Acoustic Leak Detection

Gander Newfoundland 2006
Overview

• Background on Leakage and leak Detection
• Water Loss Management
• Fundamentals of Correlation
Leakage

- The unintentional escape or loss of water from a distribution network.
- Can range from a drip to a major gusher from a burst pipe.
- Main failure due to water loss from improperly sealed joints, defective service connections & corrosion holes.
- Water is a scarce resource- in some countries water is more expensive than petrol so leaks are unacceptable.
- A pin-sized hole in a water pipe under 40 p.s.i. loses over 2,000 gallons of water a day or as much water in a week as what’s normally used in a household of four.
Causes of Leaks

- Water corrosivity
- Third party digging
- Ground heave & slip
- Thermal changes
- Earth loading
- Ground support: pipe spans
- AC corrosion from power lines
- DC corrosion from trams & utilities
- Age & neglect
- Road salts
- Ground corrosivity
- Microbially induced corrosion
- Traffic loading
Leakage Problem

• The severity of leakage problems varies across the globe, but it is significant in all parts of the world.
• In the UK, it’s legislated that a certain percentage of distribution mains must be surveyed for leaks each year.
• A pin-sized hole in a water pipe under 40 p.s.i. loses over 2,000 gallons of water a day or as much water in a week as what’s normally used in a household of four.
• One estimate states that as much as 40% of the water supply is lost as a result of pipe leakage in African cities.

http://www.dams.org/news_events/media.php?article=212
Does Leakage Matter

• Water Utilities are the largest user of electricity in the US, consuming an estimated 75 Billion kW-h annually (3% of total) Von Sacken, 2001
• 5-10 billion of electricity expended on pumping water for leaks
• Leaks can cause damage to infrastructure
• Leakage water often finds it’s way to sewage systems, where it is treated…an additional cost (Thornton et al 2002)
• Leakage requires larger infrastructure than necessary
• Watersheds are taxed unnecessarily
# Water Leakage Rates at 60 psi

<table>
<thead>
<tr>
<th>HOLE SIZE [MM]</th>
<th>LEAKAGE [LITRES/MIN]</th>
<th>LEAKAGE [LITRES/HR]</th>
<th>PERCENTAGE ADJUSTMENT FOR PRESSURES OTHER THAN 5 BAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.50</td>
<td>30.00</td>
<td>45%</td>
</tr>
<tr>
<td>1.00</td>
<td>0.97</td>
<td>58.20</td>
<td>63%</td>
</tr>
<tr>
<td>1.50</td>
<td>1.82</td>
<td>109.20</td>
<td>77%</td>
</tr>
<tr>
<td>2.00</td>
<td>3.16</td>
<td>189.60</td>
<td>89%</td>
</tr>
<tr>
<td>2.50</td>
<td>5.09</td>
<td>305.40</td>
<td>100%</td>
</tr>
<tr>
<td>3.00</td>
<td>8.15</td>
<td>489.00</td>
<td>110%</td>
</tr>
<tr>
<td>3.50</td>
<td>11.30</td>
<td>678.00</td>
<td>119%</td>
</tr>
<tr>
<td>4.00</td>
<td>14.80</td>
<td>888.00</td>
<td>127%</td>
</tr>
<tr>
<td>4.50</td>
<td>18.20</td>
<td>1,092.00</td>
<td>134%</td>
</tr>
<tr>
<td>5.00</td>
<td>22.30</td>
<td>1,338.00</td>
<td>141%</td>
</tr>
<tr>
<td>5.50</td>
<td>26.00</td>
<td>1,560.00</td>
<td></td>
</tr>
<tr>
<td>6.00</td>
<td>30.00</td>
<td>1,800.00</td>
<td></td>
</tr>
<tr>
<td>6.50</td>
<td>34.00</td>
<td>2,040.00</td>
<td></td>
</tr>
<tr>
<td>7.00</td>
<td>39.30</td>
<td>2,358.00</td>
<td></td>
</tr>
</tbody>
</table>
Pipe Leakage Evaluation

- Identify & locate high leakage areas.
- Prioritize areas for leak detection based upon data from routine network maintenance.
  - Burst & leak history
  - Water Audits (unaccounted for water consumption)
  - DMA/Flow measurement (flow into less flow out of network)
  - Hydrostatic testing (pressure testing)
- Repair leaks.
- First need to know the leakage situation
## Components and Definitions

<table>
<thead>
<tr>
<th>Water Balance Component</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Input Volume</td>
<td>The annual volume input to the water supply system</td>
</tr>
<tr>
<td>Authorized Consumption</td>
<td>The annual volume of metered and/or unmetered water taken by registered customers, the water supplier and others who are authorized to do so</td>
</tr>
<tr>
<td>Water Losses</td>
<td>The difference between System Input Volume and Authorized Consumption, consisting of Apparent Losses plus Real Losses</td>
</tr>
<tr>
<td>Apparent Losses</td>
<td>Unauthorized Consumption, all types of metering inaccuracies and data handling errors</td>
</tr>
<tr>
<td>Real Losses</td>
<td>The annual volumes lost through all types of leaks, breaks and overflows on mains, service reservoirs and service connections, up to the point of customer metering.</td>
</tr>
<tr>
<td>Revenue Water</td>
<td>Those components of System Input Volume which are billed and produce revenue</td>
</tr>
<tr>
<td>Non-Revenue Water (NRW)</td>
<td>The difference between System Input Volume and Billed Authorized Consumption</td>
</tr>
</tbody>
</table>
## AWWA – IWA Water Balance Sheet

<table>
<thead>
<tr>
<th>System Input Volume</th>
<th>Authorized Consumption</th>
<th>Billed Authorized Consumption</th>
<th>Billed Metered Consumption</th>
<th>Billed Unmetered Consumption</th>
<th>Revenue Water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Non Revenue Water</td>
</tr>
<tr>
<td></td>
<td>Water Losses</td>
<td>Apparent Losses</td>
<td>Unauthorized Consumption</td>
<td>Unbilled Metered Consumption</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Customer Meter Inaccuracies</td>
<td>Unbilled Unmetered Consumption</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Real Losses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Leakage on Transmission &amp; Distribution Mains</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Leakage and Overflows at Reservoirs</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Leakage on Service Connections up to metering point</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Billed Authorized Consumption**
- **Billed Metered Consumption**
- **Billed Unmetered Consumption**
- **Unbilled Authorized Consumption**
- **Unbilled Metered Consumption**
- **Unbilled Unmetered Consumption**
- **Apparent Losses**
- **Unauthorized Consumption**
- **Customer Meter Inaccuracies**
- **Real Losses**
- **Leakage on Transmission & Distribution Mains**
- **Leakage and Overflows at Reservoirs**
- **Leakage on Service Connections up to metering point**
Current Annual Real Losses CARL

Pressure Management

Speed and Quality of Repairs

Unavoidable Annual Real Losses UARL

Pipeline and Assets Management: Selection, Installation, Maintenance, Renewal, Replacement

Infrastructure Leakage Index ILI = CARL/UARL

UARL calculation based on mains length, number of services, customer meter location and average pressure
Unavoidable Annual Real Losses (UARL)

- UARL (gallons/day) = (5.41Lm + 0.15Nc + 7.5Lp) x P
  where
  - Lm = length of water mains, miles
  - Nc = number of service connections
  - Lp = total length of private pipe, miles = Nc x average distance from curbstop to customer meter
  - P = average pressure in the system, psi
Infrastructure Leakage Index (ILI)

- Ratio of Current Annual Real Losses (CARL) to Unavoidable Annual Real Losses (UARL); good for operational benchmarking for real loss control.
Water Loss Methodologies

• Pressure Control
• District Meter Areas (DMA’s)
• Leak Noise Surveys
• Leak Correlation Survey’s
• Noise Logger Survey’s
Locating Leaks & Breaks

• Methods used are:
  – Acoustic
  – Acoustic with Correlation
  – Infrared Thermography
  – Chemical
  – Mechanical
  – Ground Penetrating Radar

• Acoustic & acoustic with correlation are by far the most popular methods.
## Limitations of Leak Detection Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Application</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic</td>
<td>Listen for audible sound with listening sticks or ground microphone</td>
<td>• Must to be over or on pipe.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Ground dampening.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Experienced operators.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Background noises.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Have to be close to leak.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Plastic pipes a problem.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Accuracy.</td>
</tr>
<tr>
<td>Acoustic with Correlation</td>
<td>2 sensors strategically placed on opposite sides of the leak input sound spectrum to a computer. Correlation program uses delay in sound spectrum to pinpoint leak location.</td>
<td>• Can be expensive.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Contact location required.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Quiet leaks difficult to correlate.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Poor performance on PVC/large diameter.</td>
</tr>
</tbody>
</table>
## Limitations 2

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
<th>Limitations</th>
</tr>
</thead>
</table>
| **Infrared Thermography**      | Infrared radiation detector locates temperature differences caused by leaking water. | • Expensive.  
• Significant operator training & experience.  
• Accuracy  
• Weather limitations. |
| **Chemical**                   | A tracer in the pipe escapes through the leak & is detected at the surface. | • Expensive & time consuming.  
• Exact pipe location.  
• Depth limitation.  
• Accuracy. |
| **Mechanical**                 | Drilling holes or opening up pipe                                             | • Expensive & time consuming.  
• Damage to other utilities. |
| **Ground Penetrating Radar**   | Radar generates an image based on the reflection of radar waves from changing densities of soil/pipe | • Hard to interpret |
Acoustic Survey

Advantages:
• Fast, a large area may be covered quickly
• A skilled listener can hear most leaks

Drawbacks:
• Listening requires some skill
• Quiet leaks may not be heard
• Will not work on PVC if you are not close to leak or if there have been PVC repairs
• Frozen Ground is a problem for surface based survey
Acoustic Survey
Correlation Survey

Advantages:
- Can find leaks their listeners can’t
- Less dependant on listener’s skills
- More accurate method of locating leaks
- Easy to use
- Finds leaks in all types of distribution pipes

Drawbacks:
- Slower than acoustical survey
- Some areas may be difficult to correlate
- Can’t correlate hydrant leaks for dry barrel hydrants
Correlation Background

- How it works
- Bracket the leak with two sensors
- The leak noise takes longer to arrive at point 1 than point 2
- Correlator measures this difference and determines the exact leak location: \( d = vt \) where \( v \) is the acoustic wave velocity
Correlation Background 2

- Leaks makes noise
- Travels as a ‘coupled wave’
  - Fancy way of saying it travels in both the water and the pipe
  - Compression in water, dilatational in pipe
- Correlation is passive, we are not sending any signal into the pipe, only listening to the sound of the leak
Transducers
Distance Measurement

Legend:
- $H_1$, $H_2$ - hydrants
- $VK_1$, $VK_2$ - valves
- V - vertical
- L - lateral
- h - height
- d - distance
Advanced Correlation

Two signals are time shifted and added together: When the time shift is correct the correlator shows a peak

\[ C_{12}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_0^T x_1(t) x_2(t + \tau) dt \]
From the previous figure, the correlation is dependent on the similarity of the two signals to get a good ‘sharp’ correlation peak.

Sometimes peaks are not so sharp... may be very wide which affects accuracy of the locate.

Why?
Advanced Correlation 2

- Signals change as they travel through the pipe, may travel different distances
- Different fittings may have different dynamic response to the leak noise
- This can affect plastic pipes more than metallic
Advanced Correlation 3

• There is a measure of how similar the two signals are at the two sensors
• This is called ‘Coherence’
• Coherence is a measure of the similarity of the two signals
• When two signals are identical coherence is 1
‘Normal’ Correlation
Wide Correlation

Leak position is 51.7 ft from Blue station and 145.3 ft from White station, Time Delay = 0.03338 s
Physics of PVC and Large Diameter Pressure Waves

- Need to understand the wave mode: Water Hammer
- Advantage of PVC is that it damps water hammer: Not Good
- Coupled mode: Compression wave in water, circumferential mode in pipe
- Frequency: As will be seen, very low, in some cases subsonic
Wavelength

- Leak Sound in PVC has a very long wavelength
Wavelength in 6” PVC

Speed of Sound in Water (10 C): 1447 m/s

\[ \lambda = \frac{v}{f} \]

Wavelength in water at 10 C,

\[ f = 20 \text{Hz} \]

\[ \lambda = \frac{1447}{20} = 72.4 \text{m} \]
Physics of PVC and Large Diameter Leak Detection

• Need to understand the wave mode: Water Hammer
• Advantage of PVC is that it damps water hammer: Not Good
• Coupled mode: Compression wave in water, circumferential mode in pipe
• Frequency: As will be seen, very low, in some cases subsonic
Impedance

Reflection of Waves (Impedance): The rope analogy
Causes of Impedances

- These changes are called impedances in Physics, and can be caused by:
  - VALVE KEYS
  - 90 degree turns
  - Change in diameter
  - Change in material
Classic Impedance Example
Hydrophone Mounting
Case Study 1: 200mm PVC, Leak on Service Saddle; Correlation Function
Case study 1: Coherence Function

Leak Position from Blue Station: 79.5 meters, Time Delay = -0.08063 seconds

Fleming161204_PVC_200mm_122m_L...

PVC
200 mm
122 m
459 m/s
23
Case Study 2: 250mm PVC, Abandoned Service
Case study 2: Coherence
Case Study 3: 200mm PVC Service Leak
Case Study 3: Coherence

Leak position is 290.3 ft from Blue station and 55.1 ft from White station, Time Delay = -0.10200 s
Case Study 4: Same as 3, service to hydrant
Case Study 4 Coherence
Case Study 5: 8” PVC Service Leak
Case Study 5: Coherence

Leak position is 378.6 ft from Blue station and 175.4 ft from White station. Time Delay = 0.13568 s

Demursage Groove 954 ft leak at... PVC 0 in 554 ft 1695 ft/s 29
Case Study 6:

Leak position is 303.9 ft from Blue station and 410.1 ft from White station. Time Delay = 0.02667 s.
Case Study 6: Coherence
Case Study 7: 500mm CI

Leak position is 9.7 m from Blue station and 68.8 m from White station, Time Delay = 0.00413 s

Baton Rouge to Catherine 900 C... Cast iron | 580 mm | 30.5 m | 1110 psi | 75
Case Study 7: Frequency Spectrum