UNDERSTANDING SERVICE PIPE RESILIENCE

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ABSTRACT

Service connections are the neglected cousins of utility services. But while failure of an individual service connection may cause little more than an isolated inconvenience, the sheer number of service connections and their importance in connecting service users to the main system means that a seismic event has potential to cause widespread service disruption that has an immediate impact on the public, on service users and on service providers.

Detailed assessment of several thousand contractor repair records from New Zealand has helped reveal how and where different customer connections failed in actual seismic events. The interpretation of these findings has been supported by selected laboratory testing and modelling to better understand how the observed damage occurred and to what extent it can be managed or avoided.

The findings revealed some unexpected patterns of behaviour and required a rethink of previous understanding of the role of materials selection, design and installation practices on connection resilience. The improved understanding of what really happens between the network and the customers will contribute to practical guidance that is being prepared to assist asset managers and other industry practitioners improve system resilience as part of this research programme.

KEYWORDS

Resilience, service pipelines, research, industry guidance

1. BACKGROUND

Service pipes connect properties to the distribution system and are typically the smallest and weakest components in the system. Because service pipes connect to individual properties, failure of an individual service pipe, while inconvenient to the customer, is only rarely a major issue. In contrast, large-scale failure during seismic events has potential to cause a more major problem. In aggregate, hundreds or thousands of individual breaks can result in considerable loss of water from the system, and take substantial effort to track down and repair, while leaving many thousands of customers without a water supply.

2. SERVICE PIPE CHARACTERISTICS

Service pipes are properly defined by function, but they also differ from distribution lines by size, materials and installation characteristics.

- Most service pipes are small, typically <DN40, although connections for individual commercial users may be larger;
- The range of materials used may differ from those used for distribution pipelines, although there is some overlap with smaller sub main sizes. Often a mix of materials will be used;
- Service pipe connections often include a mix of different materials, typically are jointed using mechanical couplings and may include complex geometries (Figure 1);
- Responsibility for the system changes at the customer boundary. While the pipeline characteristics usually remain very similar materials and fittings used inside the boundary may differ from those used outside the boundary (Figure 2).

Figure 1. Complex geometry and mixed materials (Citycare).
The low image quality is due to use of a camera phone.

Figure 2. Complex geometry and multiple systems and materials (Citycare)

Figure 3. Fractured injection moulded compression fitting elbow showing mixed materials (Citycare).

Figure 4. Leaking PE or PP bodied compression fitting on PVC pipe, Masterton. (Citycare).

3. SERVICE PIPELINE BEHAVIOUR

Older service pipes made of copper or galvanized steel can corrode but modern plastic pipes generally do not (Figure 4). This means that failures in the pipe barrel are inherently less likely in a modern system than in a more traditional one. Typical reported figures indicate that in normal service 60% or more failures in plastic pipes occur at joints rather than in the pipes (Bjorklind, 1994).

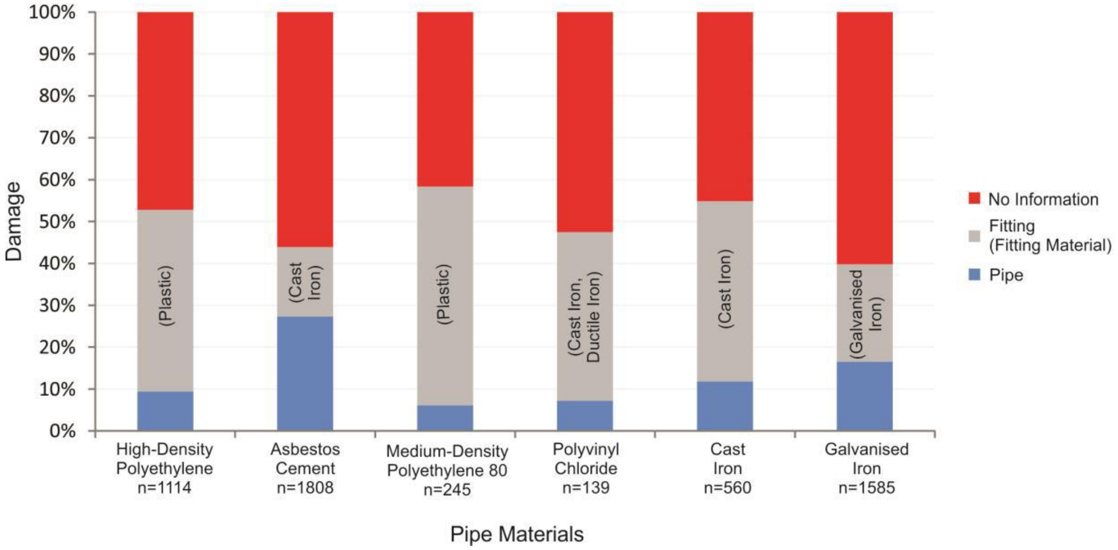
Figure 5. Perforated copper pipe leaking next to stop tap. Citycare.

A similar picture emerges from earthquake damage reports. Cubrinovski et al, 2014 reported that following the Canterbury earthquakes 80 to 90% of failures in PE service pipes occurred at joints rather than in the pipe barrel. Galvanized steel was the only service pipe system in which more failures were observed in the pipe than in the fitting. The Eketahuna event in 2013 was much smaller and caused only limited pipeline damage but six cases of damage were reported in service pipe fittings and none in the pipes (Erasmus, 2014).

Records provided by SCIRT showed approximately 2,400 service pipe failures in Christchurch, and work by Canterbury University (Cubrinovski et al, 2014) tells a similar story. The numbers are uncertain, both because the description of service pipes can differ according to sources used, and because in some cases the repair of a main or sub main will have resulted in replacement of defective service pipes that were, consequently, not counted.

In addition, information collected during a major emergency is often incomplete, sometimes because records are poor but mostly because repair teams have more pressing priorities and are working under some of the most demanding conditions imaginable (Tromans, 2004). Cubrinovski's work (Cubrinovski et al, 2014) notes that around 21% of 6,094 damage repair records for pipes of all sizes specified pipe damage, 35% specified fitting damage and the remaining 44% contained no useful information (Figure 6).

Figure 6. Major damage categories for different pipe materials through the Canterbury Earthquake Sequence over the period 4 September 2010 to 30 June 2012. The dominant fitting materials used for each pipe material are noted in parentheses.
(Figure 19 from Cubrinovski et al, 2014)



In the case of the PE pipes, of which many are service pipes, the proportion of pipe failures against fittings failures is much lower than the average for all materials, although there is still a high proportion of incomplete records.

These figures show two key points:

- Firstly that the number of failures in an earthquake far exceeds normal expectations;
- Secondly that the type of the proportion of failures in joints and pipe barrels is broadly similar to that seen in normal service.

4. RESISTANCE TO FAILURE

Photographs of damage service pipes taken after earthquakes show a variety of damage. In PE and PVC pipes, the fitting itself may be broken or the pipe deformed in tension, bent or compressed and in other cases the joint leaks without failing (Figures 7 to 10). Metal service pipes also showed fracture at threaded joints and leakage where corrosion product that was formerly blocking a perforation had been dislodged (Figure 5).

Figure 7. Fractured compression fitting elbow on blue PE pipe (Citycare).

Figure 8. Fractured threaded fitting (Citycare)

Figure 9. Leaking compression fitting assembly (Citycare)

Figure 10. Damaged compression fitting assembly (Citycare)

While a displaced joint or damage to the pipe barrel that causes leakage is undesirable, it is far worse to have a fracture of the fitting or for the pipe to pull out of the joint, since the service is lost instead of degraded and the loss of water is much greater. The ability to transfer the load from the fitting into the pipe would eliminate the risk of fitting fracture and pipe pull out. Transfer of the load from the fitting to the pipe barrel would also allow the barrel of the pipe to accommodate any displacement.

While the first two forms of deformation will cause some reduction in serviceability, only the third will cause failure, so we would expect to see mostly tensile failures with hyper extension, many fewer cases of hyperextension without failure and almost no cases of recoverable failure.

Where was tensile failure in PE pipes and ducts, (Figure 11 and Figure 12), not all of these showed hyperextension (Figure 13). The initial explanation was that the presence of water constrained the ability of the PE to deform freely, reducing the effective ductility. The ability to accommodate deformation can also prevent fracture in compressive or bending failures (Figure 14).

Figure 11. Tensile failure of black PE service pipe with hyper-extension in Christchurch following one of the seismic events (Citycare). Note that the date on the camera setting is clearly incorrect as it predates the first of the events.

Figure 12. PE100 telecommunications cable duct yielded and hyper-extended to failure. (Frank O'Callaghan, Iplex)

Figure 13. Tensile failure of black PE pipe without gross extension.

F14. Severe bending in PE80 service pipe. Despite being effectively closed off, the pipe has not failed.

The ability of a pipe joint to resist pipe pull out under tension is described as the end load resistance. Three levels of end load resistance have been defined based on the maximum loads that can arise from particular causes (IGN 4-08-01, 1998).

- Type 1 end load resistance describes the case where the joint is stronger than the pipe so that the pipe will fail before it pulls out. These fittings will transfer load and thus displacement into the attached pipe;
- Type 2 end load resistance allows the joint to withstand all normal service loads (including pre-commissioning testing). These fittings will not necessarily transfer loads to the attached pipes but there is a possibility that this will occur to some extent;
- Type 3 end load resistance describes any lower level of end load resistance. While some Type 3 fittings may resist normal service end loads, there is no guarantee of this, and since loads are not transferred to the pip, excessive loads or displacements can cause the pipe to pull out.

While full end load resistance can be achieved in service-pipe sizes through use of an insert that is easily installed, it becomes increasingly difficult to achieve at larger pipe sizes, so that the fittings become larger, heavier and more difficult to assemble, and more expensive.

The following joint types can be considered to be fully end load resistant as they effectively transform individual pipes into a continuous pipe:

- Fusion jointed PE80 and PE100 (whether jointed by butt fusion or electrofusion);
- Solvent cemented PVC;
- Butt welded steel pipe.

In normal service, well made fusion joints have a low incidence of failures. In the 1980s, typical PE pipe joint failure rates were estimated at 2 to 3 failures per 10,000 joints and a separate study in the 1990s indicated a similar rate for fusion joints (Morris, 1994). Many of these joint failures, were identified during acceptance testing and were repaired before the line went into service, so the in-service failure rate was estimated to be lower at around 2 to 3 per 100,000 joints. These low in-service failure rates are matched by very low reported failure rates in fused PE joints in both gas and water systems following seismic events.

Plastic pipes in general and PE in particular can accommodate high levels of tensile strain PE pipes can easily accommodate recoverable tensile strains of 5% and 20% strain is unlikely to cause failure. This strain capacity allows the pipe to accommodate substantial displacements of around 200 mm/metre of pipe which would allow a 6 m connection to accommodate a displacement of around 1 m.

Displacements of around 200 mm would easily pull most pipe joints apart and there was clear evidence of this level of displacement and joint pull out failure in the Canterbury Earthquake Sequence (Morris et al, 2014). In addition, once PE pipe starts to yield it can also accommodate considerable displacement through non-recoverable deformation (Figure 11 and Figure 12). Observations indicate that post-yielding extensions of the order of 100 mm can be accommodated and that failure rarely occurs at less than 200 mm of extension.

Tensile loading of a PE pipe in an end load resistant fitting is thus expected to have the following effects:

1. Displacement is transferred over a considerable length of the pipe (Morris et al, 2014) Initially this will take the form of recoverable extension of the pipe. If the pipe does not yield, then over time, the pipe will revert to its original dimensions, the stress will be relieved or some combination of the two will occur.
2. If the strain exceeds the recoverable strain limit so that yielding occurs, then the pipe will start to extend locally at the point of yielding. If it does not fail, the pipe will retain an elongated section, which will affect its serviceability through reduced capacity and increased headloss.
3. If the local yielding exceeds about 100 mm, the pipe may fail.

A testing programme was conducted to compare the response of DN25 PE80 pipes to tensile loading with different internal conditions. Standard compression fittings from a local supplier were used to attach the water connections and to apply load.

The initial tests all resulted in pull out of the pipe from the fittings. A quick inspection showed that these had been supplied without inserts (Figure 14). Further enquiries revealed that there was widespread confusion over the difference between an insert and a grip ring. Inserts were obtained and installed and while the peak loads were similar, there was no further pull out from the fitting.

Figure 15. Components of a Plasson DN 25 straight coupler.
From left: grip ring, Collar, insert, fitting body.

The test proceeded as follows:

- PE80 service pipe with mechanical couplings as supplied;
- PE80 service pipe with mechanical couplings and end-load-resistant inserts;
- PE80 service pipes with mechanical couplings and inserts and filled with water;
- PE80 service pipes with mechanical couplings, inserts and water under mains pressure;
- PE80 service pipes with mechanical couplings inserts and filled with dried beach sand.

The results (Figure 16) can be summarized as:

- Testing with standard fittings without inserts resulted in failure of the joint, and all pipe samples pulled out of the coupling.
- Testing with standard couplings and inserts resulted in drawing down of the PE pipe, and the connection remained sound – the fittings with inserts were fully end load resistant;
- When filled with water, the PE pipe drew down, and there was no leakage;
- When filled with water under pressure, the pipes drew down and there was no leakage. The reduction in diameter was slightly less than in the other tests.
- When filled with sand, the PE pipe drew down but the reduction in diameter was less than in the other cases.

Figure 16. DN25 PE80 service pipe assemblies after testing.
The top as tested is next to the 300 mm ruler. From the left:
No insert, empty pipe; Insert, empty pipe; Insert, water but no pressure;
Insert, water at mains pressure; Insert, dry beach sand.

The peak loads for all tests were similar at around 4 kN, except that pull out occurred between 2 and 4 kN. The presence of water under pressure and the dried beach sand resulted in a smaller reduction in diameter where draw down occurred but did not change the form of failure or the peak load.

The tests showed that while internal pressure (or a non-deformable filling) can limit the scope for drawing down of the pipe by constraining the ability of the pipe wall to flow on the inside face, the effect is marginal, and considerable deformation was still able to occur to an extent where the serviceability would be degraded.

Although the original intention of reproducing failure with limited ductility was not met, a clear message emerged: use of inserts allows large displacement to be transferred from the connection to the pipe. Because PE 80 pipes can experience substantial deformation without failure, use of end load resistant fittings helps retain service integrity even where there is permanent displacement in excess of 100 mm or more.

While considerable displacements can be expected where there is ground movement, there is also evidence from pipe failures and from seismic monitoring stations that shaking displacements with an amplitude in excess of 200 mm occurred in the Canterbury events (Morris et al, 2014).

5. IMPLICATIONS

Without end load resistance, PGD and larger amplitude shaking has the capacity to cause a service pipe to pull out of the fitting. This creates a break, which results in:

- loss of water;
- loss of customer service; and
- a need for repair.

Transferring displacement from the fitting into the body of the pipe preserves the integrity of the joint and allows service connections to remain functional even where there is considerable ground displacement.

Where a fully end-load resistant fitting is used, the displacement is transferred to the body of the pipe which can then accommodate recoverable deformation of the order of 20% before yielding.

Even when this recoverable strain limit is exceeded, testing showed that DN25 PE80 pipes can exhibit considerable extension in excess of 100 mm without failure.

The reduced diameter will reduce the carrying capacity and increase headloss, while the orientation and pipe wall thinning are likely to reduce the overall useful life and repairability. However, there is no loss of water; customer service is reduced rather than lost; and the need for repair is deferred rather than being immediate. All of these are clearly beneficial in the aftermath of a seismic event.

Standard good installation practice for service pipes includes taking a connection off a pipeline at an angle and snaking the pipe into the trench (Figure 13). This allows thermal expansion and contraction and minor ground movements to be accommodated by movement within the curved section of pipe and also provide some resistance to third parties snagging the pipe during excavation and other works. These practices complement the use of end load resistant fittings by increasing the ability to accommodate some of the displacement, but is unlikely alone to provide a significant reduction in the incidence of service pipe failures as a result of seismic events that include substantial ground movement.

Service pipe fittings can be made fully end load resistant simply by using an insert. These are readily available from suppliers at minimal cost, and are easy to install. There is minimal increase in installation time and their use may possibly result in a marginal reduction through making it easier to achieve a seal on the pipe.

A small component that costs less than $1/fitting has the capacity to provide a considerable improvement in retaining customer service following a seismic event, with consequential benefits to restoration times, public health and provision of fire fighting services. While retrofitting is not practice, all new connections should be made using inserts or other fitting systems that are confirmed to provide full end load resistance.

6. CONCLUSION

Fully end–load resistant fittings allow deformation and displacement to be transferred from the connection into the body of the pipe. While all well-made fused joints are fully end load resistant, fused joints in a mechanical coupling, full end-load resistance can only be achieved by use of inserts.

The use of inserts in mechanical couplings provides a substantial increase in the resilience of service pipe connections for marginal cost and with negligible impact on installation times.

Existing good installation practice complements the use of inserts but provides only limited resilience in its own right.

While use of inserts will substantially reduce the likelihood of failure due to ground movement, severe deformation has the capacity to degrade serviceability to an extent where replacement will be required. However, the fact that the connection remains intact and can provide some service (however limited) means that replacement can be deferred until after the immediate crisis has passed.

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