</td>
<td>36.23</td>
<td>35.32</td>
</tr>
<tr>
<td>1650</td>
<td>101.10</td>
<td>82.23</td>
<td>81.29</td>
</tr>
</tbody>
</table>

Diagonal Tension Failure - 1050 mm Class V RCP
Verification

- Governing failure modes
- Bending moment capacity
- Diagonal tension capacity

<table>
<thead>
<tr>
<th>Pipe Diameter (mm)</th>
<th>3_{EB} Testing</th>
<th>Pipecar Analysis @ at Soil Cover Limit (Type 2)</th>
<th>Pipecar Analysis @ at Soil Cover Limit (Type 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bending Moment (kN*m/m)</td>
<td>Shear (kN/m)</td>
<td>Bending Moment (kN*m/m)</td>
</tr>
<tr>
<td>1050</td>
<td>42.79</td>
<td>112.63</td>
<td>36.23</td>
</tr>
<tr>
<td>1650</td>
<td>101.10</td>
<td>167.72</td>
<td>82.23</td>
</tr>
</tbody>
</table>

Radial Tension Failure - 1650 mm Class V RCP
Verification

- Bending moment and shear capacity estimated using Heger’s 3EB wall force coefficients
- Actual bending moment and diagonal tension capacity in excess of predicted capacities
- Result of:
  - Increased material strengths
  - Limit state design factors

<table>
<thead>
<tr>
<th>Pipe Diameter (mm)</th>
<th>$3_{EB}$ Testing</th>
<th>Pipcar Analysis @ at Soil Cover Limit (Type 2)</th>
<th>Pipcar Analysis @ at Soil Cover Limit (Type 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bending Moment</td>
<td></td>
<td>Bending Moment</td>
</tr>
<tr>
<td></td>
<td>(kN*m/m)</td>
<td></td>
<td>(kN*m/m)</td>
</tr>
<tr>
<td></td>
<td>Shear (kN/m)</td>
<td></td>
<td>Shear (kN/m)</td>
</tr>
<tr>
<td>1050</td>
<td>42.79</td>
<td>112.63</td>
<td>36.23</td>
</tr>
<tr>
<td>1650</td>
<td>101.10</td>
<td>167.72</td>
<td>82.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Conclusion
Conclusion

• Indirect design has a long and successful service record for lower soil covers where diagonal and radial tension to not govern the design

• The use of indirect design for large diameter pipelines exposed to high external loads can ignore governing failure modes

• This exposes the Engineer, owner, and contractor to additional risk relating to failure and/or serviceability issues
Conclusion

• All large diameter pipes should be checked for governing failure modes regardless of pipe manufacturing methods (C76 or C1417)
• Available radial reinforcing should be confirmed whenever diagonal tension governs the design
• Direct design should be employed anytime stirrups are required
Conclusion

• Use in indirect design in deep cut applications will result in a pipe that’s vulnerable to:
  • Excessive cracking, exceeding service cracking criteria
  • Premature degradation
  • Ultimate failure
References:

- ACPA (1998), Concrete Pipe Handbook – Fifth Printing (1998), American Concrete Pipe Association (ACPA), Irving, TX, USA.

- ACPA (1993), Concrete Pipe Technology Handbook, American Concrete Pipe Association (ACPA), Irving, TX, USA.

- ASCE 15-17 (2017), Standard Practice for Direct Design of Buried Precast Concrete Pipe Using Standard Installation (SIDD), American Society for Civil Engineers (ASCE).


- Heger, F. (1963), Structural Behavior of Circular Reinforced Concrete Pipe – Development of Theory, Journal of the American Concrete Institute, November 1963.


- Marston, A., Schlick, W., Clemmer, H. (1917), The Supportive Strength of Sewer Pipe in Ditches and Methods of Testing Sewer Pipe in Laboratories to Determine Their Ordinary Supportive Strength, Iowa State College of Agriculture and Mechanical Arts.

Questions?

Adam Braun, P.Eng.
AECOM Canada Ltd.
Winnipeg, Manitoba, Canada
adam.braun@aecom.com