Water Research Foundation
Webcast
July 10, 2012

Long Term Performance of Ductile Iron Pipe
Water Research Foundation

Advancing the science of water to improve the quality of life
Foundation’s Contribution to the Water Community

• Practical applications to help utilities optimize operations and ensure customer satisfaction

• Early alert and proactive solutions on future issues

• Direct, immediate benefits to utility subscribers
Long-Term Performance Projects

• Long-Term Performance Prediction for PE Pipes
• Service Life Analysis of Water Main Epoxy Lining
• Long-Term Performance Prediction for PVC Pipes
• The Performance of Non-Leaded Brass Materials
• Long Term Performance of Asbestos Cement Pipe
• Performance and Life Span of Polyethylene Wrap Materials for Ductile Iron Pipe
• Long-Term Performance Prediction of Steel Pipe
Webcast Speaker

Balvant Rajani, Ph.D.
Principal, Rajani Consultants Inc.
Ottawa, Canada
Long Term Performance of Ductile Iron Pipes

Balvant Rajani\textsuperscript{1} and Yehuda Kleiner\textsuperscript{2}
\textsuperscript{1}Rajani Consultants Inc.
\textsuperscript{2}National Research Council Canada
Objectives

A. Pitting corrosion rates of ductile iron pipe to estimate times to full pipe wall perforation

B. Characterization of external corrosion pits in ductile iron pipe

C. Sampling and condition assessment of ductile iron pipes
A. CORROSION RATES OF DI PIPE

Background

Thicknes classes 1 to 6; trench types A and B

Pressure classes 150 to 350; trench types 1 to 5 & special thickness classes 50 to 56

1965

1976

1991

• Pressure class pipes in general have thinner pipe wall thicknesses than thickness class pipes

Objective of Part A

• Assess impact of change to long term performance of DI pipes
Cf. of wall thicknesses

Thickness class

Pressure class (introduced in 1991)
Design of DI pipe

- Principally emphasizes structural design (FS = 2)
- Design procedure (ANSI/AWWA C105/A21.50 and A21.5 standards) does not explicitly account for corrosion
- DI mains do not experience mechanical failures like circumferential or longitudinal splits often observed in cast iron mains
• Collation of published data (age, soil types (corrosivity), installation conditions) (Table 1.2)

• Calibrate data using suitable corrosion model (Table 1.1)

• Analyse data to estimate times (range) to full pipe wall perforation
Estimating corrosion rates

Figure 1.3: Estimating corrosion rates

- **1)** Initial pitting rate
- **2)** Instantaneous pitting rate
- **3)** Secant pitting rate

Exposure time, $\tau$ (years)

Pit depth, $d$ (mm)

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Collation of corrosion pit data

![Graph showing pit depth vs. exposure time]

- Wakelin and Fieltsch (2004)
- Calgary (2003)
- Caproco (1985)
- Fuller (1981) - DIPRA
- Romanoff (1967)
- De Rosa and Parkinson (1985)
- Fuller (1981) - CIPRA
- Fuller (1981) - European

Pit depth, $d$ (mm)

Exposure time, $\tau$ (years)
Collation of corrosion pitting rate data

Graph showing the pitting rate, $d_r$, in mm/year, as a function of exposure time, $\tau$, in years. The data points are labeled with references:

3. Caprock (1985)
4. Fuller (1981) - DIPRA
5. Romanoff (1967)
7. Fuller (1981) - CIPRA
8. Fuller (1981) - European

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Fuzzy representation of corrosion pit growth rates

Exposure time, $\tau$ (years)

Pit depth, $d$ (mm)

Exposure time, $\tau$ (years)

Pitting rate, $d'(\tau)$ (mm/year)

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Estimates of times (range) for full pipe wall penetration

![Graph showing estimates of times for full pipe wall penetration. The graph plots exposure time versus pit depth, with curves indicating minimum, most likely, and maximum scenarios.](image)

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Estimated time intervals (years) for full pipe wall penetration in DI mains

<table>
<thead>
<tr>
<th>Potential corrosivity states</th>
<th>Pressure class 350</th>
<th>Min thickness (class 50)</th>
<th>Thickness class</th>
<th>Max thickness (class 56)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(class 52)</td>
<td></td>
</tr>
<tr>
<td>Pipe diameter: 6&quot; (150 mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very low (VL)</td>
<td>125 - 190</td>
<td>125 - 190</td>
<td>455 - 540</td>
<td>1120 - 1240</td>
</tr>
<tr>
<td>Low (L)</td>
<td>30 - 42</td>
<td>30 - 42</td>
<td>270 - 315</td>
<td>805 - 880</td>
</tr>
<tr>
<td>Moderate (M)</td>
<td>11 - 14</td>
<td>11 - 14</td>
<td>23 - 52</td>
<td>335 - 415</td>
</tr>
<tr>
<td>High (H)</td>
<td>5 - 6</td>
<td>5 - 6</td>
<td>7.5 - 9.5</td>
<td>25 - 61</td>
</tr>
<tr>
<td>Very high (VH)</td>
<td>3 - 3.5</td>
<td>3 - 3.5</td>
<td>4 - 4.5</td>
<td>6.5 - 9</td>
</tr>
</tbody>
</table>
A. CORROSION RATES OF DI PIPE

Summary

• Estimated times to full pipe wall penetration get longer as pipe size gets larger, irrespective of “pressure” and “thickness class” designations

• Extra wall thickness buys additional time for full pipe wall penetration (absence of other corrosion protection measures)

• Development of a single full pipe wall penetration does not necessarily mean end of service life
B. CHARACTERIZATION OF EXTERNAL CORROSION PITS IN DI PIPE

Objectives

• Gain a thorough understanding of geometry of external corrosion pits through statistical analyses

• Factors affecting corrosion (soil properties, appurtenances, service connections thicknesses)
### Data collection

<table>
<thead>
<tr>
<th>City (Water utility)</th>
<th>Pipe size</th>
<th>Depth of cover</th>
<th>Exhumed pipe length</th>
<th>Installation year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kansas City (WaterOne)</td>
<td>300 mm (12”)</td>
<td>1.07 m (3.5 ft)</td>
<td>91.4 m (300 ft)</td>
<td>1989</td>
</tr>
<tr>
<td>St. Louis (American Water)</td>
<td>300 mm (12”)</td>
<td>1.22 m (4 ft)</td>
<td>42.7 m (140 ft)</td>
<td>1970</td>
</tr>
<tr>
<td>Louisville (Louisville Water Co.)</td>
<td>200 mm (8’)</td>
<td>1.07 m (3.5 ft)</td>
<td>91.4 m (300 ft)</td>
<td>1972</td>
</tr>
<tr>
<td>Calgary (Calgary Water Dept.)</td>
<td>250 mm (10”)</td>
<td>3.05 m (10 ft)</td>
<td>91.4 m (300 ft)</td>
<td>1969</td>
</tr>
</tbody>
</table>

- **Soil samples**: 8 - 15 m apart
- **Lab tests**: Resistivity, redox potential, chlorides, pH, sulphides, soil type, sodium?.
- Location of appurtenances (service connections), pipe crossings, etc.
Pit scanning

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Pit observation
Pit definitions
Approach to data analyses

**Ring** analyses of different lengths, $l = \{25, 50, 100, 150, 300, 450, 600 \text{ mm}\}$; consideration of pit depth maxima, pit area and pit volume
Extreme value statistical analysis

- Probability distributions tested
  - Gumbel (double exponential)
  - 2-parameter Weibull (found to have consistently best fit)
  - Exponential

- Two versions of each distribution considered: ordinary & truncated

- Quality of fit: Chi-square test (P-value)
Ring analysis: Impact of soil properties

Calgary: 50 mm rings

Soil properties: quadratic interpolation between samples
Ring analysis: Impact of soil properties

Calgary: 300 mm rings

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Ring analysis: Impact of soil properties

Calgary: 600 mm rings

[Graph showing data with axes labeled: Max pit depth (mm) on the y-axis, Length (m) on the x-axis, and Resitivity on the right y-axis. The graph displays scattered data points and a trend line.]
Example: Weibull

\[ F(x) = 1 - \exp\left[-\left(\frac{x}{\alpha(s)}\right)^\beta\right] \]

\[ \alpha(s) = \exp(\beta z) \]

Scale parameter \( \alpha \) is function of soil properties \( s \).

Likelihood-ratio test used to examine if a covariate is significant.
Ring analysis: Distribution of max. pit depth, truncated Weibull

25 mm rings

150 mm rings

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Ring analysis: Significance of soil properties

Kansas City: 50 mm & 100 mm rings

<table>
<thead>
<tr>
<th>Covariate</th>
<th>Single</th>
<th>Pair</th>
<th>Triplet</th>
<th>Quad</th>
<th>Quint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appurtenance</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Redox potential</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorides</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Sulphides</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>% fines</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Sulphide derivative</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

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Ring analysis: Prediction with soil properties

Kansas City: 50 mm, 1380 rings

Covariates: sulphides deriv., pH, % fines, appurt., chlorides

R-sq. = 0.161

Observed pit depth maxima (mm)

Calculated mean pit depth maxima (mm)

Mean line of equality
## Ring analysis: Dominant soil properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Calgary</th>
<th>Kansas City</th>
<th>Louisville</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appurtenance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redox potential</td>
<td></td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Resistivity</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Chlorides</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sodium*</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Sulphides</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% fines</td>
<td></td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Sulphide derivative</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Chloride derivative</td>
<td></td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
B. CHARACTERIZATION OF EXTERNAL CORROSION PITS IN DI PIPE

Summary (ring analysis)

• Probability distribution
  ✓ Max. pit depth – truncated Gumbel
  ✓ Area, volume – Weibull

• Soil properties examined to improve prediction:
  ✓ Some soil properties statistically significant but improvement in prediction not great
  ✓ Dominant soil properties vary between cities.
  ✓ Resistivity – not very dominant in any city

• Traditional convention not strongly supported
C. SAMPLING AND CONDITION ASSESSMENT OF DI PIPES

Objectives

• Sample the pipe to obtain distribution of pit-depth maxima.

• Infer pipe condition from distribution obtained

Offers non-destructive, non-intrusive evaluation of the condition of buried ductile iron pipe
Sampling approach

- Soil properties not explicitly considered
- Stratified sampling (balanced geographical representation)
  - Divide pipe into $n$ equal segments (sites)
  - In each randomly selected site location, extract $k$ adjacent rings
  - 3 properties examined in each ring:
    - Maximum pit depth (discussed here)
    - Corroded area
    - Corroded volume
Sampling approach

• What is the optimal combination (sampling scheme) of $n$, $k$, and ring length, for a good representation of the population?
  - Pit-depth maxima assumed to be distributed as truncated 2-parameter Gumbel (scale, location)
  - 1000 simulations for each sampling scheme
Sampling evaluation

Calgary example

Histogram of parameters (pit maxima in 50 mm rings, 4 sites, 1 ring per site)

Population

Scale, location parameters

0.20

0.15

0.10

0.05

0.00

0.00 1 2 3 4 5 6 7 8 9

Scale, location parameters

Population

Population

means

Scale

Location

0.05

0.10

0.15

0.20

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Sampling evaluation
Calgary example

Pit-depth maxima 50 mm ring sampling (1000 simulations per case)

Mean values

Standard deviation

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Sampling evaluation
Relative performance

**Accuracy:**
\[ \text{SimToPopRatio} = \frac{\text{Simulation mean}}{\text{population p value}} \]

**Precision:**
\[ \text{CoV} = \frac{\text{Simulation SD}}{\text{Simulation mean}} \]
### Sampling evaluation

#### Kansas City example

#### Accuracy: SimToPopRatio

<table>
<thead>
<tr>
<th># sites</th>
<th># rings x ring size</th>
<th>4 x 25 mm</th>
<th>2 x 50 mm</th>
<th>1 x 100 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td></td>
<td>0.97</td>
<td>0.93</td>
<td>0.95</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.98</td>
<td>0.95</td>
<td>1.01</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>0.99</td>
<td>0.96</td>
<td>0.95</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>0.98</td>
<td>1.00</td>
<td>0.96</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>0.98</td>
<td>0.97</td>
<td>0.96</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>1.00</td>
<td>0.97</td>
<td>1.00</td>
</tr>
</tbody>
</table>

#### Precision: CoV

<table>
<thead>
<tr>
<th># sites</th>
<th>4 x 25 mm</th>
<th>2 x 50 mm</th>
<th>1 x 100 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>5</td>
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<tr>
<td>9</td>
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<tr>
<td>10</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

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Sampling approach: Observations

- Scale parameter
  - **Accuracy**: quite high for all schemes (very slight improvement as number of sites increases).
  
  - **Precision**: 25 & 50 mm rings better than 100 mm. More sites – better precision. More rings/site – better precision (although adjacent).

- Location parameter
  - **Accuracy**: 25 & 50 mm rings better than 100 mm. More sites – better accuracy.
  
  - **Precision**: 25 & 50 & 100 mm rings perform same, except when only 1 ring of 100 mm. More sites – better precision. More rings/site better precision.
95% Likelihood ratio bounds (LRB): 1 ring per site
Ductile iron pipe condition

• Predominant failure mode in DI Pipes: full pipe wall perforation (leaks)
• Pipe condition = expected # of leaks in pipe
• Computation:
  ✓ Probability of a full pipe wall perforation (through-hole) in a ring.
  ✓ Return period (recurrence interval)
  ✓ 95% Likelihood ratio confidence bounds (LRB).
95% Likelihood ratio bounds (LRB): 25 mm rings
C. SAMPLING AND CONDITION ASSESSMENT OF DI PIPES

Concluding comments

• Sampling, inference – anchor research to reality

• Caution with definite conclusions (relatively small datasets)

• Tentative recommendation:
  ✓ Short rings (10 – 50 mm)
  ✓ 7 – 10 samples (sites) per ~ 100 m pipe

• More research:
  ✓ More & larger datasets
  ✓ Cost benefit of higher precision and accuracy
  ✓ Improve model for deteriorated pipes
  ✓ Extend to cast iron pipes (structural failure)
This research project on DI pipe was supported by:

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- CSIRO (Australia)
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