# RESEARCH FINDINGS ON THE SEISMIC RESPONSE OF UNDERGROUND UTILITIES

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## ABSTRACT

This paper will report on recent findings from MBIE funded research into the seismic response of underground utilities. This research programme builds on work done in the reconstruction following the Canterbury earthquakes with a specific goal of promoting evidence based guidance across New Zealand. The work is presently in the second year of a four year programme.

This paper mainly focuses on improvements in the understanding of how modern materials respond to earthquake loading, which in turn provides the foundation for more robust predictive modelling. It also explores the contribution that sub-critical damage makes to the overall impact of earthquake damage.

Sub-critical damage either degrades performance without causing failure or results in delayed failure. Because sub-critical damage can require delayed expenditure and is not immediately apparent, understanding which systems it can and can’t affect and what influences its occurrence can help improve asset management and reconstruction planning decisions.

The results will, ultimately, be used to provide improved industry guidance to assist asset owners and managers improve overall system resilience as an integral part of good asset management practices.

## KEYWORDS

**Underground utilities, pipelines, earthquake, testing, numerical analysis**

## 1 INTRODUCTION

Written records of earthquakes in New Zealand date back to 11 May 1773 and are preceded by oral histories and myths (Grapes, 2000). While earthquakes cannot be prevented, studying their effects can help to identify how to improve community resilience by identifying how to minimise damage or speed recovery.

The results described below have been developed as part of a research programme funded by the Ministry for Business Innovation and Enterprise (MBIE). The programme, described in more detail in McLachlan et al (2013), essentially provides an opportunity to build on the findings of the immediate recovery and reconstruction works so as to provide enhanced understanding of the performance and resilience of underground utilities under seismic loading.

Although the work discussed here was initiated in response to the Canterbury events of 2010 and 2011, it also draws on other New Zealand events and on studies from around the world.

## 2 CAUSES OF SEISMIC DAMAGE

Earthquakes damage buried structures through several mechanisms including the interaction of the seismic waves with the buried structures and through permanent ground deformation (PGD). PGD includes fault movements, lateral spreading resulting from liquefaction, landslips and other changes in ground level. While fault movement causes severe damage along the fault lines, liquefaction is a major problem as the PGD it causes can affect a wide area.

Reported break rates for buried utilities can be up to 10 times greater in ground susceptible to liquefaction and other PGD than in ground subjected only to shaking (Cubrinowski et al, 2014, O' Rourke et al, 2012, www.abag.ca.gov, 2002).

While the overall rate of damage is influenced by the presence or otherwise of both shaking and PGD, the specific form of damage resulting is influenced strongly by the orientation of the pipeline relative to the direction of travel of the wave. In simple terms, a seismic wave acting along a pipeline will apply alternating compressive and tensile forces to the line, and may cause local bending, while a perpendicular wave will cause lateral displacement.

Similarly, PGD will apply tensile or compressive forces when oriented along the length of the pipeline and lateral movement where perpendicular to the line. Vertical displacement can also occur where there is liquefaction and subsequent flotation of pipelines and other underground structures or consolidation and subsequent settlement.

## 3 PIPELINE RESPONSE

It is common practice to consider pipeline systems as brittle or ductile, according to the nature of the pipeline material, and segmented or continuous according to the jointing system. These factors influence the ability of a pipeline to accommodate the effects of shaking and PGD.

The use of modern pipeline systems for new construction and in renewals has increased the proportion of ductile systems in service. Some of these systems can exhibit behaviour that is not possible in more traditional pipeline systems. In some cases this simply changes the detail of how the buried system fails, but there are cases where the system response is changed so that the system performance is degraded without causing complete loss of service (Morris et al, 2015).

Sub-critical damage that results in some remaining serviceability is not exclusive to modern materials, and has been reported previously in earthenware and concrete wastewater systems in Edgecumbe (Leslie et al, 1987) and in corrugated metal culverts in Northridge (Davis and Bardet, 1999).

However, inherently ductile materials have a greater ability to accommodate deformation without actual failure which increases the range of conditions under which sub-critical damage can occur. Thus the extent of sub-critical damage can be expected to increase as more modern systems are installed. Some examples of sub-critical damage are given below along with some consideration of its potential influence on resilience planning.

### 3.1 RESPONSE TO TENSILE LOADING

Modern arc-welded steel pipelines with butt welded joints (and to a lesser extend double-welded slip joints) are considered to act as a continuous lines. Modern welded steel gas and other fuel lines are considered very resistant to tensile loads as the tensile strain can be distributed over several hundred metres even where the displacement occurs at a fault (Ballentyne, 2010). There was an example of this behaviour in Edgecumbe, where a DN300 steel gas pipeline crossing a fault line had to be uncovered to relieve stress, but was otherwise unharmed (Leslie et al, 1997).

Modern fused PE pipelines, fused PVC lines and continuous pipe linings, and possibly solvent-cemented PVC with sufficiently well-made joints are also expected to carry tensile strain over a considerable length and to have high tolerance to tensile loads. Numerous reports refer to low earthquake failure rates in PE gas and water pipeline systems (for example, O'Rourke et al, 2012, Morris 1996 to 1998, Flores-Berrones and Liu, 2003).

However, local yielding and subsequent hyper-extension has been reported in Kobe by Japanese engineers (Morris 1996 to 1998) and in unconfirmed reports in Christchurch (O'Callaghan, 2014), although hard evidence of these failures has been remarkably difficult to obtain. Considerable tensile extension has been observed in PE80 pipe assemblies (Morris, 1991 to 1996) and in tests (Figure 1) and is predicted by Finite Element modelling (Figure 2).

*Figure 1: DN25 PE80 service pipe showing substantial elongation after testing. The elongation between the arrows is approximately 300%. The green arrow indicates a secondary yield point. .*

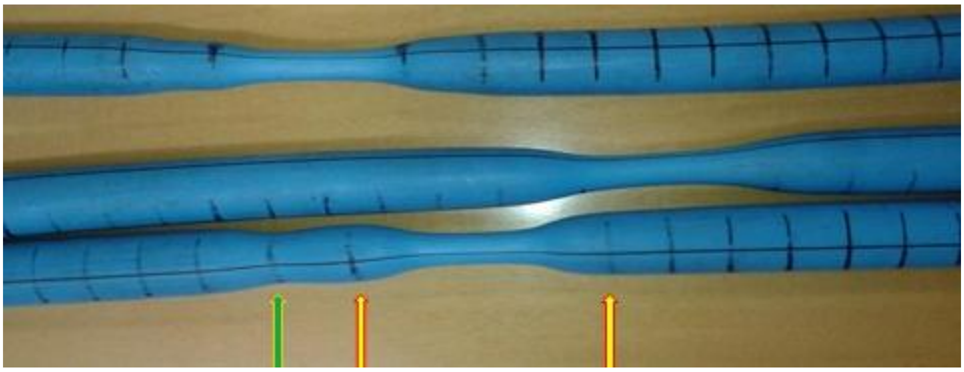
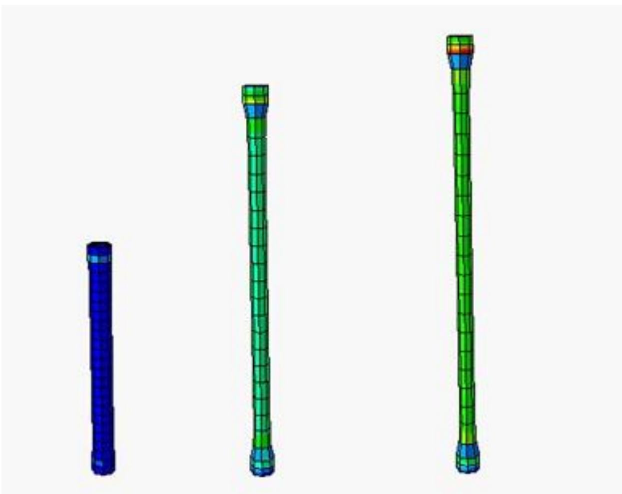


*Figure 2: Finite element model of hyper-extended PE pipeline*



In contrast, segmented pipeline joints are not intended to take substantial axial loads and because there is no mechanism to transmit tensile strain across the joint, the joints can be expected to pull apart in tension (Figure 3).

*Figure 3: Pulled joint exposed to tensile loads*


There are numerous reports of joint separation in spigot and socket jointed systems following earthquakes (for example, Dowrick, 1998, Leslie et al, 1987, Flores-Berrone and Liu, 2003, Cubrinowski et al, 2014). These reports confirm the expectation that tensile strain is not carried across joints. However, moderate displacement over many joints has been observed in more gradual soil settlements and could be expected where PGD occurs over a period of several days or weeks.

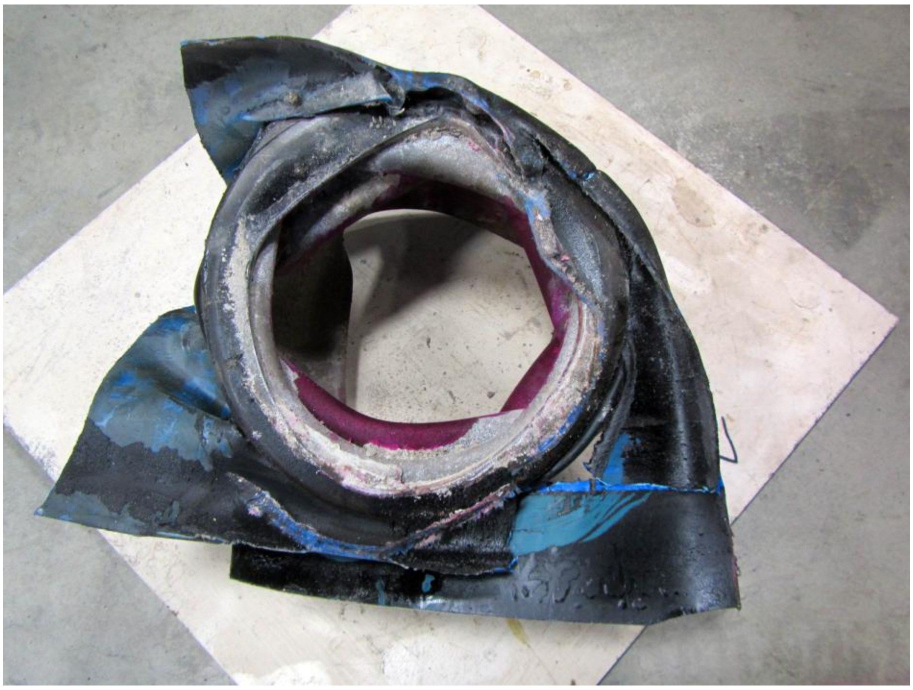
## 3.2 RESPONSE TO COMPRESSIVE LOADING

Under compressive loading, the compressive strain accumulates at the first obstruction and typically causes local failure. Once there has been any deformation, further compressive strain will tend to accumulate at this point. The loads at which bending or buckling occur are essentially the same, and the controlling factor is primarily the cover depth of soil (Eidinger, 1999).

In testing, steel pipelines were compressed by approximately 200 mm along the axis. While this caused substantial loss of the internal cement mortar lining and detachment of the external corrosion protection coating, the welds and pipe wall remained intact despite the substantial deformation (Figure 4). In service, this failure would have substantially reduced the carrying capacity and increased the head loss, and may have resulted in a brief deterioration in water quality, but some service could have been maintained.

It is possible that residents who retained some water supply may not recognise that the flow and pressure were compromised in the immediate aftermath of an earthquake. The effects would be less noticeable if the line had excess capacity to start with or if the effective demand had been reduced by local population displacement or closure of industrial and commercial consumers. While an unprotected steel pipeline in this condition would inevitably corrode leading to perforation, leakage and subsequent failure, this could take several years after the damage had occurred.

*Figure 4: Buckled steel pipe after compression test. The external PE protection and the internal concrete lining are severely damaged but the weld has not failed and the pipe retains some functionality.*



Three laboratory tests on DN160 PE drainage pipes showed two failures in bending and one in buckling at essentially identical loads, but in all cases there was some remaining free bore and in only one case was there evidence of damage that could have compromised longer term performance. There is also evidence that PVC water supply pipelines can retain some serviceability after severe bending (O'Callaghan, 2014). As with the steel pipeline, such damage could potentially go unnoticed, as there is no actual break or loss of service.

This type of sub-critical failure could be beneficial in terms of maintaining some service, but unless specifically looked for, it could easily go undetected for many years after the event. While an isolated case of damage of this type could be repaired quite easily, more widespread occurrence could impose a substantial financial and operational burden many years after any insurance deadlines had passed, and could bring forwards the need for renewals over a considerable portion of the system. The likely scale and implications of this kind of response are not yet understood.

### 3.3 SUB-CRITICAL DAMAGE

Sub-critical damage has been observed in PVC pipelines subjected to compressive loads, in which the spigot of one pipe is forced past the end of the socket and into the body of the neighbouring pipe (Figure 5). This kind of over-insertion can result in fracture of the base of the socket (Figure 5) if the socket lacks the strength and toughness to accommodate the tensile forces applied during over-insertion.

*Figure 5: Over-inserted PVC DN160 pipe during testing (left) and fractured PVC DN200 socket (right). The degree of over-insertion is similar but the DN200 socket which failed during joint assembly could not accommodate the stress resulting from over-insertion.*

While the increased rigidity of a socket on a thicker-walled pipe could potentially increase the risk of socket failure, the likelihood of compressive buckling is higher in a thinner-walled pipe (Figure 6). Work is underway to determine whether there is a convenient optimum range of dimensions in which the risk of actual failure can be minimised.

If there is a sufficiently tight fit between the two pipe barrels, the pipeline may retain sufficient seal integrity for this damage to go unnoticed in the short to medium term that pipe-to-pipe sealing is insufficient to assure acceptable performance in pressure systems in the longer term.

Over-insertion requires a number of conditions which can only be met socketed PVC pipe joints – the spigot is inside a more rigid socket that can guide the spigot into the other pipe, the pipe ends are chamfered, allowing them to be compressed and to more easily pass beyond the base of the socket. The pipe walls are relatively thin and the base material has sufficient strength and toughness to accommodate the initial distortion and resulting loads.

Instead the pipe ends will butt together. Thicker walled pipes and brittle pipes cannot undergo over-insertion because they cannot accommodate the associated deformation. Instead they experience a telescoping failure that destroys either the socket or the end of the spigot pipe (eg Cubrinowski et al, 2014).

In a collar joint there is no mechanism to drive one pipe end inside the other as there is in a spigot and socket joint. This makes no difference for a thick-walled or brittle pipeline, but thinner walled ductile pipes can cut through each other causing interpenetration (or intersection) rather than over-insertion. The increase in the effective diameter of the intersecting pipes causes failure of the surrounding collar. Intersection is easily reproduced in PVC pipes even without a restraining collar (Figure 6).

*Figure 6: Thin-walled PVC that buckled after over-insertion (left) and intersecting PVC (right)*

Another form of failure is observed where pipes have been alternately subjected to tension and compression with sufficient amplitude to completely separate the joint in tension (Morris et al, 2014). Where the spigot is partly pulled from the socket it can be reinserted under compressive loading. If, however, the spigot is fully removed from the socket, reinsertion requires perfect alignment. Any deviation, whether from vertical or horizontal displacement or bending, will either result in failure to re-insert or will cause damage to the pipe or socket. Fracture is especially likely in a brittle socket made of cast iron or Asbestos Cement but failure to re-insert would occur for any thicker-walled pipe whether brittle or ductile.

However, in thinner-walled PVC, a slight misalignment can result in the pipe intersecting the socket. This results in partial re-insertion while leaving a tag of material outside the socket (Figure 7). This will cause loss of pressure integrity in a pressure pipe but may not affect the performance of a gravity pipeline, especially if the tag is near the top and the line rarely runs full and is not subjected to liquefaction-induced silt intrusion.

*Figure 7: Reinsertion failure in thin walled PVC pipe*

## 3.4 EXTENT AND IMPACTS OF SUB-CRITICAL DAMAGE

Various forms of sub-critical damage have been reported after many earthquakes. It can be explained and understood in operational terms (where the type and severity of the failure does not degrade function to the extent where service is completely lost) and in materials terms (where the pipeline is damaged or degraded in some way without actual failure).

Because operational sub-critical damage allows the system to perform to some degree, immediate repair efforts can be focused on areas with complete loss of service. However, the damage will still need attention in the medium term as the system does not meet all its requirements.

Materials-related sub-critical damage also allows deferral of repair or restoration in the short-to-medium term, but some affected systems can potentially provide acceptable service in the longer term. Where the damage is not immediately apparent, it may only be detected during routine maintenance or other scheduled operations. However, it is likely to need replacement once identified, for example:

- a hyper-extended PE line would need to be replaced once detected since new connections could not be made to it, and the remaining life would remain uncertain;
- over-inserted PVC pipe will have locally distorted dimensions and over-thickness pipe wall and the useful life may be compromised;
- buckled or bent pipes would have locally reduced carrying capacity and increased head loss, the useful life could be compromised;
- buckled steel would have damage to the corrosion protection systems.

In the majority of these materials-related cases, the operational impact of the damage would be modest because the damage would extend only over a small length of pipe so that replacement of the damaged section should be sufficient for the damaged component. At this stage, however, there are reservations over how to determine the full extent of the damage in a pipeline, and replacement of complete pipe lengths might be more prudent.

## 3.5 FUTURE CONSIDERATIONS

The form and extent of sub-critical damage is likely to take on increased importance over time:

- While the increased use of more modern ductile materials for new constructions and for renewals is likely to increase the incidence of sub-critical damage in future events, the scale of this relatively new form of damage is difficult to predict for a number of reasons.
- sub-critical failures are more likely in modern materials, while most historic data relates to older materials;
- By their very nature, they do not necessarily cause immediate loss of service and can therefore go unnoticed. After an earthquake, the focus is on stabilisation and restoration of the damaged parts of the system. Areas of reduced performance or at higher risk of corrosion damage will not be identified when looking for failures, and will only be encountered by chance while performing other works, or some time after the event when they finally do fail or when they pose an operational problem. Even then, the likelihood of these issues being identified as earthquake damage is low.
- There are numerous examples where data recorded by repair crews is limited (eg Morris 2002, Tromans, 2004, Cubrinowski 2014). This is because of their operational priorities rather than from any complacency. While there are examples of service crews and operators reporting unusual forms of damage in both electrical power lines and water systems, they are much less likely to report damage that has not caused failure.

Some other forms of sub-critical damage have been reported anecdotally, but have not yet been fully confirmed. These include cases where the host pipe of a lined system has been damaged but the lining has prevented immediate failure.

Even where damage does not require replacement, sub-critical damage could reduce the remaining useful life of the assets. This is important for renewals planning and for valuation purposes. If renewals are required early, this can affect budgets and scheduling while impairments to the existing system may need to be reflected in the assigned value.

It is also important to consider the implications of the observed behaviour of pipeline systems on renewals options. If a particular material, jointing system or installation practice has a materially better or worse performance under expected earthquake conditions, then this should be accommodated in design and selection guidance for both new constructions and for renewals. If observed and predicted performance consistently favours a more expensive option over a cheaper option, then the policy on optimised renewals may need to be justified to auditors, councils and communities. The Office of the Auditor General has made it clear on a number of public occasions (for example the NAMS Forum in 2012) that they expect to see evidence-based justification for renewals decisions.

Because sub-critical damage may not be detected until well after the event that caused it, it is possible that this will result in initial underestimation of the true scale of damage of an event that affects a system containing a high proportion of more modern materials. While, deferred repair needs can be beneficial in the immediate aftermath of an event, they could lead to under-claiming of insurance payments or of support funds if they are not identified until after claims deadlines have expired.

# 4 CONCLUSIONS

The ability of some systems to withstand major events and still provide some measure of service is clearly desirable as a means of reducing the immediate impact of major seismic events. However, all of the observed and expected forms of damage will result in increased repair need or require early renewals, and have potential to cause future operational problems.

The extent to which this form of damage is beneficial (through delaying immediate repair need and allowing some service to be retained) has yet to be established. Benefits will need to be balanced against the potential negative impacts of increased uncertainty over renewals and repair needs and the possibility that repair needs could be underestimated when making insurance claims.

Having identified that sub-critical failures are an important factor in more modern systems, future work will attempt to quantify their impact to determine whether they are an academic curiosity or if they have a material effect that needs to be accommodated in asset management planning.

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