Research into Seismic Response of Underground Utilities

- Information Gathering
- Physical Testing
- Finite Element Analysis
- Local Government Act 2002 Amendment Bill (No 3)
- Infrastructure Strategy

- Provide for the resilience of infrastructure assets by identifying and managing risks relating to natural hazards
Guidelines to Improve Resilience

- How will the system behave immediately after an earthquake?
  - How much damage might occur?
  - Where is it likely to occur?
  - How will damage affect system performance?
- How to improve resilience?
  - Reduce vulnerabilities in the existing system?
  - Make new parts more robust?
- How do we integrate resilience into asset management?
Key Findings
Extensive Cost to Rebuild Water Networks

- Potable water – NZ$ 100 M
- Stormwater – NZ$ 800 M
- Wastewater – NZ$ 1 B
Damage Contained to Parts of City
Performance of the Ground is Key
Ground Causes Damage & Blockages
• Ground Conditions Make Repairs Difficult
Liquefaction Can Be Predicted
Lateral Spread Makes Things Worse
Longitudinal Forces Caused Most Damage
Watch out for Discontinuities
We Can Estimate Break Rates

- Break Rates
  - Non-liquefied – increase as PGA increase
  - Ground conditions have bigger impact than PGA up to 0.8g
  - Lateral spreading break rate is double that of liquefied zones
PVC is More Resilient

- Break Rates
  - Similar break rates for non-liquefied and liquefied ground
  - Break rate within 0.1-0.2 breaks/km target
  - Break rate in lateral spread area roughly in line with average for all materials
Effect of Distance From River

- Break Rates
  - decrease with distance from river bank in liquefied zones
Modern Materials Are Resilient
- Concrete

Conclusions
- Form of failure similar to that observed in field
- If rubber ring install incorrectly socket fails at 46kN
- If installed correctly socket can sustain more than 1,000kN
Modern Materials Are Resilient - PVC

Conclusions

- Smaller PVC pipes and ducts with spigot and socket joints can survive compressive displacements of several hundred mm without failure, although performance and useful life are compromised.
- Buckling and bending that does not cause failure may retain some serviceability.
- Larger pipes are more resilient.
Modern Materials Are Resilient - PE

Conclusions

• Few EF joints failed.
• If the joint is so poor as to be a weak point, pre-commissioning test failure or in-service failure before an earthquake would be expected.
Service Pipe Connections

Conclusions

- All service pipes are vulnerable to ground movements and displacements
- Fittings are most vulnerable.
Service Pipe Connections - PE

Conclusions

- PE can accommodate tensile deformation better than any other material up to a point
Conclusions
  • Connections are vulnerable
Service Pipe Connections - PE

- Resilience increased by:
  - Snaking pipes
  - Fully end load resistant joints
  - Inserts in mechanical connections
• Estimate of Restoration of Service

- Earthquake Intensity vs Chemical Toilets & Portaloos

No chemical toilets were delivered or no data recorded for chemical toilets deliveries after the Sep 2011 EQ but nearly 30,000 chemical toilets were delivered since Feb 2011 EQ. A slight peak of chemical toilet deliveries happened after the Jun 2010 EQ. This trend agrees with the results shown in the water quality parameter plot, i.e., the Feb 2011 EQ caused significantly more damage to the wastewater system than other EQs.

Disposal tanks for chemical toilets were removed starting Oct 2011, which coincide with the time when the number of portaloos start to decrease, indicating the recovering of the wastewater system. The date of tank removal however could be later than the actual dates of wastewater system recovering time.

More portaloos were used after the Feb 2011 EQ and they stayed in use for longer, suggesting a slower recovery (more extensive damage) of the wastewater system compared to the Sep 2010 EQ.
We Can Predict:

- How much damage might occur
- Where is it likely to occur
- How long it will take to repair

Modern materials provide good level of resilience in most locations

But How Do We Increase Resilience
Service is Key
It is all About People

<table>
<thead>
<tr>
<th>Need</th>
<th>Addressed through provision of</th>
<th>Water directly needed</th>
<th>Water indirectly necessary to support provision at local sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>Unpolluted air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>Clean water for drinking and cooking</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Food</td>
<td>Adequate supplies of nutritious and non-poisons food</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Shelter</td>
<td>Protection from wind, cold, and rain</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Security</td>
<td>Protection from threats to the person or property</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hygiene</td>
<td>Protection from infectious disease or contagious disease and from toxins and pollutants</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Education</td>
<td>Socialisation in the skills and information needed in a given society</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Healing</td>
<td>Care and treatment for the sick and infirm</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Housekeeping</td>
<td>Resources for food storage and preparation, cleaning (of people, clothes, and waste), waste disposal</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Work</td>
<td>Gainful labour</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Means of exchange</td>
<td>Money, credit, or other forms of trading power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Information</td>
<td>Access to prevailing media of information and communication (books, newspapers, postal and telecommunications services, etc)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td>Private and public transport, roads, railways, etc</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Personal relationships</td>
<td>Family life, intimate relationships, acquaintance and friendship networks</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Religious</td>
<td>Spiritual or ritual practices</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Involvement in group activities</td>
<td>Participation in political, social, or economic activities</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Play</td>
<td>Social, cultural, and physical recreation</td>
<td></td>
<td>✔</td>
</tr>
</tbody>
</table>
## Level of Service

<table>
<thead>
<tr>
<th>Purpose of LOS</th>
<th>Amount, Quality</th>
<th>Location, user supplied</th>
<th>Duration</th>
<th>% City</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of Life - Firefighting</td>
<td>SNZ PAS 4509:2008</td>
<td>Priority locations</td>
<td>Immediately</td>
<td>All</td>
</tr>
<tr>
<td>Emergency Response</td>
<td>20l/p/d*</td>
<td>Civil defence centres, Emergency service centres</td>
<td>2 days**</td>
<td>All</td>
</tr>
<tr>
<td>Care of injured &amp; elderly</td>
<td>60l/p/d, potable</td>
<td>Hospitals, Age care centres</td>
<td>3 days**</td>
<td>All</td>
</tr>
<tr>
<td>Drinking, cooking, basic hygiene</td>
<td>20l/p/d*</td>
<td>Within 500m households</td>
<td>3 days**</td>
<td>90%</td>
</tr>
<tr>
<td>Loss of life, emergency response – fire fighting</td>
<td>SNZ PAS 4509:2008</td>
<td>Relocation centres, Civil defence centres, Emergency service centres, Hospitals, Age care centres</td>
<td>3 days</td>
<td>All</td>
</tr>
<tr>
<td>Community spirit, Education</td>
<td>Potable water at pre-earthquake quantity, firefighting at SNZ PAS 4509:2008</td>
<td>Schools</td>
<td>15 days</td>
<td>90%</td>
</tr>
<tr>
<td>Housekeeping</td>
<td>70l/p/d, potable</td>
<td>Households</td>
<td>30 days</td>
<td>90%</td>
</tr>
</tbody>
</table>
Framework for Improving Resilience

1. Set Target Levels of Service
2. Vulnerability Assessment (where will system be affected)
3. Estimate Restoration Times (how long system affected)
4. Identify where Levels of Service are not achieved
5. Identify & Prioritise Resilience Projects & Recovery Actions
Guidelines – Vulnerability Assessment
Vulnerability Assessment

1. Assess earthquake ground motions
2. How will the ground respond
3. Classify underground utilities
4. How will underground utilities behave
5. How will system performance be affected
6. Estimate post event levels of service
Assess Earthquake Ground Motions

- Estimate parameters for the design earthquake and derive Peak Ground Accelerations (PGA) and earthquake magnitudes
  - From the *NZS 1170.5:2004* (Standards New Zealand, 2004) and the *Bridge Manual SP/M/022* (NZTA, 2016).
  - Alternatively estimate from an earthquake scenario, based on attenuation relationships.

- Predict how ground will respond
Assess Damage Rates – Pressure Pipes

<table>
<thead>
<tr>
<th>Description</th>
<th>Laterals (service connections)</th>
<th>Mains</th>
<th>Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>40mm &amp; below</td>
<td>Above 40mm but under 200mm</td>
<td>200mm &amp; above</td>
</tr>
<tr>
<td>System</td>
<td>Galvanized Iron *1</td>
<td>Other systems *2</td>
<td>Flexible *3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rigid Segmented *4</td>
</tr>
<tr>
<td>Shaking Only</td>
<td>$4 \times \text{Equation 2}$</td>
<td>3</td>
<td>2 Equation 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2 Equation 2</td>
</tr>
<tr>
<td>Liquefaction *5</td>
<td>55</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Lateral Spread</td>
<td>90</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>55</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>Fault Crossing</td>
<td>Assume failure at crossing unless utility has been specifically designed.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope Failure</td>
<td>Assume failure unless utility has been specifically designed *6.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
\text{Damage rate} \left[ \frac{\text{breaks}}{10km} \right] = 17.6 \times \text{PGA} [g] - 1.6
\]
Gravity systems can remain functional when damaged so damage has been categorised as:

- **Restoration** – damage that will stop the system from functioning and will need to be repaired to restore a functional service
- **Reinstatement** – further damage that may not need to be repaired to enable the system to function but is required to be repaired to reinstate the system to its pre-earthquake condition
# Gravity Pipes – Restoration Damage

<table>
<thead>
<tr>
<th>Ground Conditions</th>
<th>Pipeline system</th>
<th>Damage Rate (Breaks/10km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaking only (for PGA in range of 0.2 – 0.3 g)</td>
<td>All</td>
<td>Nominal, 0.3</td>
</tr>
<tr>
<td>Liquefaction</td>
<td>Rigid, segmented AC &amp; EW (older systems ¹)</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>Rigid, segmented RCRRJ</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Flexible, segmented PVC</td>
<td>20</td>
</tr>
<tr>
<td>Lateral Spread</td>
<td>Rigid, segmented AC &amp; EW (older systems ¹)</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>Rigid, segmented RCRRJ</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>Flexible, segmented PVC</td>
<td>50</td>
</tr>
<tr>
<td>Fault Crossing</td>
<td>Assume failure at crossing unless utility has been specifically designed.</td>
<td></td>
</tr>
<tr>
<td>Slope Failure</td>
<td>Assume failure unless utility has been specifically designed ².</td>
<td></td>
</tr>
</tbody>
</table>
## Gravity Pipes – Reinstatement

<table>
<thead>
<tr>
<th>Ground Performance</th>
<th>Pipeline Material</th>
<th>Frequency of works to reinstate condition</th>
<th>Spot Repair (Breaks/10km)</th>
<th>Relay / Rehabilitate (% by length)</th>
<th>Dip (&lt;25%) (% by length)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaking only (for PGA in the range of 0.2 – 0.3g)</td>
<td>Rigid, segmented AC &amp; EW* (older systems)</td>
<td>9</td>
<td>6%</td>
<td>Minimal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rigid, segmented RCRRJ</td>
<td>1</td>
<td>0.6%</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flexible, segmented PVC</td>
<td>0.5</td>
<td>Minimal</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>Liquefaction</td>
<td>Rigid, segmented AC &amp; EW (older systems (Note 1))</td>
<td>35</td>
<td>40%</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rigid, segmented RCRRJ (modern systems)</td>
<td>12</td>
<td>10%</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flexible, segmented PVC</td>
<td>3</td>
<td>Minimal</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>Lateral Spread</td>
<td>Rigid, segmented AC and EW (older systems (Note 1))</td>
<td>-</td>
<td>100%</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rigid segmented RCRRJ</td>
<td>-</td>
<td>40%</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flexible segmented PVC</td>
<td>-</td>
<td>5%</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>Fault Crossing</td>
<td>Assume that utilities at crossings will have been repaired to restore service.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope Failure</td>
<td>Assume failure unless utility has been specifically designed.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Guidelines – New Installations
Process for Design of New Installations

- Establish Importance Level and Design Earthquake Parameters
- Assess ground performance
- Locate Utilities to avoid hazards and risk of consequential damage
- Establish maximum tolerable break rates
- Establish Design Method
- Design utility
Design Priorities

- Reduce exposure
- Reduce the impact of damage
- Increase Repairability
- Reduce likelihood of damage (robust utilities)
- Reduce the impact on service (redundancy)
## Sophistication of Design Method

<table>
<thead>
<tr>
<th>Importance Level</th>
<th>Design Method</th>
<th>Acceptable Solution</th>
<th>Equivalent Static Load</th>
<th>Finite Element Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1 &amp; 2 (Connections and Distribution)</td>
<td></td>
<td>√</td>
<td>√¹</td>
<td></td>
</tr>
<tr>
<td>Level 3 (Trunk)</td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Level 4 (Lifelines)</td>
<td></td>
<td></td>
<td></td>
<td>√²</td>
</tr>
</tbody>
</table>
Acceptable Solutions – Ground Shaking Only

- Utilities installed in accordance with NZS 4404 are acceptable solutions
- Where mechanical couplings are used on PE water pipe it is recommended for an insert or stiffener be used
Acceptable Solutions - Liquefaction

- Avoid if practical
- Locate utilities where they can be easily accessed for repair
- Do not install utilities deeper than 3.5m
- Do not install connections deeper than 2.5m
  - Where sewers are deeper than 2.5m, laterals can be routed to manholes, collector or rider sewers.
  - Alternatively, collector sewers for connection of laterals can be installed above the main sewer.
Acceptable Solutions – Liquefaction – Gravity Pipes

- Wrap pipe joints
- Install pipes as steep as practical
- Consider using other technologies such as pressure or vacuum sewer
• Fault Crossings, Landslides and Areas of Lateral Spread

• Avoid wherever possible. Assume utility will be damaged by earthquake

• Specifically design pipes to withstand the expected seismic loads using the equivalent static method

• Use flexible continuous pipelines

• Locate utilities as far away as practical from other services or structures.

• Locate utilities where they can be easily accessed for repair,

• Do not install utilities deeper than 3.5m. Do not connect laterals to main pipes in areas subject to faults, landslide or lateral spread

• Consider installing flexible couplers to provide fuses

• Install additional services away from the area of high vulnerability to provide redundancy
Connections to Structures

- Reduce the movement of the structure by:
  - Locating the structure in a position where it is not vulnerable to earthquake induced ground movements.
  - Undertake ground improvements or found the structure on piles.
- Install isolation valves inside the structure itself and ideally a second isolation point located away from the structure on stable ground.
- Make the connection at the wall of the structure more robust than the connecting pipeline.
- Use flexible continuous pipelines to accommodate vertical and horizontal movements.
- Make the connection as shallow as practical.
- Over-steepen gravity inlet pipes.
Manholes

Important factors covered in *NZS 4404:2010* that reduce the risk of manhole floatation are:

- A manhole base that extends beyond the manhole riser
- Permeable backfill to reduce pore water pressures and therefore the risk of floatation
- Rocker pipes at each side of the manholes to accommodate movement
Performance of the ground is key

- Ground performance has big impact on pipe performance
- Liquefaction and lateral spread cause:
  - increased break rates
  - increased blockages
  - increased time to restore service
- System is damaged less and can be restored quickly if not in an area that liquefies
- Modern Material Offer Good Resilience

- Less joints less damage
- More flexible less damage
- PVC damage not affected by liquefaction
- All pipes types are damaged by lateral spread
- Good installation is key
  - Use inserts in PE lateral pipes
  - Install rubber rings in concrete pipes correctly
  - Avoid discontinuities
  - Avoid voids in backfilling
All Pipes Will be Damaged

- Avoid areas of liquefaction and lateral spread
- Reduce depth of pipes/connections in liquefied areas
Post Event Level of Service

- Communication tool to explain the network status to communities and their leaders.
- A tool to plan response & capital improvements
- A management tool for asset managers to explain why investment is needed
- An aid to tracking recovery to normal Levels of Service after seismic event.
Questions