Structural Pipe Design

Paul Imm, P.Eng. – Cambridge, Ontario, Canada
Riley Dvorak, P.E. – Maple Grove, MN

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OVERVIEW

• Rigid vs flexible pipe behavior

• Design methods in AASHTO LRFD Section 12 Buried Structures:
  • Concrete pipe – Indirect Design with Standard Installations
  • Plastic pipe – Limit states design

• Summary
These structures become part of a composite system comprised of the pipe and the soil envelope.

12.10 – Reinforced Concrete Pipe
- Direct Design Method
- Indirect Design Method

12.12 – Thermoplastic Pipes
- Strength Limit States
- Service Limit States
ENGINEER OF RECORD RESPONSIBILITY

The professional engineer responsible for preparation of engineering drawings is also responsible for the structural design of pipe installations.

In all cases, designers shall keep a record of structural design calculations associated with each project. Design calculations for specific projects shall be provided to the City upon request.
RIGID vs FLEXIBLE PIPE

**Rigid Pipe:** VAF > 1.0
- the pipe carries most of the load

**Flexible Pipe:** VAF < 1.0
- embedment soil carries most of the load
RIGID vs FLEXIBLE PIPE

4 bedding types & 5 pipe classes for economical design options

Installation sensitive and complex design method

Passive side soil support to control deflection
INSTALLATION DETAILS

ASTM C1479 for Concrete Pipe

ASTM D2321 for Plastic Pipe
EVOLUTION OF RCP DESIGN

1930s – Marston-Spangler Model
Traditional Beddings – Class A, B, C, D
Indirect Design Method only

1980s – Heger Pressure Distribution
Standard Installation Beddings – Type 1, 2, 3, 4
Direct Design or Indirect Design Methods
3-EDGE BEARING TEST (D-LOAD TEST)

Criteria in ASTM C497:

• 0.01 in. design crack (D-Load)
• Ultimate strength

Dime is 0.053” thick
5 times the D-Load
RCP STRENGTH CLASSIFICATIONS

Example:
What is the minimum load required for a 18 inch Class V pipe in a 3EB Test?

\[
D_{0.01} = \text{Strength} \times \text{Pipe length} \times \text{Inside Dia}
\]
\[
= (3000 \text{ lbs/ft/ft})(8 \text{ ft})(1.5 \text{ ft})
\]
\[
= 36,000 \text{ lbs}
\]

\[
D_{ult} = (3750 \text{ lbs/ft/ft})(8 \text{ ft})(1.5 \text{ ft})
\]
\[
= 45,000 \text{ lbs}
\]

<table>
<thead>
<tr>
<th>ASTM C76</th>
<th>(D_{0.01}) (lbs/ft/ft)</th>
<th>(D_{ult}) (lbs/ft/ft)</th>
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</thead>
<tbody>
<tr>
<td>Class I</td>
<td>800</td>
<td>1200</td>
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<tr>
<td>Class II</td>
<td>1000</td>
<td>1500</td>
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<tr>
<td>Class III</td>
<td>1350</td>
<td>2000</td>
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<tr>
<td>Class IV</td>
<td>2000</td>
<td>3000</td>
</tr>
<tr>
<td>Class V</td>
<td>3000</td>
<td>3750</td>
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</table>
Reinforced Concrete Pipe Design

Indirect Design Method with Standard Installations
CONCRETE PIPE DESIGN OPTIONS

First Principles
Accurate, but tedious

PipePac software
www.pipepac.com
Efficient, but understand design principles

Fill Height Tables
Quick, but understand the assumptions used
INDIRECT DESIGN OVERVIEW

\[ D_{0.01} = \left( \frac{W_E + W_F}{B_{FE}} + \frac{W_L}{B_{FLL}} \right) \left( \frac{FS}{Dia} \right) \]

• Determine all loads – Earth \((W_E)\), Live \((W_L)\), Fluid \((W_F)\), Surcharge
• Select a Standard Installation bedding type
• Determine Bedding Factors \((B_{FE} & B_{FLL})\)
• Apply a Factor of Safety \((FS) = 1.0\) for \(D_{0.01}\)
• Calculate D-Load to produce 0.01” crack \((D_{0.01} \text{ in lb/ft/ft})\)
• Select a standard pipe strength class

See ACPA Design Data 9
Standard Installations and Bedding Factors for the Indirect Design Method
RCP INSTALLATION TYPES

**Trench Installation**
Upward friction from trench walls reduces the earth load

**Embankment Installation**
Drag down friction from side soil increases the earth load

Assume the Worst-Case Use positive projection embankment for design.
WEIGHT OF THE PIPE

- Concrete pipe wall thickness may vary by producer

**Direct Design** – must consider pipe self-weight

**Indirect Design** – pipe self-weight is ignored since already accounted for in the 3EB Test

Where:

\[ A \text{ wall} = \frac{D_i}{12} \]

\[ B \text{ wall} = \frac{D_i}{12} + 1 \]

\[ C \text{ wall} = \frac{D_i}{12} + 1.75 \]

\( D_i = \) inside diameter in inches
AASHTO 12.10.2.1:
Unit weight of soil (w) cannot be < 110 lb/ft³. Typically 120 lb/ft³ used

VAF for Embankment:

\[
D_{0.01} = \left( \frac{W_E + W_F}{B_{FE}} + \frac{W_L}{B_{FLL}} \right) \left( \frac{FS}{D_{ia}} \right)
\]

AASHTO (12.10.2.1-1):
\[
W_E = F_e w B_c H
\]

ACPA (Design Data 9):
\[
W_E = VAF \cdot \left( w \left[ H + \frac{D_o(4 - \pi)}{8} \right] D_o \right)
\]
FLUID LOAD ($W_F$)

**AASHTO 12.10.2.2:** Weight of fluid inside the pipe must be considered in design

- Fluid Load is assumed to be supported by lower part of the pipe (like earth load)

$$D_{0.01} = \left( \frac{W_E + W_F}{B_{FE}} + \frac{W_L}{B_{FLL}} \right) \left( \frac{FS}{Dia} \right)$$

$$W_F = \gamma_w \cdot \pi \left( \frac{D_i}{24} \right)^2$$

Where:
- $D_i =$ inside diameter in inches
- $\gamma_w =$ unit weight of water $= 62.4 \text{ lb/ft}^3$
LIVE LOAD ($W_L$)

**AASHTO 3.6.1.2.6a:** For single span culverts – live load (truck) is negligible when depth of fill is greater than 8 ft and exceeds the span.

**Highway Loads** – ACPA Design Data 1

**Aircraft Loads** – ACPA Design Data 2

**Railroad Loads** – ACPA Design Data 3

\[
D_{0.01} = \left( \frac{W_E + W_F}{B_{FE}} + \frac{W_L}{B_{FLL}} \right) \left( \frac{FS}{Dia} \right)
\]
BEDDING FACTORS ($B_f$)

$B_f = \frac{M_{\text{Test}}}{M_{\text{Field}}}$

Embankment Earth Load Bedding Factors ($B_{FE}$):

<table>
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<tr>
<th>Pipe Dia (in.)</th>
<th>Standard Installation</th>
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<tr>
<td></td>
<td>Type 1</td>
</tr>
<tr>
<td>12</td>
<td>4.4</td>
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<td>24</td>
<td>4.2</td>
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<td>36</td>
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<td>72</td>
<td>3.8</td>
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<td>144</td>
<td>3.6</td>
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Live Load Bedding Factors ($B_{FLL}$):

<table>
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<tr>
<th>Pipe Dia (in.)</th>
<th>Fill Height (ft.)</th>
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<tr>
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<td>&lt; 2.0 ft</td>
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<td>18</td>
<td>3.2</td>
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<td>24</td>
<td>3.2</td>
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<tr>
<td>30 and larger</td>
<td>2.2</td>
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</table>

Note: These $B_{FLL}$ in LRFD (8th Ed) is not the same as the 7th Ed or the ACPA DD9.
ACPA LRFD FILL HEIGHT TABLES

- Based on **Indirect Design** as per LRFD Bridge Design Specification (7TH Ed)
- **Positive Projecting Embankment**
- **C wall** for all sizes >> max. prism load
  - Soil unit weight = 120 lb/ft³
- AASHTO **HL-93** live load
- For Type 1: D-Loads increased by multiplying installation factor of **1.10** (AASHTO 12.10.4.3.1)
### Table 3: Reinforced Pipe Classes for 0.01 inch Crack Per ASTM C 76 (lbs/ft²/ft)

<table>
<thead>
<tr>
<th>Class</th>
<th>Condition</th>
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<tr>
<td>I</td>
<td>1 ≤ 800</td>
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<tr>
<td>II</td>
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<td>IV</td>
<td>1 ≤ 2000</td>
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<tr>
<td>V</td>
<td>1 ≤ 3000</td>
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<tr>
<td>Special</td>
<td>&gt; 3000</td>
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**Fill Height Tables are based on:**
1. 6 – 120 psi load
2. AASHTO HL-93 live load
3. Positive Pressure Embankment Condition

#### D-Load (lb/ft²) for Type 3 Bedding

<table>
<thead>
<tr>
<th>Pipe Size (in)</th>
<th>Fill Height in Feet</th>
<th>Class I</th>
<th>Class II</th>
<th>Class III</th>
<th>Class IV</th>
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</tbody>
</table>

**TYPE 2**

**TYPE 3**
Plastic Pipe Design
12.12 Thermoplastic Pipes

**Strength Limit States:**
- Thrust
- Buckling
- Combined strains

**Service Limit States:**
- Deflection

Also, check flotation

AASHTO LRFD assumes that native soil is stiff and ignores the transfer of load to the in-situ trench walls.

Commentary C12.12.3.5:

The width of structural backfill is an important consideration when the in situ soil in the trench wall or the embankment fill at the side of the structural backfill is soft. Currently, only AWWA Manual M45, The Fiberglass Pipe Design Manual, addresses this issue.
FILL HEIGHT TABLES

Common assumptions used in plastic pipe fill height tables:

• Pipe is installed in accordance with ASTM D2321
• Water table is below the pipe (no hydrostatic pressure)
• Native soil is very stiff

Example: 48 in. HDPE pipe with Class 2 backfill compacted to 95%
PLASTIC PIPE PROPERTIES

• Pipe performance depends on profile wall geometry which vary significantly
  • Moment of inertia ($I$)
  • Radius to centroid of pipe profile ($R$)
  • Spacing of corrugations ($\omega$)
  • Wall area ($A_g$) and effective wall area ($A_{\text{eff}}$)

• Short and long-term mechanical properties vary by type of plastic pipe
  • See LRFD Table 12.12.3.3-1

Source: NCHRP Report 631
C12.12.3.2

Historically, AASHTO bridge specifications have contained minimum values for the moment of inertia and wall area of thermoplastic pipe; however, these values have been minimum values and are not meaningful for design. This is particularly so since provisions to evaluate local buckling were introduced in 2001. These provisions require detailed profile geometry that varies with manufacturer. Thus, there is no way to provide meaningful generic information on section properties. A convenient method for determining section properties for profile wall pipe is to make optical scans of pipe wall cross-sections and determine the properties with a computer drafting program.
SOIL PRISM PRESSURE ($P_{sp}$)

$P_{sp}$ is calculated for 3 possible conditions:

1. Water table above top of pipe and at or above the ground surface

\[
P_{sp} = \frac{H + 0.11 \frac{D_o}{12}}{144} \gamma_b
\]

2. Water table above top of pipe and below the ground surface

\[
P_{sp} = \frac{1}{144} \left[ \left( H - \frac{D_o}{24} \right) + 0.11 \frac{D_o}{12} \right] \gamma_b + \left( H - \frac{D_o}{24} \right) \gamma_s
\]

3. Water table below top of pipe

\[
P_{sp} = \frac{H + 0.11 \frac{D_o}{12}}{144} \gamma_s
\]

*Evaluate multiple conditions if water table fluctuates.

Also check for FLOTATION
THRUST

- Check both springline & crown of pipe
- Total load contributes – soil load, live load & hydrostatic load
- Short & long-term material properties need to be evaluated due to time-dependent nature of plastic pipe

\[
\varepsilon_{uc} = \frac{\varepsilon_{yC}}{1000(A_{eff}E_p)} \leq \Phi_T \varepsilon_{yC}
\]

\[
T_u = \left[ \eta_{EV} \left( \gamma_{EV} K_1 E K_2 VAF P_{sp} + \gamma_{W} P_{w} \right) + \eta_{LL} \gamma_{LL} P_L \right] \frac{C_L F_1 F_2}{2} D_o
\]

in which:

\[
VAF = 0.76 - 0.71 \left( \frac{S_H - 1.17}{S_H + 2.92} \right)
\]

\[
S_H = \frac{\phi_M R}{E_p A_g}
\]

\[
C_L = \frac{L_w}{D_o} \leq 1.0
\]

\[
F_1 = \frac{0.75 D_o}{L_w} \geq F_{\text{min}}
\]

\[
F_{\text{min}} = \frac{15}{D_i} \geq 1
\]

\[
F_2 = \frac{0.95}{1 + 0.6 S_H}
\]
BUCKLING

- Pipe wall must have sufficient stiffness to remain stable under compression loads.

$\varepsilon_{uc} \leq \Phi_{bck} \varepsilon_{bck}$

Resistance factor = 0.7

Factored compressive strain

Buckling strain capacity of pipe

Poor soil support decreases pipe’s ability to resist buckling

$\varepsilon_{bck} = \frac{1.2C_n \left( E_p I_p \right)^{\frac{1}{3}}}{A_{eff} E_p} \left[ \frac{\phi_s M_s (1-2v)}{(1-v)^2} \right]^{\frac{2}{3}} R_h$

in which:

$R_h = \frac{11.4}{11 + \frac{D}{12H}}$

(12.12.3.10.1e-2)

(12.12.3.10.1e-3)
COMBINED STRAINS

• Must check combined strains at extreme fibers since bending strain from deflection creates tension (T) and compression (C) zones
DEFLECTION

- Caused by bending deformation plus circumferential shortening due to thrust
- Controlled by proper soil support and must be verified with a deflection test
- Maximum allowable deflection = 5.0%

\[ \Delta_t = \frac{K_B (D_L P_{sp} + C_L P_L) D_o}{1000 \left( \frac{E_p I_p}{R^3} + 0.061 M_s \right)} + \varepsilon_{sc} D \]

- Soil Load
- Live Load
- Circumferential Shortening
- Pipe Stiffness
- Soil Stiffness
SECANT CONSTRAINED SOIL MODULUS ($M_s$)

- All backfill soils are combined into three broad groups
  - $S_n$ – sands and gravels
  - $S_i$ – silts
  - $C_l$ – clays

- More useful than $E'$ soil stiffness for deep installations since $M_s$ increases with depth
EMBEDMENT SOIL & DEFLECTION

Given:
- $D_i = 48$ in.
- $D_o = 54.26$ in.
- $R = 25.27$ in.
- $E_{pi} = 110$ ksi
- $E_{p75} = 21$ ksi
- $I_p = 0.65$ in$^4$/in
- $H = 25$ ft
- $K_B = 0.1$
- $D_L = 1.5$
- $C_L = 1.0$
- $P_w = 0$ psi
- $A_g = 0.441$ in$^2$/in
- $P_{sp} = 21.2$ psi
- $P_L = 0.336$ psi
- $P_{SP} = 21.2$ psi
- $P_{PL} = 0.336$ psi
- $H = 25$ ft
- $KB = 0.1$
- $DL = 1.5$
- $CL = 1.0$
- $P_{SP} = 21.2$ psi
- $P_L = 0.336$ psi

\[
\Delta_t = \frac{K_B(D_L P_{sp} + C_L P_{L})D_o}{1000 \left( \frac{E_p I_p}{R^3} + 0.061M_s \right)} + \varepsilon_{sc}D
\]

Various soils @ 95% compaction:

<table>
<thead>
<tr>
<th>Soil Type &amp; Compaction</th>
<th>$M_s$</th>
<th>Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn-95</td>
<td>3.50</td>
<td>4.6 %</td>
</tr>
<tr>
<td>Si-95</td>
<td>1.89</td>
<td>7.2 %</td>
</tr>
<tr>
<td>Cl-95</td>
<td>0.75</td>
<td>13.5 %</td>
</tr>
</tbody>
</table>

Sn soil with various compaction:

<table>
<thead>
<tr>
<th>Soil Type &amp; Compaction</th>
<th>$M_s$</th>
<th>Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn-100</td>
<td>5.63</td>
<td>3.2 %</td>
</tr>
<tr>
<td>Sn-95</td>
<td>3.50</td>
<td>4.6 %</td>
</tr>
<tr>
<td>Sn-90</td>
<td>1.82</td>
<td>7.4 %</td>
</tr>
<tr>
<td>Sn-85</td>
<td>0.66</td>
<td>14.7 %</td>
</tr>
</tbody>
</table>
EMBEDMENT SOIL & DEFLECTION

SOIL TYPE & COMPACTION LEVEL

- Sn-100: 3.2%
- Sn-95: 4.6%
- Sn-90: 7.4%
- Sn-85: 14.7%
- Si-95: 7.2%
- Cl-95: 13.5%

DEFLECTION (%)

5% Max
DEFLECTION TESTING

• Plastic pipe requires a deflection test to verify proper soil embedment

• Frequency of deflection tests:
  • No sooner than 30 days after backfill – AASHTO Section 30
  • Prior to final acceptance or end of warranty
  • As part of on-going pipe maintenance

• Plastic pipe products have different \textit{Base Inside Diameters}
Load Lag, Deflection Lag, and Time Lag
Amster Howard
TECH NOTE: Supplement to Pipeline Installation

“... the maximum load on a pipe does not occur until three to six months after backfilling...”
12.12 Thermoplastic Pipes

**Strength Limit States:**
- Thrust – *Compressive limits of the pipe material*
- Buckling – *Dependant on both soil and pipe properties*
- Combined strains – *Material limits with deflection strains added*

**Service Limit States:**
- Deflection – *Installation sensitive, verify with deflection test.*

Also, check flotation
FUNDAMENTAL DIFFERENCES IN DESIGN

RIGID CONCRETE PIPE
• Standard strength classes
• Indirect or Direct Design
• Primary structure is pipe (60-75%)
• Structure built & tested at plant with 3EB test
• Design life based on historical performance data
• Design software available

FLEXIBLE PLASTIC PIPE
• Wide range of pipe products/profiles
• Direct design only
• Primary structure is soil (50-90%)
• Structure built & tested in field with deflection test
• Design life based on time-dependent behavior of material
THANK YOU