# UNDERGROUND UTILITIES - SEISMIC ASSESSMENT AND DESIGN GUIDELINES

EDITION 1

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*Underground Utilities – Seismic Assessment and Design Guidelines*

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# Preamble

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## Abbreviations

| | |
|---|---|
| ABS | Acrylonitrile butadiene styrene |
| AC | Asbestos Cement |
| CDEM | Civil Defence Emergency Management Act |
| CES | Canterbury Earthquake Sequence |
| CI | Cast Iron |
| CIPP | Cured in place pipe |
| DN | Nominal Diameter |
| GI | Galvanised Iron |
| LDRP | Land Drainage Recovery Programme |
| LOS | Levels of Service |
| L-waves | Love waves |
| LSN | Liquefaction Severity Numbers |
| MBIE | Ministry of Business, Innovation and Employment |
| MMI | Modified Mercalli Intensity scale |
| Mb | Body wave magnitude |

| | |
|---|---|
| Mw | Moment Magnitude (Mw) |
| Ms | Surface wave magnitude |
| NA | Not Applicable |
| PE | Polyethylene |
| PGA | Peak Ground Acceleration |
| PGD | Peak Ground Displacement |
| PGV | Peak Ground Velocity |
| PHA | Peak Horizontal Acceleration |
| PVA | Peak Vertical Acceleration |
| PVC | Polyvinyl Chloride |
| P-waves | Primary waves |
| Rn | Return period factor |
| R-waves | Rayleigh waves |
| S-waves | Shear waves |
| ULS | Ultimate limit state |
| Z | Zone factor |

## Units

| | |
|---|---|
| l/p/d | litres per person per day |
| m | metres |
| km | kilometres |

## Limitations

The guidelines do not cover:

- Buried structures such as pump stations or tanks
- Above ground components such as pipe bridges or reservoirs
- The effects of tsunamis, fires and other events that might arise as a consequence of an earthquake
- Culverts with a cross sectional area greater than 3.5 $m^2$, which are covered by the NZ Transport Agency *Bridge Manual SP/M/022*

# Executive Summary

## Background

Much of New Zealand is susceptible to earthquakes as the country is situated at the active boundary between the Australian and Pacific tectonic plates. Our communities and economy depend on being able to respond and bounce back quickly from seismic events.

The vulnerability of underground utilities to damage from earthquakes was highlighted by the Canterbury Earthquake Sequence (CES) of 2010 and 2011. The earthquakes caused significant damage to parts of the underground utility networks in Christchurch and Kaiapoi, disrupting supply to households and businesses and cost several billion dollars to repair.

The CES however is not a one off sequence of events. Much of New Zealand is at a risk of similar sized earthquakes occurring as shown in Figure 0-1. Hence, it is essential to develop underground infrastructure networks capable of withstanding seismic events in a uniquely New Zealand context.


Figure 0-1 Map of seismicity in New Zealand

# Scope

The Guidelines mainly focus on underground utility networks of:

- Potable water
- Wastewater
- Stormwater

However, they are also applicable to underground telecommunication, power and gas networks.

The Guidelines provide processes that enable practitioners to:

- Identify sections of networks that are vulnerable to damage, to assess the amount of damage likely to occur and estimate the Levels of Service expected after an earthquake;
- Identify measures to improve the resilience of the existing networks. This includes the development of response plans and capital works programmes to improve the robustness and redundancy of the system and to make it easier to restore service after a seismic event. Direction is given on how to incorporate these activities into asset management planning;
- Determine how to restore a network following an earthquake and to assess the long-term implications of the damage sustained;
- Design and install new utilities that provide an acceptable level of resilience.

The Guidelines aim to improve the ability of underground utility networks to function and operate during and following earthquakes for safety, economic and community wellbeing reasons. The Guidelines recognise that earthquakes may cause some limited and manageable damage. Although they do not attempt to prevent all damage, they do seek to help manage and contain it.

The Guidelines are based on findings from a research project titled *The Seismic Response of Underground Services* funded by the Ministry of Business, Innovation and Employment (MBIE). While the Guidelines draw heavily on information from the CES of 2010 and 2011, they also incorporate findings from other events in New Zealand and include material from other international and national sources.

# Structure

The Guidelines are structured as follows:

1 **Introduction** defines the scope and context of the guidelines.

2 **Resilience of Underground Utilities** demonstrates the case for improving resilience. The section highlights the benefits that arise from improving resilience in terms of protection to lives, economic growth, job creation and resulting in more liveable communities. Examples of resilience projects that have reaped benefits more than six times the amount invested are cited.

Government policy and legislation concerning infrastructure resilience are discussed. These require local authorities to:

» Identify and assess risks to underground utilities from earthquakes
» Plan and respond should an earthquake occur
» Identify options for improving resilience of underground utilities
» Design and install utilities in a manner that ensures an acceptable level of resilience

The Guidelines adopt the Intergovernmental Panel on Climate Change's definition of infrastructure resiliency being "the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a shock or stress in a timely manner".

The Guidelines assess and evaluate measures to improve infrastructure resiliency to seismic events through the consideration of post-event Levels of Service (LOS). Levels of Service are developed for various user groups that consider:

- User type
- The amount of service provided
- The duration of restricted supply
- Percentage of the community affected (being a proxy to the community's ability to adapt after a natural disaster)

A six step process for assessing and improving resilience is outlined which involves:

- Establish target post-event LOS
- Assess the system's vulnerability
- Estimate the post-event LOS considering the quality of service and the duration that a degraded service maybe provided. Consider also the effect of after-shocks
- Identify gaps in resilience where target levels of service are not likely to be met
- Identify and evaluate improvement projects based on the improvement they will make to post-event LOS
- Where the desired post-event LOS cannot be achieved in a practical or cost effective way, consult with the community and stakeholders to determine appropriate post-event LOS and alternate services that balance cost, risk and the community's ability to adapt. Examples might include provision for storage, emergency toilets, tankered water and if necessary pumping sewage into rivers

3 **Establish Target Post-Event LOS:** This section sets out criteria for establishing target post-event LOS which serve as the basis for assessing and prioritising works to improve resilience.

4 **Assess System Vulnerability:** The process outlined in this section of the Guidelines involves:

- Estimate parameters for the design earthquake and derive peak ground accelerations (PGA), utilising processes outlined in *NZS 1170.5*: 2004 and *Bridge Manual SP/M/022*.
- Predict how the ground may respond during and after the earthquake. Observations from the CES and elsewhere indicate that permanent ground deformations significantly influence the type and amount of damage sustained by underground utilities. They also influence the extent of service lost and the time required to restore service. It is, therefore, important to understand where the following might occur:

– Surface fault rupture
– Liquefaction (including subsidence and lateral spreading)
– Slope failures or landslide

- Classify the underground utilities system as being either:

– Pressurised systems, non-pressurised systems or other systems such as cables.
– Continuous or segmented
– Rigid or flexible

These classifications are used to determine the vulnerability of the utilities to damage under conditions expected from the earthquake.

- Predict how underground utilities will behave. Estimating the extent of damage likely to be sustained by considering:

– Transient movements
– Permanent ground deformations
– The classification and size of the underground utility
– Other risk factors such as connections and discontinuities

- Then undertake a sensitivity analysis to allow for inherent limitations associated with the predictions.
- Estimate the time it will take to restore service to the expected LOS, and compare with post-event LOS defined earlier, considering the extent and location of damage, redundancy within the system, response resources and the availability of alternative supplies.

Key lessons learnt from the CES and elsewhere that have been incorporated into the Guidelines include:

- The performance of the ground and associated ground damage has far more influence on damage than the shaking that occurs during earthquakes.
- Axial forces along utilities cause the majority of damage. Most of the damage occurs at pipe joints. Bending and transverse loading tends to only cause damage in brittle pipes.
- All utility materials sustained damage in the CES but modern flexible pipe materials generally suffered a lot less damage than older, more brittle pipe materials.
- Larger pipelines typically sustain less damage than smaller pipelines. Service pipe connections sustain the most damage. Even modern PE service pipe sustained significant damage in the CES. This was attributed to failure at mechanical couplings where inserts had not been used.
- Pipe grades may be reduced and dips may occur in areas that experience liquefaction or lateral spread. This is due to the significant differential settlements that can occur in these areas. Therefore, it affects pipes of all pipe materials. This can be particularly problematic for gravity pipes.
- The performance of the ground influences the ability of the system to remain in service. Experience in the CES was that if the ground liquefied, then the wastewater system could become blocked regardless of the amount of damage sustained. This was because of sand and silt entering through gully traps and manholes.
- The time it takes to restore service is affected by both the amount of damage sustained and the ground conditions with excavation in areas of liquefaction or poor ground stability being particularly problematic. Ground conditions affect ground stability and liquefaction during aftershocks which hinder access for repair and inspection.
- The quantum of damage sustained to non-critical pipes often controlled the time it took to restore service. For example, the lifting of the boil water notice on the potable water system after the CES was largely governed by the time it took to repair the multitude of small leaks that occurred on service connections rather than the condition of the larger pipelines to which the service pipes were connected.
- Alternative means of providing service, such as provision of portaloos, can be used but they take time to install and the public can only tolerate them for so long.

» Restoration of service involves several phases. It may take many years to fully restore service to the pre-earthquake condition. Priorities and needs change as restoration progresses through these phases.

5 **Improve Resilience of Existing Systems** discusses measures to improve resilience, by reducing exposure to hazards, increasing the speed and effectiveness of response, increasing the flexibility of the system to adapt and improving the robustness of utilities.

Improvement measures are prioritised based on value for money in terms of improvement in post-event levels of service.

The resilience of existing systems can be improved significantly through a combination of response planning, renewals prioritisation and capital expenditure works. In many cases, this does not involve significant capital expenditure.

6 **Providing New Utilities that are Seismically Resilient** gives guidance on design and installation of new utilities to provide an acceptable level of resilience. The focus in descending order of priority is:

» Locating utilities to

- avoid areas of poor ground performance
- avoid consequential damage to other utilities and features
- improve the ease of repair
- Providing redundancy in the system
- Providing robust utilities

The Guidelines specify increasing levels of design sophistication based on the importance level assigned to the utility. For Importance Level 1 and 2 utilities, acceptable solutions which do not require any further specific design to be undertaken are defined. These utilities make up the majority of most systems. More sophisticated methods are proposed for utilities with Importance Level 3 or 4, such as the equivalent static design method and finite element modelling.

# 1 Introduction

## 1.1 Background

After the Canterbury Earthquake Sequence (CES and the initiation of the subsequent rebuild, it was clear that a set of guidelines for underground utilities in a New Zealand context was needed.

International standards and guidelines are available for underground utilities subjected to earthquake loads but just how to apply these to New Zealand conditions was not clear.

During the Christchurch rebuild, specific guidelines for the recovery were developed. These were modified during the rebuild depending on changes in rebuild philosophy over time.

The guidelines developed in this document aim to provide a consistent approach for assessing the vulnerability of underground utilities to seismic events, for identifying and prioritising measures to improve resilience and for the design and installation of underground utilities so as to provide an acceptable level of resilience to earthquakes.

Consequently, the Guidelines are intended to be applicable for use throughout New Zealand.

The Guidelines reference other relevant international and national documents for further information and guidance where necessary. Additionally the text is supplemented by Technical Notes and other material as referenced in the text.

While the Guidelines draw heavily on information from the Canterbury events of 2010 and 2011, they also incorporate findings from other events in New Zealand and elsewhere.

## 1.2 Development of the Guidelines

The Guidelines are based on findings from a research project titled *The Seismic Response of Underground Services* funded by the Ministry of Business, Innovation and Employment (MBIE). This research was commissioned after the CES (2010 and 2011), for the period from 2012 to 2016. The principal objective of the research was to enhance understanding of the performance and resilience of underground utilities under seismic loading.

The research included information gathering, physical testing and finite element analysis, refer Figure 1-1. Specific components include:

- Reviewing national and international research and guidelines
- Assembling a database of damage sustained to utilities following the CES
- Enhancing the findings from the damage database and literature review by undertaking 3D finite element analysis and large scale physical testing

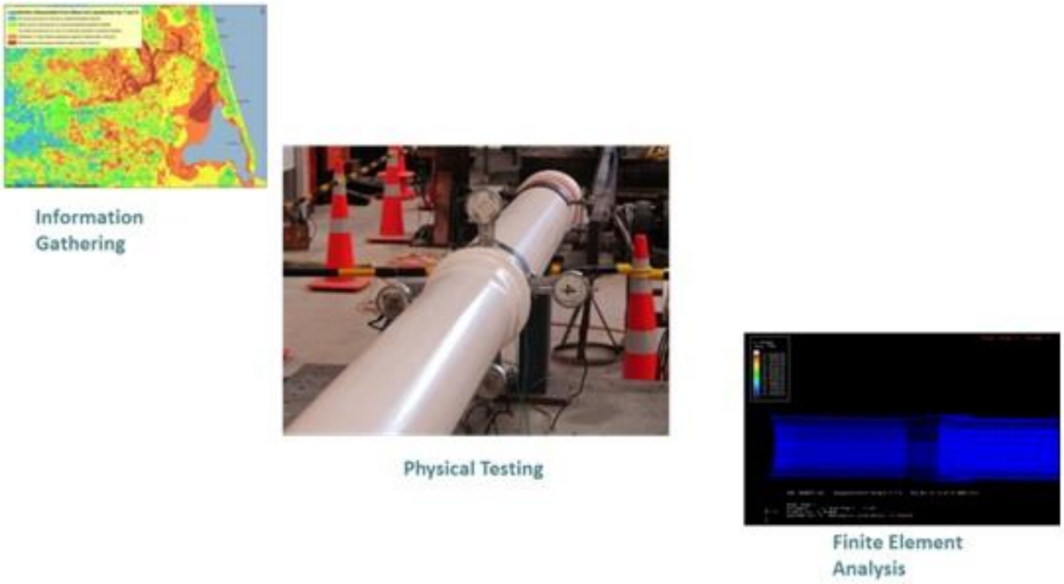


**Figure 1-1. Research components**

The research provided information to better understand the seismic performance of underground systems. This in turn helped to develop predictive tools such as materials and system selection guides as well as modelling fragility functions. Fragility functions are probability distributions that are used to indicate the probability that an element of the system may be damaged. These tools can be used to assist in forward planning to understand the likely scale and form of damage that may be caused by an earthquake and to assist in post-event management.

## 1.3 Guideline Objectives

Guidance is provided on how to assess and improve the resilience of existing and new underground utilities. Furthermore, Technical Note 01 – Interaction Between Seismic Resilience and Asset Management explains how improving seismic performance can be incorporated into asset management.

The processes outlined in the Guidelines endeavour to limit damage to manageable levels that subsequently enable communities to 'bounce back' quickly from seismic events.

Guidance is provided to enable practitioners to:

- Identify the sections of networks that are vulnerable to damage, to assess the amount of damage likely to occur and estimate the LOS expected after an earthquake.
- Identify measures to improve resilience of the existing networks. This includes the development of response plans and capital works programmes to improve the robustness and redundancy of the system and to make it easier to restore service after an event. Direction is given on how to incorporate these activities into asset management planning.
- Determine how to restore a network following an earthquake and to assess the long-term implications of the damage sustained.
- Design and install new utilities that provide an acceptable level of resilience.

The Guidelines have been tailored for New Zealand conditions. As such they complement Standards for designing and installing underground utilities under normal operating conditions.

## 1.4 Scope of Guidelines

The Guidelines mainly focus on underground utility networks of:

- Potable water
- Wastewater
- Stormwater

However, they are also applicable to underground telecommunication, power and gas networks.

## 1.5 Role of the Guidelines in New Zealand Metadata Schemata

The New Zealand metadata schemata for New Zealand's Three Waters and Building describe and define the data and analytics required for evidence-based investment decision-making within an asset management environment.

Figure 1-2 shows a schematic of the Global Asset Metadata Schemata and indicates where these Guidelines fit into the overall framework which contributes to Volume 4 Schema by providing Evidence Based Investment Decision Making Analytics for assessing resilience and vulnerability of underground utilities, with regards to seismic events.

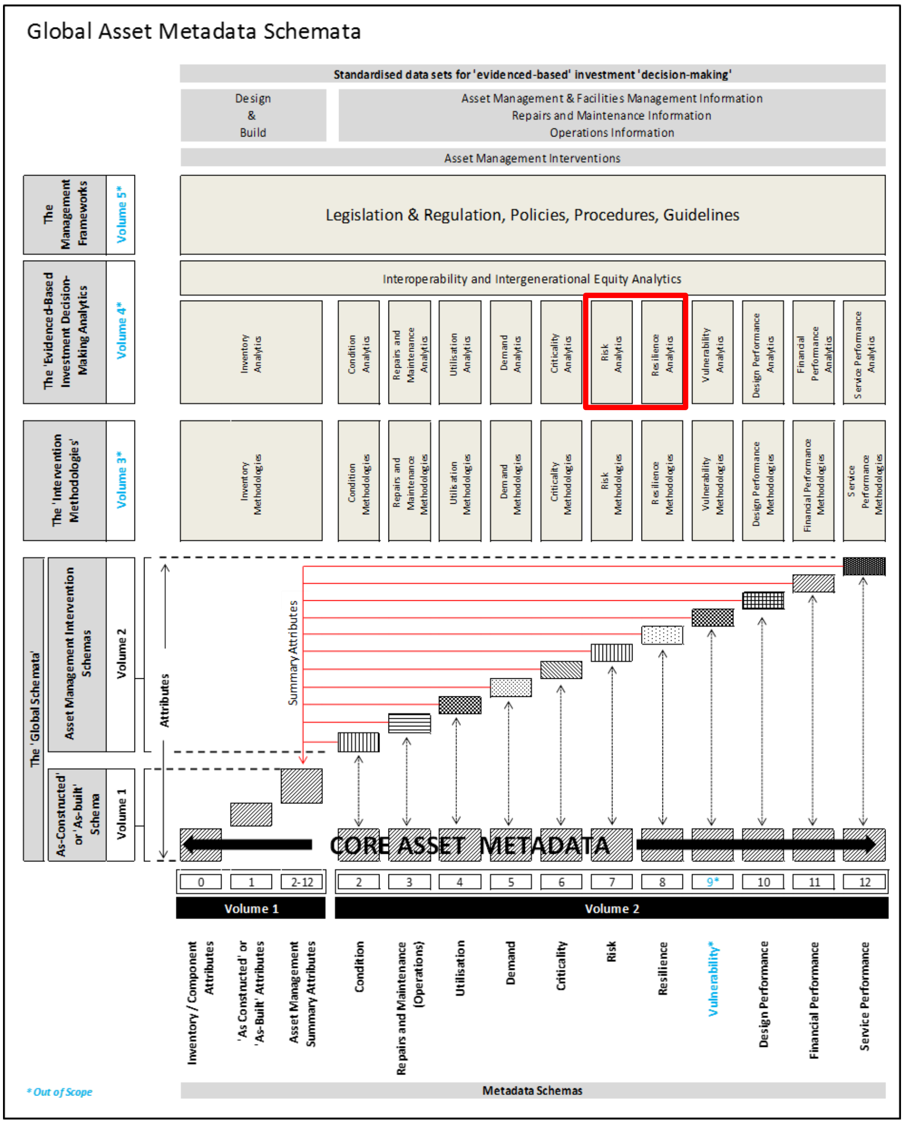


**Figure 1-2. NZ metadata schemata**

## 1.6 Technical Notes

The technical notes listed below provide supplementary information to the Guidelines. Each technical note focuses on a certain aspect of the research undertaken to develop the guidelines and is referenced in the relevant section. The technical notes contain guidance and/or findings from the research which may be of benefit in understanding and applying the Guidelines.

Technical Note 01 – Interaction Between Seismic Resilience and Asset Management

There is a strong relationship between seismic resilience and asset management that needs to be understood before any improvements are made to a system. Levels of service, composition of the system, managing risk, selecting options, managing renewals and managing financial aspects are all elements that require seismic considerations. These elements are discussed to emphasise the relationship between seismic resilience and asset management.

Technical Note 02 – The Basis for Defining Post-Event Levels of Service (LOS)

Defining post-event LOS is essential, but not easy. This document helps to define some key concepts including; disaster recovery stages, service restoration categories, community resilience and the role of utilities. These concepts are explained to help provide an overarching understanding for defining the level of service following an event and is intended to be read in conjunction with the report.

Technical Note 03 – Earthquake Behaviour Information

An earthquake occurs when tectonic plate boundaries slide against each other and strain energy is released. The amount of energy released determines the size of the earthquake and it is characterised by the amplitude, frequency and duration of seismic waves. Ground shaking and permanent ground movement can occur. The damage from ground shaking is lower but effects the whole system, whereas, permanent ground movement is usually localised with higher damage rates. Seismic wave effects tend to decrease with depth but shallow pipelines and utilities may be damaged by falling debris. During an earthquake, liquefaction may occur and cause ground subsidence, uplift of buried utilities, liquefy historical channels and cause failures of structural foundations. This technical note provides information about an earthquake's behaviour and its potential effects on structures and the environment.

Technical Note 04 – The Liquefaction Phenomenon

Liquefaction is a hazard which earthquakes pose on the surrounding environment. The phenomenon of liquefaction is where soil strength rapidly decreases due to strong ground shaking in saturated soils. This technical note focuses on explaining the Liquefaction phenomenon, documenting the nature and distribution of soils that are susceptible to soil liquefaction and the effects causes by this hazard.

Technical Note 05 – Response of Buried Assets Other Than Water Pipelines

Most of the studies on damage caused by earthquakes to buried assets relate to water assets, and especially to water supply systems in which damage is more readily observed and identified, and where loss of supply has an important and fast-acting effect. This technical note reviews the key features of other buried utility services and summarises the kind of damage observed

Technical Note 06 – Basis for Damage Rate Prediction for Pressure Pipes

This technical report presents the results from studies on how the water, wastewater and stormwater networks in Christchurch performed during the CES, focusing on the two most damaging aftershocks of February and June 2011. The performance has been studied for the main pipe material types present in the three networks, and is described through fragility models which are functions of both shaking and ground conditions. Brief information on the events and the three networks affected are provided, followed by a description of the data and methodologies used to derive the fragility models.

Fragility models to simulate damage or disruption to three waters (potable, waste and storm water) networks have been derived. The choice of model to use depends on the availability of the required input data.

Finally, the shortcomings of the hazard, network and damage data are discussed, focusing on the effects on the proposed fragility models.

Technical Note 07 – Kaiapoi Wastewater Damage
This technical note evaluates damage assessments to the wastewater reticulation in Kaiapoi after the September 2010 Darfield earthquake. It is noted that the performance of the wastewater system was influenced significantly by the behaviour of the ground and varied depending on pipe material.

The technical note develops fragility models that enable practitioners to assess the vulnerability of wastewater and stormwater networks to seismic events in order to develop plans for responding to events and to identify works to improve resilience.

Technical Note 08 – Sensitivity Analysis for Seismic Damage Prediction
Forecasting the damage expected to occur after a seismic event is a subjective process. Some predictions can give false impressions hence sensitivity analysis is required. This document reviews potential sources of error and indicates how to accommodate uncertainty and variations. Currently the best tool for sensitivity analysis are break rates based on predicted event, soil risks, system composition and fragility functions. The document recommends considering a worst case based on double the predicted breaks and a best case scenario considering half the predicted breaks.

Technical Note 09 – Photobook of Damaged Underground Utilities
This Photobook presents a selection of photographs to help develop a greater understanding of the damage sustained to buried infrastructure in an earthquake. Damage and defects are categorised as follows; pipes, joints, fittings, existing and other. Each picture identifies the material used, description and cause of the damage, the process needed to repair and any other general comments.

Technical Note 10 – Effect of Deterioration on Seismic Resistance of Underground Pipelines Systems
This technical note discusses the effects of corrosion and deterioration on seismic resistance of pipelines. Corrosion and deterioration can reduce the ability of pipeline systems to withstand loads and pressures, which can potentially degrade its seismic resistance. However, many of the reported examples of the effect of corrosion on observed break rates actually relate to improvements in materials manufacturing practices and installation practices over time rather than to degradation of the material in service.

Many traditional materials degrade over time. In most cases, degradation can be expected to reduce the tolerance to seismic loading by weakening joints or reducing load bearing sections of the pipelines themselves. However, many pipelines that are affected by corrosion were also vulnerable to seismic damage even when new.

While corrosion does weaken pipeline systems in ways that increase vulnerability to seismic loads and any resulting surges, other factors such as change in technology can account for some of the reported effects of corrosion. The role of corrosion in seismic failures may be overstated because while corrosion may increase the likelihood of failure or the extent of damage, seismic failures can also occur whether there is corrosion or not.

Technical Note 11 – Effect of Pipe Linings and Patch Repairs on Seismic Performance

The performance of gravity and pressure pipelines can be improved by lining the inside of the pipes. Linings are installed to form one continuous new pipeline inside the original pipe whereas patches are used to fix localised damage in one length of pipe. Continuous lining systems are weakly bonded to the original pipe and can improve seismic resilience and accommodate greater tensile and compressive displacements. Patches, however, are bound much more tightly to the pipe and cannot accommodate high tensile and compressive strains.

Technical Note 12 – Post-Event Damage Assessment

Post-event damage assessments are essential to determine the scale and distribution of damage to underground services, which may be heavily affected by ground movements. Different types of ground movement cause different extents of damage at varying severities. The impact of this damage is not necessarily visible right away. The Technical Note develops a comprehensive 8 step assessment strategy with guidelines to assess the extent of seismic damages to underground services. This covers quantifying the extent and impact of damage through to developing a repair or replacement strategy. The note emphasizes that it is essential to pre-plan an emergency assessment response and prepare for the consequences the predicted damages will have. Damages may be very different than predicted and vary from locality to locality, so it is important to have a long-term repair strategy that functions alongside first-response lifeline response plans.

Technical Note 13 – Improving Seismic Resilience in New and Existing Systems

Resilient pipeline systems can either resist damage or they can be easily restored after a seismic event. New buried pipelines can minimise seismic risk by being located away from hazards, use resilient materials and have redundancy built into the system. If replacing an existing pipeline is not practical or cost effective, system redundancy, isolation points and automated control systems can be put in place to improve seismic resistance. This technical note provides an overview of how the seismic resilience of new and existing pipeline systems can be improved in a cost-effective way.

Technical Note 14 – Effect of Installation Practice on Seismic Response of Buried Pipeline Systems

Poor installation of buried pipelines is likely to reduce the service life of the system. Large stones can create a point load on the pipe which could result in bending failures or cracking. Inadequately placing the fill materials around the pipeline can cause voids to form. This is highly undesirable because voids can create uneven loading and distort the shape of the pipe which can result in buckling. Where seismic loading could occur, it is usually more beneficial to follow good installation practices rather than modifying the design of the pipeline system.

Technical Note 15 – Manhole Flotation

Manhole flotation refers to the phenomena of manholes protruding above the ground after seismic events either due to ground settlement around it or upward forces that have pushed the manhole above ground. As they pose a significant hazard to the public and cause damage to surrounding infrastructure, manhole flotation should be reduced as much as possible. Modelling of manhole flotation is subject to limitation due to its assumptions of a water table at ground level, complete liquefaction of soil, a lack of overlying material and no benching. Models in this technical note indicate that in the Christchurch Earthquake Series, manhole flotation was a rare phenomenon (only ~3.5% of manholes) and occurred due to settlement of the ground around it. When the shear strength of soils surrounding the manholes exceeded 5kPa, flotation stopped occurring. If a wide flange was present inside the pipes, 2KPa of soil shear strength was sufficient to prevent flotation. Thus, flotation can be prevented by avoiding soils that are likely to liquefy, and by using flanged bases on manholes.

Technical Note 16 – Equivalent Static Method

This technical note provides a worked example of the Equivalent Static Method for a DN450 steel pipe or DN300 Class C PVC pipe.

# 2 Resilience of Underground Utilities

## 2.1 The Impact of the Canterbury Earthquakes on Underground Utilities

Figure 2-1 shows the location and magnitude of seismic activity that occurred during the CES of 2010 and 2011. The CES demonstrated the importance of providing resilient utilities as thousands of Canterbury residents were adversely affected by disrupted utility services. Overall the earthquakes caused extensive damage to 300 km of sewer pipes and 124 km of water mains (SCIRT, 2011). The cost to rebuild all horizontal infrastructure was estimated, in mid-2013, as just over $3.3 billion. This includes roads, three waters and the Land Drainage Recovery Programme (LDRP). The LDRP alone was estimated to cost over $1 billion in a multi-decade programme.

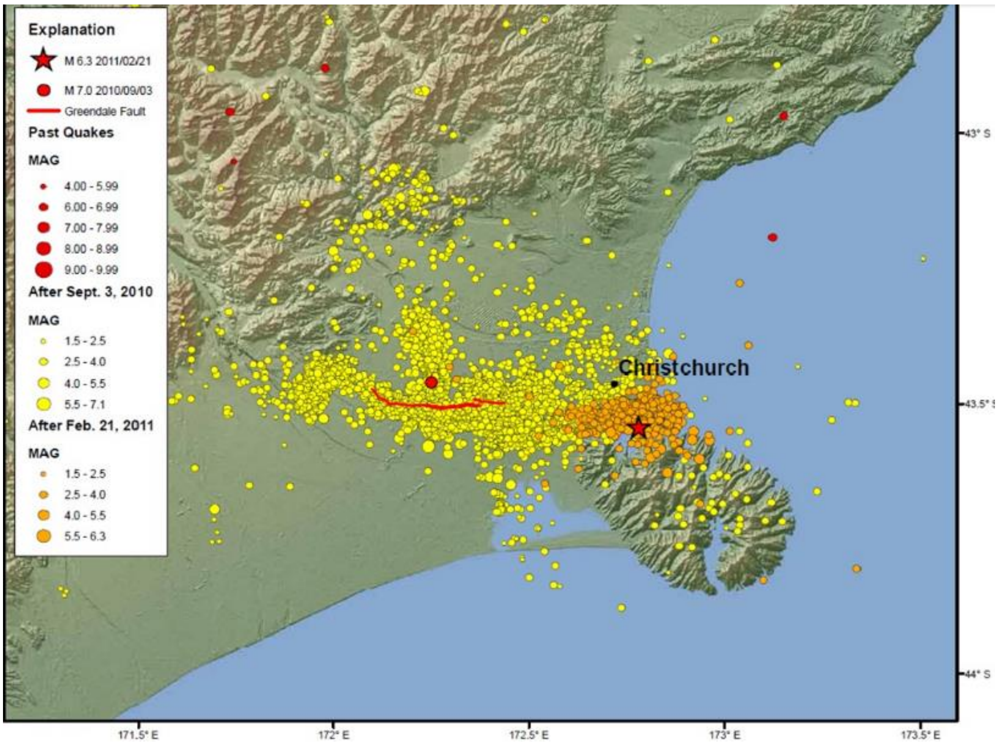


Figure 2-1. 2010/11 Extent and location of the Canterbury Earthquakes

Although the CES caused extensive damage to underground utilities, the damage was limited to discrete locations, as shown in Figure 2-2.

It is important to understand why in some locations utilities were damaged significantly and in others they were not and draw learnings to improve resilience.

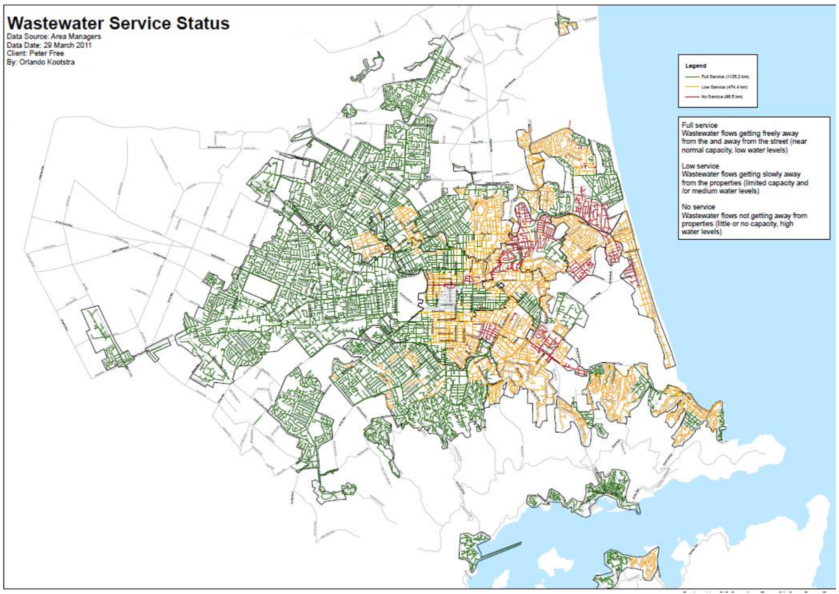


**Figure 2-2. Damage to Christchurch Wastewater System**

## 2.2 The Case for Resilient Utilities

'High-impact, low-probability' disasters appear to be occurring more often, with 2011 being the most expensive year in history in terms of economic losses (Swiss Re Ltd, 2015). Each year more than 200 million people are directly affected by droughts, floods, tropical storms, forest fires and other hazards (Pan American Health Organization, 2006). These events have widespread effects due to the increasing connectedness of the global economy.

A strong case for improving infrastructure resilience is articulated in the following quote from *The Chengdu Declaration of Action* of August 2011. "There is no such thing as 'natural disasters'. Natural hazards – floods, earthquakes, landslides and storms – become disasters as a result of human and societal vulnerability and exposure, which can be addressed by decisive policies, actions and active participation of local stakeholders. Disaster risk reduction is a no-regret investment that protects lives, poverty, livelihoods, schools, businesses and employment" (United Nations Office for Disaster Risk Reduction, 2011).

Investing in improving infrastructure resilience can demonstrate a legacy of leadership, provide economic growth and job creation and result in more liveable communities.

*The Global Assessment Report* developed by the United Nations Office of Disaster Risk Reduction highlights examples where organisations have reaped benefits in the ratio of 1:10 (The United Nations Office for Disaster Risk Reduction, 2015). The American Society of Civil Engineers estimates federal spending on levees pays for itself six times over (Wimmers, 2013).

In New Zealand the electricity company, Orion estimated the $6 million they spent on seismic strengthening saved $30 to $50 million in direct asset replacement costs following the CES of 2010 and 2011 (National Infrastructure Unit, 2012). The balance between costs and benefits would have been more pronounced if societal benefits had been taken into account (Kestral Group Ltd, 2011).

It is estimated New Zealand's underground utility network is valued well in excess of $30 billion (The Department of Internal Affairs, 2009). The benefits from Orion's investment in earthquake strengthening indicate that nationwide savings of $1.2 billion in reduced damage could be achieved by improving infrastructure resilience.

## 2.3 Government Policy and Legislation

### 2.3.1 Government Policy

Government policy regarding infrastructure resilience is defined in the *New Zealand Infrastructure Plan* (National Infrastructure Unit, 2015) . This is reflected in the *Civil Defence Emergency Management Act* (2002) and the *Local Government Act* (2002). The new *Health and Safety at work Act* (2015) is also relevant to construction works.

These policies and legislation require local authorities to:

- Identify and assess risks to underground utilities from earthquakes
- Plan and respond should an earthquake occur
- Identify options for improving resilience of underground utilities

### 2.3.2 National Infrastructure Plan

Resilience is one of *The New Zealand Infrastructure Plan's* 2015 guiding principles. The Plan describes the Government's intentions for infrastructure development over a 30-year timeframe. The vision is that "By 2045 New Zealand's Infrastructure will be resilient and coordinated, and contribute to a strong economy and high living standards" (National Infrastructure Unit, 2015).

Resilience in this context has been defined as "National infrastructure networks are able to deal with significant disruption and changing circumstances" (New Zealand Government, 2011).

The 2015 Plan states that "a better understanding of the levels of service we want to deliver is needed, together with more asset management practices and use of data, and more effective decision-making that considers non-asset solutions" (National Infrastructure Unit, 2015).

### 2.3.3 Civil Defence Emergency Management Act 2002

The *Civil Defence Emergency Management Act* (2002) defines lifeline utilities as entities that provide essential infrastructure services to the community such as water, wastewater, transport, energy and telecommunications. These services support communities, enable businesses to function and underpin the provision of public services.

A lifeline utility must be able to function to the fullest possible extent, even though this may be at a reduced level, during and after an emergency. Utility operators are required to undertake readiness activities, such as:

- Developing, reviewing and improving their emergency plans
- Maintaining arrangements to respond to warnings
- Incorporating risk management principles to form part of normal business operations
- Incorporating emergency response and recovery planning into their business continuity arrangements
- Planning, training, exercising, and equipping themselves in co-ordination with interdependent agencies

In the event of an emergency, lifeline utilities' operators are required to:

- Remain responsible for managing their own response
- Maintain or restore the services they provide

### 2.3.4 Local Government Act 2002

The *Local Government Act 2002 Amendment Bill (No 3)* introduces requirements for the development of infrastructure strategies and implementation of asset management planning.

Section 102B of the *Local Government Act* (2002) requires local authorities to prepare and adopt a strategy that identifies the significant infrastructure issues the authority is likely to face over the next 30 years. It also requires them to identify the principal options for managing those issues.

Infrastructure strategies must include the following utilities which are covered by the guidelines:

- Water supply
- Sewerage and the treatment and disposal of sewage
- Stormwater drainage
- Flood protection and control works

Infrastructure strategies must also include roads and footpaths.

These strategies are required to ensure infrastructure assets are resilient by:

- Identifying and managing risks relating to natural hazards
- Making appropriate financial provision for those risks

### 2.3.5 Health and Safety at Work Act 2015

The *Health and Safety at Work Act* (2015) is New Zealand's key work health and safety law. The Act requires that all parties involved in construction work must communicate and inform all related parties (workers and others) about the health and safety risks of the work in terms of the whole life of the construction. Duties are not transferable or able to be contracted out of, but reasonable arrangements can be entered into to ensure duties are met. For further information on how this may relate to specific projects, please refer to [www.business.govt.nz/worksafe/](www.business.govt.nz/worksafe/).

## 2.4 What is Meant by Resilient Infrastructure?

### 2.4.1 Concept of Resilience

The *National Infrastructure Plan 2011* says resilient infrastructure are "networks are able to deal with significant disruption and changing circumstances." (New Zealand Government, 2011). This definition can be expanded to include "the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a shock or stress in a timely manner" (IPCC, 2011).

Figure 2-3 shows in a schematic form the concept of resilience and how it affects the communities.

Key points to note are:

- Natural disasters affect utility system performance, which in turn affects community wellbeing.
- Mitigation measures can reduce the amount of infrastructure that is damaged by an event.
- Recovery controls can reduce the impact of damage through measures such as providing alternative supplies, speeding up the response or through provision of community support and communication.
- Resilience planning needs to consider that disasters do not always occur in isolation. Multiple events may occur concurrently.

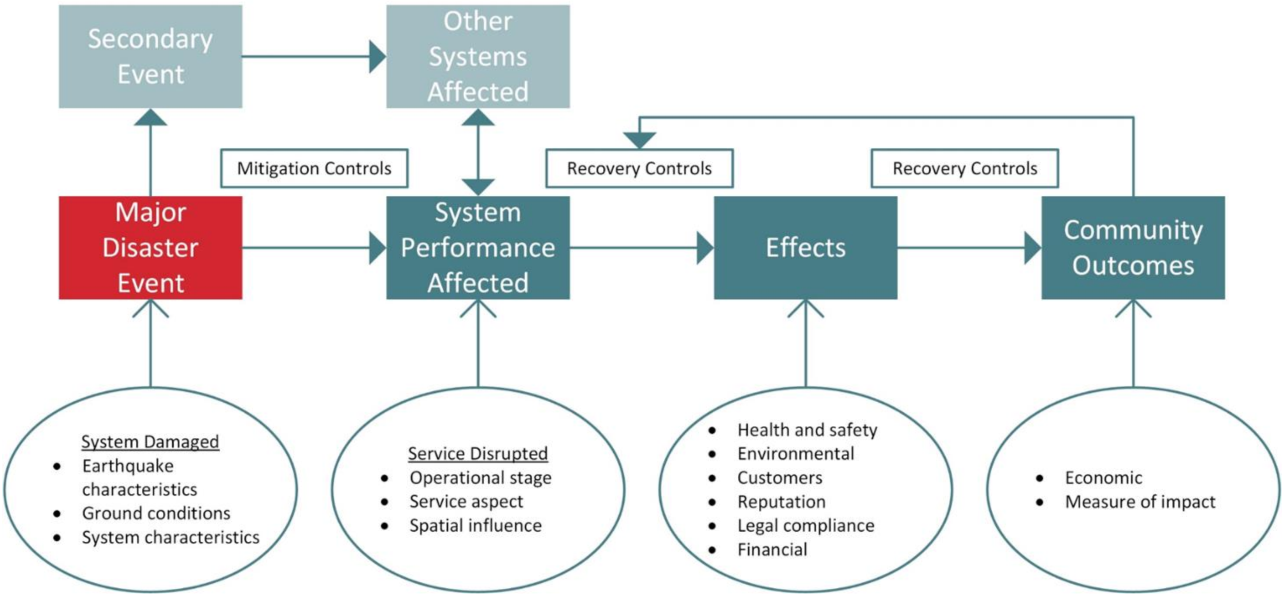


**Figure 2-3. Concept of resilience and how it effects the community**

To help make communities more resilient, several factors need to be considered. Infrastructure resilience recognises that installing utilities to withstand hazards, such as earthquakes, is not always practical, feasible or cost effective. Asset failures occur and measures need to be in place to contain damage and bounce back from events.

This concept is shown in Figure 2-4.

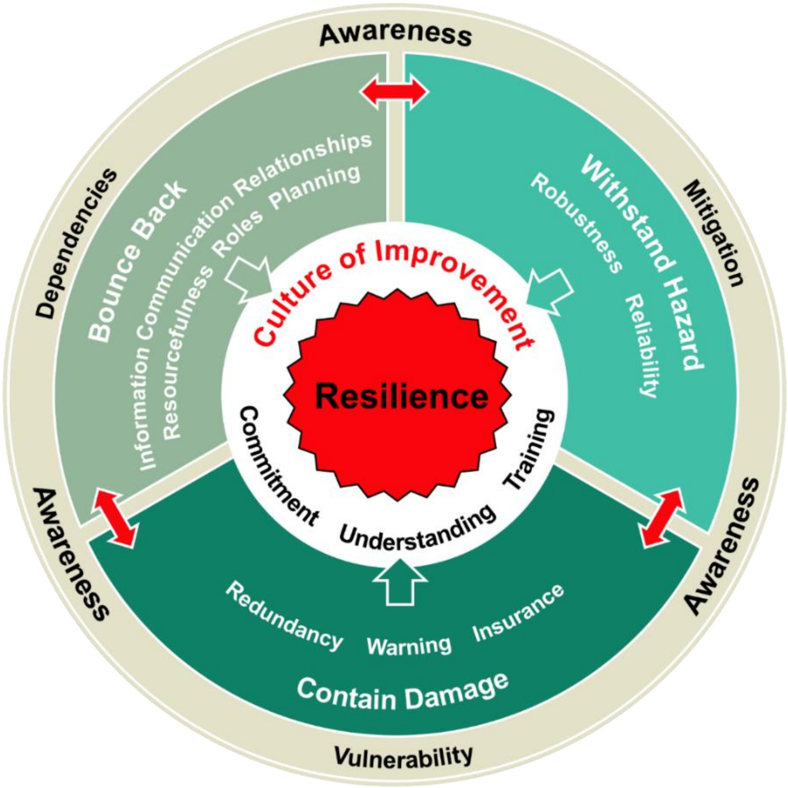


Figure 2-4. Infrastructure resilience

The Guidelines, therefore, aim to improve the ability of underground utility networks to function and operate during and following earthquakes for safety, economic and community wellbeing reasons. The Guidelines recognise that earthquakes may cause some limited and manageable damage. They do not attempt to prevent all damage, they do seek to manage and contain it.

## 2.5 Levels of Service Assessment

The Guidelines assess and evaluate measures to improve seismic resilience by considering post-event LOS.

### 2.5.1 Assessment Process

A summary of the six step process to improve the resilience of infrastructure, with reference to the relevant Guideline section, is outlined below and in Figure 2-5:

- Firstly, target post-event LOS are established (Section 3)
- The system's vulnerability is then assessed (Section 4)
- The time to restore service after an earthquake is assessed to determine the current post-event LOS. This is covered in more detail in Section 4.
- Identify where target LOS are not met
- Improvement projects are identified and evaluated based on improvements made to post-event LOS. Improvement projects might, for example, be contingency measures to improve response times if an event should occur (Section 5.3.3) or capital works to improve the robustness or redundancy in the utility system (Section 5.4)
- In some cases, the desired post-event LOS may not be able to be achieved in a practical or cost effective way. In these cases, the community should be consulted to determine appropriate post-event LOS that balance cost, risk and the community's ability to adapt

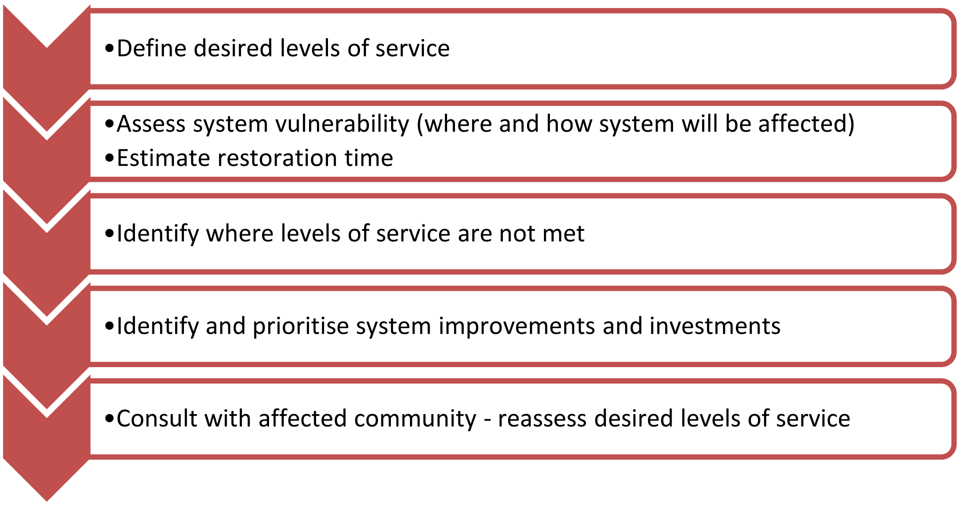


**Figure 2-5. Process for assessing and improving utility resilience**

The process described above is an evolution of a framework developed by Kameda (2000) which introduces the concept of mass acceptance for evaluating resilience projects. Mass acceptance is the sum of each individual in the region's level of acceptance. This concept recognises that:

- Damage to assets affects individuals and how they go about their activities.
- Post-event LOS will vary across the community, with some sections possibly having very little disruption, while others are significantly affected.

This concept is supported by the findings of the aftermath of the CES which saw widespread and varied LOS with immense impact on local communities.

To simplify this process and avoid the need to estimate levels of mass acceptance for each resilience project, a set of prioritized post-event LOS have been developed. These recognise mass acceptance after an event is influenced by:

- The actual (reduced) LOS provided
- The duration that the reduced LOS is provided
- The particular needs of individuals and different sections of the community
- The portion of the region affected, i.e. if only a small section of the region is affected then additional resources can be mobilized to that area to assist the people affected and there is scope for residents to be relocated to other sections of the community. This is not the case if a large portion of the community is affected

The components that describe post-event LOS targets are shown in Figure 2-6.


**Figure 2-6. Formation of LOS**

## 2.6 Supplementary Information

Technical Note 1 – Interaction Between Seismic Resilience and Asset *Management* provides information on how resilience can be incorporated in renewals and construction programmes.

# 3 Establish Target Post-Event Levels of Service

## 3.1 Why Establish Post-Event Levels of Service?

Establishing target post-event LOS provides a basis for assessing and prioritising works to improve resilience.

## 3.2 What to do to Establish Target Post-Event Levels of Service

Establish target post-event LOS using the framework given in Levels of Service Performance Measures for the Seismic Resilience of Three Waters Network Delivery (Water New Zealand).

## 3.3 How to Establish Post-Event Levels of Service

The process for defining and establishing current and post-event LOS for various user groups within the community is set out in Levels of Service Performance Measures for the Seismic Resilience of Three Waters Network Delivery (Water New Zealand).

Levels of service should be developed for the user groups shown in Figure 3-1.


**Figure 3-1. Example of the range of user groups in the community requiring different three waters LOS.**

Examples of three waters post-event LOS are shown in Table 3-1 below. This matrix clarifies the wide variety of LOS the various community sectors need – from the firefighters' urgent need for non-potable water to fight fires as and where they occur, to the 20 litres per person per day (20 l/p/d) potable water provided for the bulk of the community to collect from nearby locations.

A bullet point (▪) denotes a negotiable LOS component around which to engage the community. As each community will have different circumstances and priorities, quantities, quality and other factors different from those in this template may also need to be consulted upon.

**Table 3-1. Post-event LOS**

| Purpose of LOS | Amount, Quality | Location, user supplied | Duration | % of City |
|---|---|---|---|---|
| Firefighting | SNZ PAS 4509:2008 | Priority locations<br>▪<br>▪<br>▪<br>▪ | ▪ | All |
| Emergency Response | 20l/p/d<br>SNZ PAS 4509:2008 | Civil defence centres<br>Emergency operation centres<br>Ports, airports & other lifelines | 2 days | All |
| Loss of life, emergency response – fire fighting | SNZ PAS 4509:2008 | Relocation areas<br>Hospitals<br>Age care centres<br>Prisons<br>Ports, airports & other lifelines<br>Civil defence centres<br>Emergency operation centres | 3 days | All |
| Care of injured, elderly and others that cannot be moved | 60l/p/d, potable<br>SNZ PAS 4509:2008 | Hospitals | 3 days | All |
| | 20l/p/d, potable<br>SNZ PAS 4509:2008 | Age care centres<br>Prisons | 3 days | All |
| Drinking, cooking, basic hygiene | 20l/p/d<br>SNZ PAS 4509:2008 | Relocation centres | 3 days | All |
| | 20/l/p/d | Within 500-1000m of households | 3 days | ▪ |
| | 20l/p/d, potable | At household | ▪ | ▪ |
| Community development, Education | 20l/p/d, potable Firefighting at SNZ PAS 4509:2008 | Schools | ▪ | ▪ |
| Community development – meeting places | Potable water at pre earthquake quantity, Firefighting at SNZ PAS 4509:2008 | Community meeting places, e.g. cafes, sports centres | ▪ | ▪ |
| Governance | Potable water at pre-earthquake quantity, firefighting at SNZ PAS 4509:2008 | Central & government facilities | ▪ | All |
| Employment | Potable water at pre-earthquake quantity, firefighting at SNZ PAS 4509:2008 | Shopping, business and industrial areas | ▪ | ▪ |
| Housekeeping | 70l/p/d, potable | Households | ▪ | ▪ |

## 3.4 Supplementary Material

Levels of Service Performance Measures for the Seismic Resilience of Three Waters Network Delivery (Water New Zealand) prepared by Opus and the Quake Centre which sets out the process for defining and establishing current and post-event LOS.

Technical Note 02 - The Basis for Defining Post-Event Levels of Service provides context and background to the Levels of Service Performance Measures for the Seismic Resilience of Three Waters Network Delivery.

# 4 Assess System Vulnerability

Figure 4-1 shows an overview of the methodology for assessing the vulnerability of underground utility systems.

The process utilised in the Guidelines starts by identifying the earthquake hazards and the motions expected to be generated. This information is used to determine how the ground is likely to respond to the earthquake event.

Underground utilities are classified into categories that reflect their vulnerability to damage depending on factors such as their location, depth, surrounding media and material composition.

The earthquake motions and ground behaviour are then used to predict how the various types of underground utilities in the system will be affected and the extent of damage.

The expected type and amount of damage and the expected ground behaviour influence the time it will take to restore the system. The likely post-event LOS can be predicted when these factors have been assessed.

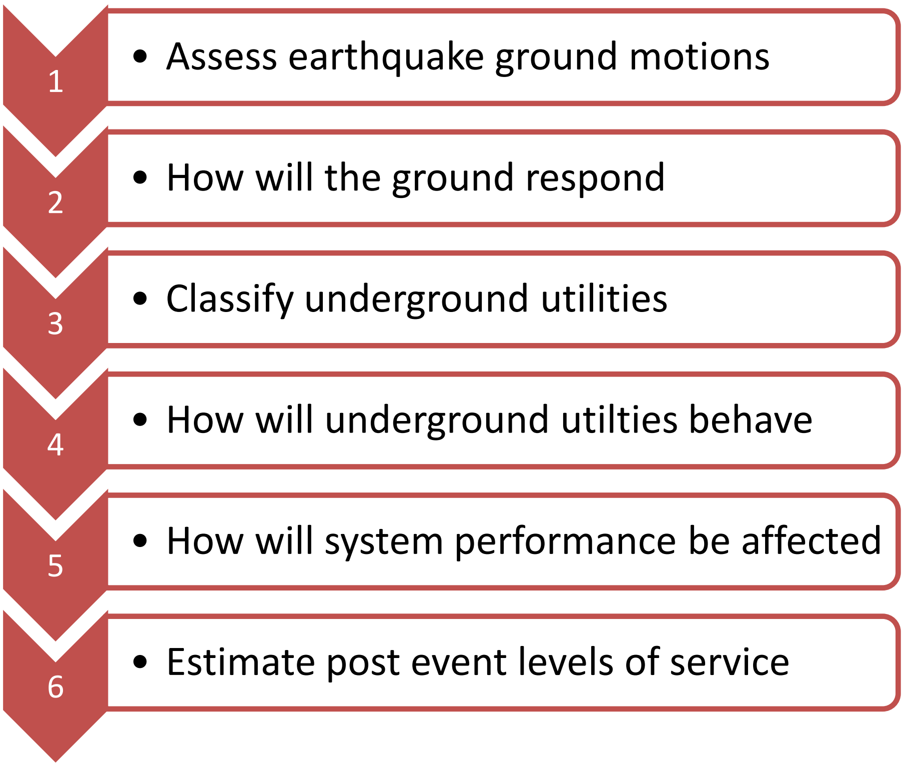


**Figure 4-1. Process for assessing system vulnerability**

It is envisaged that the process outlined in the guidelines will be used to undertake an initial screening to identify areas of potential concern. Then if necessary, further analysis will be undertaken to refine the predictions. This may involve undertaking further:

- Geotechnical site investigation and/or additional analysis of ground performance
- Additional analysis of utility and system performance

## 4.1 Assess Earthquake Ground Motions

### 4.1.1 Why Assess Earthquake Ground Motions?

The parameters established below are used to predict how the ground will respond and in turn how underground utilities will behave under the design earthquake.

### 4.1.2 What to do to 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) which provides the most relevant earthquake parameters for design of infrastructure such as underground utilities. Probabilistic earthquake parameters are used generally for the design of infrastructure, including underground utilities.

Where appropriate, assess the potential peak ground accelerations from an earthquake scenario, based on attenuation relationships. This is usually assessed by an experienced seismologist. Scenario earthquakes are generally used in the assessment of existing infrastructure in plausible earthquake scenarios to aid in assessing the effects on communities and planning emergency response. These are generally not used in design.

### 4.1.3 Assessing Earthquake Ground Motions

The methodology included below enables the calculation of earthquake motions expressed as PGA using *NZS 1170.5:2004* (Standards New Zealand, 2004) and *Bridge Manual SP/M/022* (NZTA, 2016).

#### 4.1.3.1 Importance Level

To enable the PGA to be calculated from the various parameters detailed in Equation 1 , several general requirements related to the importance level for structural design must be assessed.

*AS/NZS 1170.0:2002* (Standards New Zealand, 2002) Table 3.1 provides a basis for classifying the importance of buildings and other parts of the built environment. The importance levels can be assigned to underground utilities, depending on their importance to society, as shown in Table 4-1.

Table 4-1. Importance Level of underground utilities

| Importance Level | Description | Comment |
|---|---|---|
| IL1 | Low importance facilities | Utilities providing a service to:<br>• Public recreational areas |
| IL2 | Normal facilities | Utilities providing a service to:<br>• Residential properties, commercial and industrial areas |
| IL3 | Important facilities | Utilities providing a service to:<br>• Primary schools, colleges or adult education facilities<br>• Health care facilities with a capacity of 50 or more resident patients but not having surgery or emergency treatment facilities.<br>• Airport terminals, principal railway stations with a capacity greater than 250.<br>• Correctional institutions.<br>• Emergency medical and other emergency facilities not designated as post-disaster.<br>• Power-generating facilities, water treatment and wastewater treatment facilities and other public utilities not designated as post-disaster.<br>• Other facilities that play an important role in enabling the community to function, e.g. central business district, significant businesses.<br>Trunk main utilities serving a downstream population of more than 10,000 people.<br>Trunk mains providing water supply to downstream fire hydrants that are important for firefighting in the aftermath of an earthquake. |
| IL4 | Facilities with post-disaster functionality | Utilities providing a service to:<br>Facilities designated as essential facilities<br>Facilities with special post-disaster function<br>Medical emergency or surgical facilities<br>Emergency service facilities such as fire, police stations and emergency vehicles garages<br>Utilities or emergency supplies or installations required as backup facilities for post-disaster response.<br>Designated emergency shelters, designated emergency centres and ancillary facilities. |

#### 4.1.3.2 Earthquake Recurrence Interval

Derive the earthquake recurrence interval for design from *AS/NZS 1170.0:2002,* Table 3.3, (Standards New Zealand, 2002) based on the design working life of the facility and the importance level.

Table 4-2 summarises the earthquake recurrence intervals for Ultimate Limit State design of three water utilities assuming a 100 year design life which is commonly accepted for three waters utilities (Standards New Zealand, 2010).

**Table 4-2. Earthquake Recurrence Intervals for 100 Year Design Life**

| Importance Level | Description | Earthquake Recurrence Intervals for ULS Design |
|---|---|---|
| IL1 | Low importance facilities | 250 years |
| IL2 | Normal facilities | 1000 years |
| IL3 | Important facilities | 2500 years |
| IL4 | Facilities with post-disaster functionality | 2500 years or greater |

#### 4.1.3.3 Return Period Factor

Determine the return period factors ($R_u$) for deriving earthquake motions based on *NZS 1170.5:2004* (Standards New Zealand, 2004) depending on the earthquake recurrence intervals. Return period factors for various important level utilities are presented in Table 4-3.

**Table 4-3. Return Period Factor**

| Importance Level | $R_u$ |
|---|---|
| IL1 | 0.75 |
| IL2 | 1.3 |
| IL3 | 1.8 |
| IL4 | 1.8 |

#### 4.1.3.4 Unweighted Peak Ground Acceleration Coefficient

Determine the Unweighted Peak Ground Acceleration Coefficient (C0,1000) for a 1,000 year return period, from the contour maps provided in Section 6 of the *Bridge Manual SP/M/022* (NZTA, 2016).

#### 4.1.3.5 Site Class

Classify the site in line with the soil properties and thicknesses provided in Table 3.3 *of NZS 1170.5:2004* (Standards New Zealand, 2004). The soils underlying the site are known to modify the level of ground shaking at a location.

Classify the site subsoils from Class A to E in *NZS 1170.5:2004* (Standards New Zealand, 2004) for the purposes of deriving earthquake loads and the spectral shape factor.

#### 4.1.3.6 Subsoil Class Factor

Determine the subsoil class factor $f$ based on the site subsoil class as per Table 4-4.

**Table 4-4. Derivation of Subsoil Class Factor, $f$**

| Site Class | A/B | C | D | E |
|---|---|---|---|---|
| $f$ | 1 | 1.33 | 1 | 1 |

#### 4.1.3.7 Near Fault Factor

The near fault factor (N(T,D)) is the factor applied to the calculation in Equation 1 to take into account the proximity of the site to a known fault line. N(T,D) is taken as 1 for peak ground acceleration with a zero period in accordance with *NZS 1170.5:2004* (Standards New Zealand, 2004).

### 4.1.4 Calculating Earthquake Ground Motions

Calculate the Peak Ground Acceleration (PGA) using from the following equation;

**Equation 1 Peak Ground Acceleration**

$$PGA = C0{,}1000.\frac{R_u}{1.3}.f.N(T,D)$$

Where:

***$C_{0,1000}$*** *=1000 year return period PGA coefficient from Bridge Manual* (NZTA, 2016) *Section 6 maps or table of locations*

***f*** *=subsoil class factor*

***$R_u$*** *=the return period factor for Ultimate Limit State (ULS), determined from Table 4-2 but limited such that Z x $R_u$ does not exceed 0.7*

***N(T,D)*** *=the near fault factor determined from NZS 1170.5:2004 ,* (Standards New Zealand, 2004), *Clause 3.1.6*

*Note that Equation 1 derives the earthquake elastic horizontal motions. For permanent deformation and vertical motions more detailed analysis is needed, see Section 4.1.4.1 & 4.1.4.2, and NZS 1170.5:2004,* (Standards New Zealand, 2004). *section 3.2.*

#### 4.1.4.1 Site Specific Seismicity for Strategic Facilities

For strategic facilities, such as those assigned importance levels IL3 or 4, site specific earthquake motions may be derived instead of using the earthquake acceleration estimates based on *NZS 1170.5:2004.*, (Standards New Zealand, 2004). In this instance, the guidance given in *NZS 1170.5:2004* , (Standards New Zealand, 2004),.may be used to engage a specialist to assess these ground motions.

#### 4.1.4.2 Scenario Earthquake

For scenario earthquakes, determine specific ground motions with distance from the fault rupture source using attenuation relationships. Scenario earthquakes are used when there is a need to assess the effects of a particular earthquake scenario on the community and to plan for emergency response. For example, scenario earthquakes such as a characteristic earthquake on the Wellington Fault in Wellington, or a characteristic rupture of a section of the Alpine Fault in the South Island are considered in emergency response planning.

### 4.1.5 Supplementary Information

Technical Note 03 - Earthquake Behaviour Information gives background information on earthquakes, explains why earthquakes occur and describes the seismic waves and ground motions generated.

## 4.2 How Will the Ground Respond

### 4.2.1 Why Assess how the Ground will Respond?

The way that the ground performs during and after an earthquake has a significant bearing on the amount and type of damage sustained by utilities.

Ground performance also influences the LOS experienced after an earthquake and the time to restore service.

### 4.2.2 What to do to Assess how the Ground Will Respond

Determine whether the ground will be subject to transient seismic wave propagation only (through ground shaking) or whether earthquake induced permanent ground deformations may also occur. These may include:

- Surface fault rupture
- Slope failures or landslide
- Liquefaction (including lateral spreading and settlement)

Site specific assessment of the above permanent ground deformations should be undertaken with regards to the location of the utilities under consideration.

### 4.2.3 How to Assess Ground Response

#### 4.2.3.1 Introduction

The ground will respond to earthquake motions in several ways. The actual response will be site specific and depend on several factors.

Underground utilities can be damaged by either transient seismic wave propagation (through ground shaking, ie the expected PGA calculated in Section 4.1.4) or by permanent movement of the ground during and after the event. In general, damage from transient ground movement tends to be less severe than that from permanent ground movements but it affects the whole of the underground system, whereas damage from permanent ground movement tends to be localised but with high damage rates (Tromans, 2004).

Technical Note 03 - Earthquake Behaviour Information and Technical Note 04 - The Liquefaction Phenomenon discusses in further detail the parameters that influence the way the ground responds to transient and permanent deformation.

This section discusses the following types of permanent ground performance:

- Surface fault rupture
- Slope failures or landslides
- Liquefaction (including lateral spreading and settlement)

#### 4.2.3.2 Surface Fault Rupture

An active fault's surface rupture can cause severe damage to utilities within or crossing the fault rupture zone.

Figure 4-2 shows the major faults in New Zealand. The New Zealand Active Fault Database gives further details of known active faults throughout NZ.

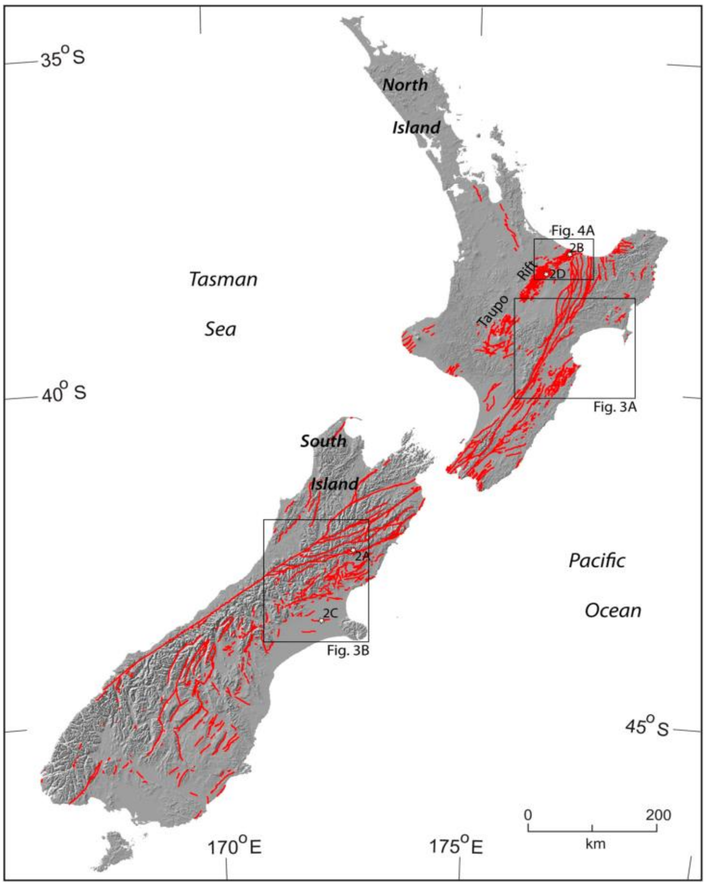


**Figure 4-2. Map of New Zealand highlighting the active faults, extract from Langridge (2016)**

To assess fault rupture hazards:

1. Determine if there are active faults in the area under consideration from Figure 4-2.

2. If there are active faults in the area, then determine the locations of the active faults from the Active Fault Database, and geological maps of the area. If there may be active faults in the area, then engage a suitably experienced geotechnical engineer to undertake Steps 3 and 4 below.

3. Determine the characteristics of the active faults by review of available information, to assess the recurrence interval of the fault, the potential magnitude of displacements in the vertical and horizontal directions and the sense of movement with respect to the fault.

4. Consider the geology of the area, to assess the potential magnitude and distribution of the ground deformation and the fault rupture zone, at the location of underground utilities.

5. Use existing paleo-seismic studies to better characterise ground damage, or in the absence of specific information, carry out more detailed field studies if the fault rupture affects critical facilities.

Figure 4-3 shows the typical form of ground damage from active faults observed in the 4 September 2010 Darfield earthquake.

**Figure 4-3. The 2010 surface rupture trace of the Greendale Fault, Canterbury, courtesy of R Jongens, GNS Science.**

#### 4.2.3.3 Slope Failure or Landslides

Earthquakes can cause slope failures or landslides on moderate to steep slopes. However, landslides have also been recorded on relatively minor slopes, depending on the underlying geology. Recent earthquakes (such as the Kumamoto earthquake in Japan 2016) have also shown that more gentle slopes in sensitive volcanic soils can be affected by landslides.

To assess slope effects:

1. Determine from topographical maps whether the underground utilities are in an area of steep terrain, sensitive volcanic soils or they cross ground with a significant difference in level.

2. Find out whether there are earthquake induced slope or landslide hazard maps for the area. Earthquake induced slope failure hazard studies have been carried out and published for some regions of New Zealand (e.g. Wellington). The studies provide general guidance on the distribution of slope failure hazards in the area, at a regional or district level. At a localised level, slope hazards that are less documented may exist which can have a significant effect.

3. Determine the stability of the sloping ground along or adjacent the underground utilities in earthquakes. Often utilities follow road corridors or alignments that have been modified by construction. This can lead to localized earthquake induced slope failure hazards. For example, sidling cut and fills are often formed to construct roads, and sidling fill is often placed in a loose state or supported by retaining walls, which may be vulnerable to movement or failure in an earthquake. Underground utilities located downslope of potential landsides are also more vulnerable to damage from ground movement.

4. If there are no slope failure hazard studies and utilities are located on moderate to steep or sensitive ground, engage a geotechnical engineer experienced in earthquake slope failures, to assess the earthquake induced slope failure hazards. This will involve a review of the geology and ground conditions, review of aerial photography and site reconnaissance along the pipeline corridors (Brabhaharan, 2010).

#### 4.2.3.4 Liquefaction and Associated Ground Damage

Loose to moderately dense, saturated cohesionless sands, silts and sandy gravels can liquefy during strong earthquake shaking and lose much of their strength and stiffness, refer Figure 4-4.

**Figure 4-4. Liquefaction – lack of ground support**

Liquefaction can cause:

- Loss of strength and stiffness, and support to underground utilities
- Ground subsidence (vertical deformation)
- Differential settlement (due to variable soils strengths over the pipe network)
- Sand boils
- Intrusion of sand and silt into pipelines through joints, defects and damage
- Buoyancy and uplift of underground utilities
- Foundation failure of associated structures founded on liquefiable ground
- Lateral spreading of the ground, particularly towards free surfaces such as watercourses

To assess liquefaction hazard:

1. Determine if liquefaction hazard maps have been developed and published for the area in question and use these if available.

2. If liquefaction hazard maps are not available, engage a geotechnical engineer with experience in liquefaction hazard mapping to assess the liquefaction hazards for an underground utility network. (Brabhaharan, 2010) provides guidance on liquefaction hazard mapping for utility facility assessment.

3. Assess liquefaction and ground damage effects using the guidance provided by the New Zealand Geotechnical Society (2010).

4. Determine the consequences of liquefaction, ie subsidence of the ground, and potential for lateral spreading, based on the liquefaction assessment and the terrain, ie presence of watercourses.

5. Estimate the magnitude of lateral spreading as this can be very damaging to underground utilities, see Figure 4-5 and Brabhaharan (2010).

6. Assess the presence of historic watercourses/channels that have been cut off. Reclaimed land has the potential to liquefy but may not be immediately apparent on maps or the surface. These areas can be found using historical accounts and regional maps. It was found after the CES that significant liquefaction damage occurred at historic watercourses / channels that had been cut off since the 1850s and old land reclamation areas (Wotherspoon, Pender, & Orense, 2010).

**Figure 4-5. Lateral spread**

### 4.2.4 Supplementary Material

Technical Note 04 - The Liquefaction Phenomenon describes liquefaction and, the nature and distribution of soils that are susceptible to soil liquefaction.

## 4.3 Classifying Underground Utilities

### 4.3.1 Why Classify Systems?

To group pipeline systems into broader categories that reflect their vulnerability to damage. The classification helps highlight trends in behaviour for planning purposes.

### 4.3.2 What to do to Classify Underground Utilities

Classify the underground utilities system as being:

- **Pressurised** systems - e.g. potable water systems
- **Non-pressurised** systems - e.g. stormwater systems
- **Other** systems - e.g. cables

Classify the underground utility as being either continuous or segmented:

- Utilities are classified as **continuous** if the strength and stiffness of the joints is similar to that of the pipe barrel.
- Utilities with joints where movement can occur are classified as being **segmented**.

Classify the underground utility as being either rigid or flexible:

- Pipelines with a high degree of stiffness compared to the soil stiffness are classified as **rigid**.
- Pipelines which have comparatively low stiffness are classified as being **flexible**. Cables are typically classified as being flexible.

Classify the underground utility by size:

- Mains are larger pipelines typically with few or no connections to individual properties.
- Distribution systems are medium sized pipelines which carry material from mains to near the point of use. Most customer connections are made to distribution pipelines.
- Laterals and service pipes used to connect properties to the distribution system.

Classify pipeline rehabilitation systems the same way as for a new construction.

### 4.3.3 How to Classify Underground Utility Pipes

#### 4.3.3.1 Pressure or Non Pressurised

Internal pressure (including any surge effects) dominates design of pressurised systems while external loads usually dominate the design non-pressurised systems. These design considerations and resulting construction can influence the form of failure in a seismic event.

Table 4-5 shows systems that are typically pressurised or non-pressurised.

Table 4-5. System Classes

| | Pressurised | Non Pressurised | Other |
|---|---|---|---|
| Potable Water | √ | | |
| Wastewater | √ | √ | |
| Stormwater | √ | √ | |
| Gas | √ | | |
| Electrical | | | √ |
| Telecommunications | | | √ |

#### 4.3.3.2 Continuous or Segmented

Underground utilities are generally formed from either continuous or segmented pipes. Continuous pipelines are either created from single lengths with no joints or if there are joints, they are formed such that strength and ductility are essentially unchanged across the joint. In contrast, the joints of segmented pipelines provide a discontinuity in strength or ductility or both.

Continuous pipes include:

- Coiled polyethylene (PE) and polypropylene pipes and ducts
- Fusion jointed PE pipelines and potentially polypropylene and fusible polyvinyl chloride (PVC) lines
- Solvent cemented PVC
- Glass reinforced plastic pipes with laminated joints
- Modern welded steel pipelines
- Cured in place pipes, spiral wound liners and fold & form liners installed between manholes in a single length

Segmented pipes include:

- All pipes with flanged joints, rubber ring joints, lead run joints, mortared joints, collars, compression joints, gibaults and threaded joints
- Ducts and cables where the joints result in a substantial change to strength or ductility

#### 4.3.3.3 Flexible or Rigid

Flexible pipes can deflect vertically at least 2 percent, and often a lot more, without structural distress. These flexible pipelines rely primarily upon side support from the soil around the pipes to resist vertical loads (Standards New Zealand, 2002). Flexible pipes include:

- Plastic pipes such as PVC, PE, PP, GRP
- Steel
- Cured in place pipes, spiral wound liners and fold & form liners

Rigid pipes generally start showing signs of structural distress before 2 percent vertical deflection. Hence they are assumed to support the full force of the soil prism and live loads above the pipes without any side support from the surrounding soil. Rigid pipes include reinforced concrete, earthenware, asbestos cement and cast iron pipes.

In addition, older steel pipelines (lap welded, riveted, lockbar) with substantial discontinuity resulting from fabrication are considered rigid since these fabrication systems cannot accommodate any significant displacement, especially if the pipe is deteriorated.

#### 4.3.3.4 Mains, Distribution or Service Pipeline

Classify pipelines based on size as follows:

- Mains are larger pipelines, usually >DN200 for water mains, but typically considerably larger for wastewater and stormwater systems. Water mains typically have few or no connections to individual properties.
- Distribution systems are medium sized pipelines which carry water from mains to near the point of use or convey waste or stormwater from the collection point to larger mains. Most customer connections are made to distribution pipelines.
- Connections (laterals and service pipes) are used to connect properties to the distribution system. For water supply they are usually DN40 or less and typically include several components and material types (for example flow meters and stop valves). New wastewater and stormwater connections are usually DN150 or larger, but older ones may be smaller.

Break rates are usually higher in smaller pipelines, and lower in larger pipelines (Morris, 2002). Reasons for this include:

- Larger pipelines are typically more critical and are accordingly designed in more detail. Since there are few direct connections, re-routing to avoid known hazards is more feasible and construction supervision is typically to a higher standard. The materials and jointing systems tend to be stronger and more robust and are more likely to have been deliberately selected for the system.
- Smaller connecting pipelines have to run from a property to the nearest distribution line, so there is limited choice of location and direction. Bends, intermediate fittings and changes of material are common, and the materials are often relatively weak due to their small size or from the type of fittings required. The low cost of individual connections discourages high levels of construction supervision, detailed design and materials selection.

### 4.3.4 Summary

Table 4-6 shows the typical pipeline system classifications used in New Zealand.

**Table 4-6. Classification of pipeline systems commonly used in New Zealand**

| | Continuous | Segmented |
|---|---|---|
| Flexible | Modern PE[1] with fused joints or mechanical joints with inserts.<br>Fusible PVC<br>Solvent jointed PVC Modern welded steel<br>Laminated GRP<br>Cured in place pipe (CIPP) linings | PE (older materials and other joints)<br>Polyvinyl Chloride (other joints)<br>Steel that is not welded<br>Older steel (riveted, lap welded, lockbar)<br>Ductile Iron[2]<br>Other GRP |
| Rigid | | Asbestos Cement<br>Cast Iron<br>Concrete<br>Earthenware<br>Wooden pipes |

**Notes:**

1. Only PE80 and PE100 pipes can be considered as modern PE.
2. Ductile Iron with earthquake resistant joints can behave as a continuous pipe.
3. The different forms of PVC can be considered the same here.
4. Acrylonitrile butadiene styrene (ABS) can be considered the same as PVC with the same joint type.
5. PE80 and PE100 can both be considered the same here.
6. Older steel can behave as a flexible system but may fail along the seam in a more brittle manner.

## 4.4 Predict How Underground Utilities Will Behave

### 4.4.1 Why Predict How Underground Utilities Will Behave?

A well-made prediction identifies those assets that are most vulnerable to damage and provides a general indication of the extent and type of damage that might occur, including:

- Failures requiring repair to restore service
- Damage to be rectified to reinstate condition, including sub-critical damage that degrades service but does not result in complete loss of function
- Earthquake related damage that is only minor and does not warrant repair

This is used to estimate post-event LOS to develop response plans and to identify and prioritise measures to improve resilience, including:

- Quantifying the amount of repair works that may need to be required, e.g. for insurance and planning purposes, and
- Prioritising renewal works to improve resilience

### 4.4.2 What to do to Predict How Underground Utilities Will Behave

Predict the extent of expected damage from the following risk factors and a suitable fragility function:

- Ground shaking
- Liquefaction
- Lateral spreading of land
- Slope failures
- Fault crossings
- Connections and discontinuities
- Undertake a sensitivity analysis

### 4.4.3 How to Predict How Underground Utilities Will Behave?

- Estimate the PGA for the design earthquake in accordance with Section 4.1
- Predict how the ground will respond in accordance with Section 4.2
- Classify underground utilities in accordance with Section 4.3
- Use this information to estimate the extent of expected damage in accordance with the following sections

#### 4.4.3.1 Pressure Systems

Predict the expected extent of damage for pressure pipes using the damage rates given in Table 4-7 based on size and system type. Note that most modern pipeline systems can also experience sub-critical damage or delayed failures, as well as outright damage, so there may be additional failures in future as a result of seismic events. However, since subcritical failures and delayed failures will not usually be detected until well after an event, it is not currently possible to quantify their effect.

**Table 4-7. Damage Rates for Pressure Systems (breaks per 10km)**

| Description | Laterals (service connections) | | Mains | | Transmission | |
|---|---|---|---|---|---|---|
| Size | 40mm & below | | Above 40mm but under 200mm | | 200mm & above | |
| System | Galvanized Iron [1] | Other systems [2] | Flexible [3] | Rigid Segmented [4] | Flexible [3] | Rigid Segmented [4] |
| Shaking Only | 4 × Equation 2 | 3 | 2 | Equation 2 | 2 | Equation 2 |
| Liquefaction [5] | 55 | 5 | 5 | 20 | 5 | 20 |
| Lateral Spread | 90 | 25 | 25 | 55 | 25 | 55 |
| Fault Crossing | Assume failure at crossing unless utility has been specifically designed. | | | | | |
| Slope Failure | Assume failure unless utility has been specifically designed [6]. | | | | | |

**Notes:**

1. Galvanized Iron is singled out as it had particularly high break rates
2. There was insufficient information to reliably distinguish the performance of copper, PE and PVC. Modern PE joints with inserts and fused systems would probably have break rates of half or less.
3. Includes continuous (PE) and segmented (steel and PVC). There was limited information on Ductile Iron pipe but it appears to have behaved as a flexible pipeline system.
4. In practice, these are obsolete systems such as AC and Cast iron and older steel pipes.
5. Liquefaction is the process of cohesionless soils transforming from a solid state to a liquefied state as a consequence of increased pore pressure and reduced effective stress. In this context liquefaction is caused by earthquake ground shaking leading to the above process.
6. Some flexible continuous pipelines may be able to withstand small slope failures.

Use Equation 2 to predict damage in areas where the only damaging factor is shaking.

**Equation 2 Damage rate for pressure pipelines subjected to shaking only**

$$Damage\ rate\ \left[\frac{breaks}{10km}\right] = 17.6 \times PGA\ [g] - 1.6$$

Use Equation 3 to initially predict damage rates for pressure pipes within 200 m of watercourses where liquefaction is predicted but a geotechnical assessment has not been undertaken to determine the extent of lateral spread.

**Equation 3 Damage rate for pressure pipes in areas subjected to liquefaction and near watercourses**

$$Damage\ rate\ \left[\frac{breaks}{10km}\right] = Lateral\ Spread\ damage\ rate\ from\ \text{Tablee4-7} \times \left(1 + \left(\frac{200 - distance\ from\ watercourse}{200}\right)\right)$$

For shallower tributary channels (typically 2-3 m deep as opposed to 3-5 m deep main stream channels), the lateral spreading zone can be reduced to 100m on either side of the watercourse, measured from the banks.

Assume utilities that cross faults or that experience slope failures will be damaged and require repair unless the utilities have been specifically designed.

#### 4.4.3.2 Gravity Systems

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

In most systems, less work is required to restore service than to fully reinstate the pre-event condition. However, in some vulnerable systems such as earthenware pipelines, the damage may be so extensive that restoring the function effectively requires a complete reconstruction of the system.

Note that the damage tables below only include damage rates for PGA up to 0.3g as there was insufficient information available from the CES for peak ground accelerations above 0.3g in areas where shaking occurred without liquefaction or other effects.

##### 4.4.3.2.1 Restoration of Gravity Systems

Predict the extent of works needed to restore service using the damage rates in Table 4-8.

This assessment enables asset managers to:

- Communicate with stakeholders regarding the possible location and duration of service outages
- Plan response activities such as identifying priorities and estimating the amount of resources that might be required
- Prioritise renewals works to improve system resilience

It is likely that most of this damage can be repaired by CIPP patching, although some open cut excavation for spot repairs may be needed to clear collapsed and severely displaced sections.

**Table 4-8. Gravity Pipelines - Damage Rates for Restoring Service (Break per 10km)**

| Ground Conditions | Pipeline system | Damage Rate (Breaks/10km) |
|---|---|---|
| Shaking only<br>(for PGA in the range of 0.2 – 0.3 g) | All | Nominal, 0.3 |
| Liquefaction | Rigid, segmented AC & EW (older systems [1]) | 250 |
| | Rigid, segmented RCRRJ | 70 |
| | Flexible, segmented PVC | 20 |
| Lateral Spread | Rigid, segmented AC & EW (older systems [1]) | 500 |
| | Rigid, segmented RCRRJ | 160 |
| | Flexible, segmented PVC | 50 |
| Fault Crossing | Assume failure at crossing unless utility has been specifically designed. | |
| Slope Failure | Assume failure unless utility has been specifically designed [2]. | |

**Notes:**

1. This would include any older concrete pipes with mortared or lead run joints.
2. Some flexible continuous pipelines may be able to withstand small slope failures.

#### 4.4.3.2.2 Reinstatement of Gravity Systems

Predict the extent of further work that may be needed, on top of damage repaired to restore service, to reinstate the system to the pre-earthquake condition using the damage rates given in Table 4-9.

This assessment enables asset managers to:

- Quantify the amount of works that may need to be repaired, e.g. for insurance and planning purposes
- Prioritise renewal works to improve resilience

**Table 4-9. Gravity Pipes - Damage Rates for Reinstating Condition**

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

**Note**

1. This would include any older concrete pipes with mortared or lead run joints.

It is likely that all asbestos cement and earthenware pipes with dips greater than 25% will need to be relaid. However, it may be appropriate to accept dips greater than 25% in concrete and PVC pipes where more frequent jetting to remove material that might accumulate at the dip can be accepted.

Spot repairs can generally be undertaken by either patching and/or open-cut repairs. Approximately half of pipes requiring relay or rehabilitation are likely to be able to be rehabilitated by structural lining. If dips are to be removed, then lining is not appropriate and the pipes will need to be re-laid.

Further research is required to establish damage rates for peak ground accelerations above 0.3g in areas where shaking only is expected to occur.

#### 4.4.3.3 Other Systems

The guidelines focus on the three waters systems (potable, waste and storm) as these systems are usually the worst affected in seismic events. However, the research work that supported the development of the guidelines also considered the seismic performance of other underground systems including:

- Gas pipelines
- Ducted services
- Electrical cables
- Telecommunications cables

Technical Note 05 - Response of Buried Assets Other Than Water Pipelines provides an overview of the behaviour of these systems. As would be expected, most of these utility services performed similarly to comparable systems used in three waters applications. As with three-waters utilities, there was evidence that damage included sub-critical damage, delayed failures and hidden failures, and evidence that installation practice influenced damage rates.

### 4.4.4 Basis of The Proposed Damage Rates

The basis for the damage rate prediction for pressure pipelines is provided in Technical Note 06 - Basis for Damage Rate Prediction for Pressure Pipes. These predictions are based on observations from the CES of 2010 & 2011, as well as other international experience.

The basis for the damage rate prediction for gravity pipelines is provided in Technical Note 07 - Assessment of Kaiapoi Wastewater Damage. These predictions are based on observations from Kaiapoi from the 2010 Canterbury Earthquake. Similar observations from Christchurch city during the CES of 2010 & 2011 were also used to cross-check the proposed damage rates (Cubrinovsk, et al., 2014)

The performance of the ground significantly impacts upon damage rates. For example damage rates are a lot higher when liquefaction occurs than where shaking only occurs, and are a lot higher again when lateral spread, fault rupture or slope failure occurs.

It is important to note that fragility functions for predicting damage rates are based on limited empirical data from only a few past earthquakes and should be used with caution. These damage rates are provided as first-cut information to help with a quick assessment and screening of the network vulnerabilities to earthquake shaking and its secondary effects.

More detailed damage rate models can be found in Technical Note 06 - Basis for Damage Rate Prediction for Pressure Pipes and in similar guidelines developed by the American Lifelines Alliance (2005). These detailed models are recommended where the above initial assessment warrants a more detailed analysis. These models require more hazard information such as Liquefaction Severity Number (LSN), post-liquefaction reconsolidation settlement index ($S_{V1D}$) or an estimation of permanent ground displacement that may not be readily available for an initial assessment.

It is also worth mentioning that research both in New Zealand and overseas has shown that in the absence of permanent ground deformation (e.g. liquefaction) where transient ground motions are the dominant cause of damage, Peak Ground Velocity (PGV) better correlates with damage to underground pipes than PGA. However, since the primary aim of this section of the guidelines is to provide the necessary information required for a preliminary assessment of likely damage to underground utilities from earthquakes, the use of readily available PGA information is recommended in the above calculations. This is deemed to be adequate for the present guidelines.

Despite their limitations, the proposed damage rates in this section of the guidelines provide one of the most useful initial guides to estimating overall patterns of behaviour in New Zealand

### 4.4.5 RiskScape

RiskScape may be used to predict the extent of damage. It is a multi-hazard regional impact and loss modelling tool designed and developed to assist organisations with estimating impacts from natural hazards including both material and human losses.

The RiskScape impact calculation module enables modelling of earthquake damage and losses to underground potable, waste and stormwater pipe networks spatially, considering variations in the network composition, severity of shaking, ground conditions etc. across the network. The module helps estimate the likely number of breaks and the consequent repair time and cost for both existing and future pipe networks. Impact simulation results are reported in the form of average number of breaks, and average repair times and costs for each suburb (or any other aggregation unit of choice). These results can then be compared against the target levels of service and decisions can be made on the necessary actions to improve resilience.

RiskScape comes pre-loaded with the necessary earthquake shaking hazard information to enable damage modelling. Depending on the average annual exceedance probability of the earthquake shaking selected by the user (as described in Section 4.1), a list of representative events for the specified return period is displayed to choose and run a scenario to simulate the impacts. Network GIS information can be easily put in a RiskScape asset module format using the asset module builder that comes with the RiskScape software. The damage rate models described in the previous sections are built into the software and both simple and more detailed models can be used. All other necessary modules including liquefaction susceptibility information (resource modules) and network sub-system boundaries for aggregating the results (aggregation modules) can be uploaded onto the RiskScape module repository using the relevant builder tools and used within RiskScape. All the necessary builder tools come as part of the software package. More information about RiskScape in general can be found at www.riskscape.org.nz.

### 4.4.6 Sensitivity Analysis

As noted above, the proposed damage rates are based on limited empirical data from only a few past earthquakes, and since no two earthquakes or systems are the same they should be used with appropriate caution. Causes of uncertainty can include the following factors:

- Gaps in asset information on material types, sizes, soil types, etc.
- Historic changes in materials usage, manufacturing standards and installation practices
- Pre-existing damage due to construction defects, aging or post-construction damage
- Seasonal changes in water table level and its effect on susceptibility to liquefaction and lateral spreading
- Incomplete knowledge of fault locations
- Tectonic subsidence or uplift from an earthquake and its effect on susceptibility to liquefaction or flooding in future events

Some form of sensitivity analysis is recommended to allow for the inherent inaccuracy of forecasting, and to address the impact of uncertainty on response plans. Technical Note 08 – Sensitivity Analysis for Seismic Damage Prediction provides further information.

### 4.4.7 Key Lessons from Canterbury Earthquakes and Elsewhere

Review of reports of damage from New Zealand and elsewhere provides an insight into factors that control damage to underground systems in earthquakes. Technical Note 09 - Photobook of Damaged Underground Utilities is a photographic guide to damage observed in recent seismic events in New Zealand (mostly from the CES) that provides illustrations of how different pipeline systems responded. Key findings are summarised below

- The performance of the ground has far more influence on damage than shaking and other forces resulting directly from earthquakes.
- Axial forces along utilities cause the majority of damage. Most of the damage occurs at pipe joints, especially in tension.
- Tension separated unrestrained rubber joints and mechanical joints, particularly in areas of lateral spread as shown in Figure 4-6.

**Figure 4-6. Pipe failure under tension in area of lateral spread**

- Compression caused local bending or buckling damage and caused damage to joints. Bending generally occurred in shallow-buried pipelines with a high aspect ratio (where the diameter is small relative to the length).
- Bending and other transverse loading tended to cause most damage in older rigid pipeline systems. All utility materials sustained damage in the CES, but modern flexible pipe materials generally suffered a lot less damage than older, more brittle pipe materials. Figure 4-7 and Figure 4-8 demonstrate the ability of PVC to withstand significant compressive movement.
- Larger pipelines typically sustain less damage than smaller pipelines. This has been recognised for some time (Morris, 2002). Contributing factors include:
    - » Larger pipelines are usually stronger than smaller ones
    - » Site-specific design is generally undertaken for larger pipes whereas less design input tends to be put into smaller pipes
    - » Construction supervision standards are typically greater for larger and more critical pipelines

- Service pipe connections sustain the most damage. This is because service pipes are often formed from older materials with weak joints and have multiple bends and other weak points. However, even modern PE service pipe sustained significant damage in the CES. This was attributed to failure of mechanical couplings where inserts had not been used (Morris, McFarlane, Cook, & Hughes, 2015). If inserts are used, fully end load resistant joints can be achieved and the likelihood of failure significantly reduces because displacement can be transferred from the joint or fitting into the barrel of the pipe which can accommodate greater deformation.

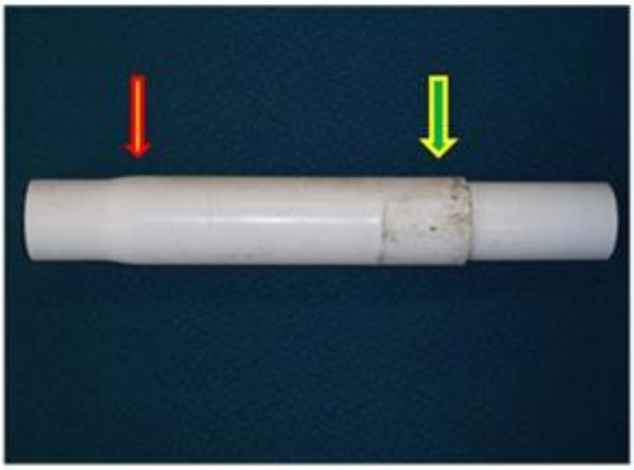

**Figure 4-7. Modern PVC displaying capacity to resist failure in compression.**

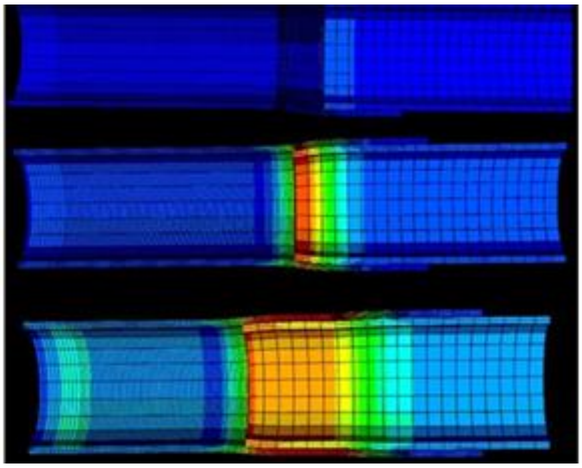

**Figure 4-8. Finite Element model showing distribution as the pipe travels past the base of the socket**

- Degradation reduces the tolerance of underground utilities' to seismic loads, refer Figure 4-9. However, the older pipeline systems that are most vulnerable to deterioration would also be vulnerable to seismic failure even when new and because the joints and pipe barrels have limited tolerance to movement, refer Figure 4-10. In addition, by the time a pipeline has degraded enough to be appreciably more vulnerable to seismic loads, it will also be at risk of failure in normal service and may already have been replaced. In short, although earthquakes bring forward failure in degraded pipes, the effect is often less than expected. Technical Note 10 - Effect of Deterioration on Seismic Resistance of Underground Pipelines Systems discusses the matter in more detail.

Figure 4-9. Steel pipe leaking due to dislodgement of corroded material

Figure 4-10. Asbestos cement pipe joint failure

- Damage can occur at connections and discontinuities where the movement of buried utilities during earthquakes is restricted or where there is differential movement between connecting or adjacent structures. Figure 4-11 shows an example of a PVC pipeline that has been bent around a rigid concrete structure. Despite the severe distortion, the pipe did not leak although it was almost closed off and was effectively not functional. Figure 4-12 shows a PVC pipe running through the concrete abutment of a bridge. The clearance around the pipe in this case is sufficient to prevent damage occurring due to differential movement between the pipe and the abutment.

Figure 4-11. PVC pipe bent around rigid structure

Figure 4-12. Pipe running through concrete abutment of a bridge

- Pipeline renovation systems – Whilst pipe lining systems are being used more frequently to renew pipelines, particularly gravity pipelines, there is very limited experience in New Zealand and elsewhere on lined pipes being exposed to seismic loads.

  There was one case reported in the CES where a CIPP liner installed in an ovoid brick sewer partially collapsed. This appears to be due to additional hydrostatic loading being applied to the liner as a result of the ground around the liner liquefying. This highlights the need to consider possible liquefaction loads in the design of liners.

Although the liner collapsed over a length of some 15m, the pipe still functioned without a noticeable drop in service which indicates that CIPP liners provide a good level of resilience.

With all lined pipes, the most vulnerable point is where service pipes and other connections are present since only a small displacement can result either in disconnection or closure of the opening. Strongly bonded strong connections that are attached to flexible lateral or service pipe connections have the best chance of accommodating displacements and relative movements between pipe and the customer connection.

The sealing between the liner and the host pipe at the manhole connection may be vulnerable to failure due to differential movements between the liner and the host pipe. This can result in exfiltration or inflow. However, this should be fairly straight forward to repair.

Technical Note 11 - Effect of Pipe Linings and Patch Repairs on Seismic Performance provides further discussion on the performance of pipes containing lining and patch repairs.

### 4.4.8 Supplementary Material

Technical Note 05 - Response of Buried Assets Other Than Water Pipelines

Technical Note 06 - Basis for Damage Rate Prediction for Pressure Pipes

Technical Note 07 - Assessment of Kaiapoi Wastewater Damage, which outlines basis for the prediction of damage rates for gravity pipelines

Technical Note 08 - Sensitivity Analysis for Seismic Damage Prediction

Technical Note 09 - Photobook of Damaged Underground Utilities, provides a condensed collection of several thousand phonographs of damaged pipes and related infrastructure taken after the CES.

Technical Note 10 - Effect of Deterioration on Seismic Resistance of Underground Pipelines Systems

Technical Note 11 - Effect of Pipe Linings and Patch Repairs on Seismic Performance

# 4.5 Predict How System Performance Will be Affected

### 4.5.1 Why Predict System Performance

The expected system performance is used to estimate post-event LOS to develop response plans and to identify and prioritise measures to improve resilience.

### 4.5.2 What to do to Predict System Performance

Estimate the time it will take to restore service to the post-event LOS defined in Section 3 considering the following:

- Extent and location of damage
- Redundancy
- Response resources
- Availability of alternative supplies

### 4.5.3 How to Predict System Performance

The time required to restore service after an earthquake is described in the following formula:

**Equation 4 Restoration Time**

$$T_r = T_b + T_p \qquad if\ T_p > \left(\frac{Extent_{of_{General_{Damage}}}}{Repair_{Rate}}\right)$$

$$T_r = T_b + \left(\frac{Extent_{of_{General_{Damage}}}}{Repair_{Rate}}\right) \qquad if\ T_p < \left(\frac{Extent_{of_{General_{Damage}}}}{Repair_{Rate}}\right)$$

$\boldsymbol{T_r} = Restoration\ time$

$\boldsymbol{T_b} = Time\ to\ begin\ restoration$

$\boldsymbol{T_p} = Time\ to\ restore\ pinch\ point$

The elements influencing service restoration timing are shown in Table 4-10.

**Table 4-10. Factors influencing restoration times**

| Item | Inferences |
|---|---|
| Time to begin restoration ($T_b$ ) | • Priority of service/service element<br>• Access to site<br>• Availability of manpower, staff, equipment and materials |
| Extent of general damage | • Amount of damage (as predicted in Section 4.4)<br>• Availability of alternative measures<br>• Redundancy |
| Repair rate | • Number of crews<br>• Production rate<br>• Location, depth, ease of access, ground conditions |

| Item | Inferences |
|---|---|
| | • Repair method, other factors, e.g. system re-block in liquefied areas<br>• Knowledge of system |
| Restoration of pinch points. $T_p$<br>(e.g. restoration of services across areas where significant permanent deformation occurred (e.g. fault crossing, landslides, lateral spread) or restoration of pump stations) | • Ease of access, difficulty of making permanent repairs<br>• Time to provide alternative/temporary suppler<br>• Criticality of asset, e.g. is the asset essential or can service be provided without it. |

#### 4.5.3.1 Redundancy

Redundant utilities, where supply can be provided through two or more utilities, increase post-earthquake operational reliability, provided the redundancy meets the following criteria:

- Damage to one utility is unlikely to lead to damage on other redundant utilities
- The redundant services are spatially separated by an adequate distance through potential ground deformation zones (landslide, fault movement, ground failure, lateral spreading, etc.). They should be located so that if ground deformation occurs, each redundant utility would not be subject to the same conditions.

Determine reliability in a redundant system using Equation 5:

**Equation 5. Reliability in a system**

$$R = 1 - (1 - R_{1)}(1 - R_2)(\dots)(1 - R_{L_R})$$

Where $R_{LR}$ is the reliability of the $L_R$ the redundant pipeline.

If, for example, service can be provided through two pipelines, one with a 90% likelihood of providing service after a particular event and the other a 85% likelihood. Then reliability of the system is 98.5%, as calculated below:

$$R = 1 - (1 - 0.9)(1 - .85) = 0.985$$

### 4.5.4 Key Lessons Learnt from Canterbury Earthquakes and Elsewhere

- The performance of the ground influences the ability of the system to remain in service. Experience in Christchurch was that if the ground liquefied then the wastewater system blocked regardless of the amount of damage sustained due to sand and silt entering through gully traps and manholes.
- The time it takes to restore service is affected by both the soil conditions and the amount of damage sustained. In Christchurch, the earthenware portions of the wastewater system that were in liquefied ground tended to take the longest to restore to service as sand continued to enter the system through pre-existing faults and damage from the earthquake, refer Figure 4-13. On the other hand, it took less time to restore the PVC portions in liquefied ground as although they initially blocked they tended to not re-block once they had been cleaned. PVC is also relatively easy to clean in normal service conditions (PIPA, 2009) and this may assist in removal of silt and other debris. Likewise, service could be restored to earthenware systems in ground that did not liquefy fairly early in the recovery process.

- Excavations in liquefiable material were difficult and expensive because of the high water table and unstable ground. To excavate below 1.5m, sheet piling and well pointing was often required, refer Figure 4-14. In many cases, trenchless repairs using CIPP patches proved more efficient.
- The quantum of damage sustained to non-critical pipes often controlled the time it took to restore service. For example, the lifting of the boil water notice on the potable water system was largely governed by the time it took to repair the multitude of small leaks that occurred on service connections rather than the condition of the larger pipelines that the service pipes were connected to.

**Figure 4-13. Failed earthenware pipe**

**Figure 4-14. Use of sheet piles in pipeline construction**

- Alternative means of providing service can be used but they take time to install and the public can only tolerate them for so long. For example, in Christchurch, areas were serviced for significant periods using portaloos placed on the berm outside properties. Over time, as the wastewater system was restored to enable intermittent service to be provided, the portaloos were replaced with portable chemical toilets that could be used inside homes. These in turn were replaced where necessary by chambers installed outside properties that enabled the occupants to use their wastewater system as normal with waste being removed by sucker trucks.
- Restoration of service is multi-faceted. It has been identified from studies after the Los Angeles earthquake (Davis, 2011) that it is an over-simplification to consider the restoration of service as one element. Instead there are different categories of service that need to be considered. For example, water supply can be categorised into water delivery, quality, quantity, fire protection, and functionality. The time it takes to restore these service categories can vary significantly with some categories being restored within an hour and others taking many weeks or even years.

Restoration of service involves several phases as shown in Figure 4-15.It may take many years to fully restore service to the pre-earthquake condition. Priorities and needs change as restoration progresses through these phases.

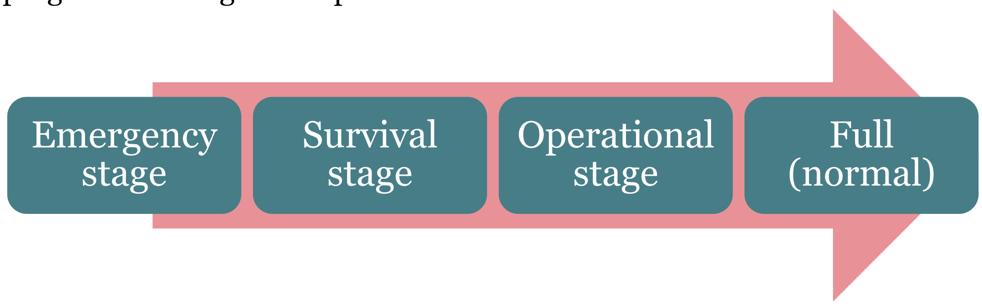


**Figure 4-15. Disaster recovery stages**

# 5 Improve Resilience of Existing Systems

## 5.1 Why Improve the Resilience of Existing Systems?

The impact of earthquakes on communities and the economy can be reduced through a combination of response planning, renewals prioritisation and CAPEX works which have the potential to significantly improve the resilience of existing systems. In many cases this does not involve significant capital expenditure.

## 5.2 What to do to Improve Resilience of Existing Systems

To improve resilience in an existing system the following measures should be considered:

- Reduce exposure of the system to the hazard
- Increase speed and effectiveness of the response to the disaster
- Increase the flexibility of the system to adapt to hazardous events, reducing the post event consequences
- Increase the robustness of utilities

Prioritise improvement measures based on the improvement in post-event levels of service achieved for the investment required.

Develop an action plan for improving resilience.

## 5.3 How to Improve Resilience of Existing Systems

The resilience of the network is a function of both the ability of the utility organisation to respond to the event and the resilience of the infrastructure.

### 5.3.1 Organisational Resilience

The factor that clearly distinguishes organisations that bounce back from disruptions quickly, and even profit from them, is their corporate culture (Sheffi, 2007). “Smart organisations practice crisis management in good and bad times. Thus, they experience substantially fewer crises and are substantially more profitable” (Mitroff, 2005).

Common traits of these organisations are (Sheffi, 2007):

- Continuous communications among informed employees
- Distributed power
- Passion for work
- Conditioning for disruptions

Additional information about planning for events and improving organisational resilience can be obtained from www.resorgs.org.nz. The website includes a survey tool that organisations can use to measure their organisational resilience. New Zealand companies are advised to actively adopt and practice corporate resilience.

### 5.3.2 Infrastructure Resilience

The resiliency of existing utility systems can be improved through a combination of the measures outlined in Table 5-1.

**Table 5-1. Measures to Improve Resilience of Existing Systems**

| | Response Planning | Prioritised Renewals | CAPEX Improvements |
|---|---|---|---|
| Reduce exposure to adverse conditions, e.g. relocating underground utilities to areas less susceptible to ground damage | | √ | √ |
| Increase speed of response after an earthquake | | | |
| • Planning – spares, records and plan availability, triggers for different actions or for calling in outside help | √ | | |
| • Improving ease of repair | | √ | √ |
| • Reduce impact of damage to roads and other services caused by slips, washouts, etc. | | √ | √ |
| Increase flexibility of the system | | | |
| • Add facilities for alternative supplies, e.g. installation of connections to enable potable water to be provided to community buildings via tankers. | | | √ |
| • Increase redundancy - line duplication, ring mains, extra storage | | | √ |
| • Improve ability to maintain and restore service – isolation points for vulnerable sections, telemetry to aid status monitoring and performance | | √ | √ |
| Increase robustness of utilities – reducing the likelihood of underground utilities being damaged. | | √ | √ |
| • Alternate supply routes – locating utilities where they have greater likelihood of survival | | | √ |
| • Use modern, more robust systems in new and replacement systems | | √ | √ |
| • Retrofit damage control systems for example, anti-flotation valves in manholes to stop them rising and additional isolation valves to control the flows within the system. | | | √ |

### 5.3.3 Response Planning

To assist with response planning, develop an emergency response plan that:

1. Identifies hazards (refer Section 4.1 & 4.2), system vulnerabilities (refer Section 4.4) and key users (refer Section 2.5)
2. Describes general strategies for prioritising repairs so that post-event LOS are improved as quickly and efficiently as possible. Figure 5-1. shows general recovery priorities


**Figure 5-1. Recovery priorities**

3. Includes a repair strategy – Identifying types of defects that might be repaired and where and how alternative supplies may be provided, e.g. after the CES, overland water supply pipelines and portaloos were used extensively to restore levels of service to tolerable levels.
4. Considers the extent of repairs that might be undertaken. In Kaiapoi, the decision was made that initially the system would only be repaired enough to restore service. Renewal of the network to its pre-earthquake condition was not attempted except in a few specific cases. This decision was made in order to restore services as quickly as possible and to ensure that when renewal works were carried out these would be the correct works for the long term. This decision proved appropriate as it was subsequently decided to abandon significant portions of Kaiapoi and not reinstate the water and wastewater networks in these areas.
5. Identifies personnel, material and equipment requirements. Determine how these might be obtained, addresses requirements for stockpiling materials or providing back up equipment and establish relationships with contractors and other organisations who could help during an emergency.
6. Plans for control rooms and other facilities for coordinating the response and developing communication protocols.
7. Identifies information needs for the response, e.g. as-built drawings, maps and system models. Considers how these will be made available during the event.
8. Develops strategies for assessing system performance and condition of assets and reviewing repair strategies, recognising that in reality the actual situation after an event will most likely be different to that envisaged in the response plan. Refer Technical Note 12 - Post-event Damage Assessment.

Other key components for the implementation of a successful response plan include:

- Communication – the procedures for communicating before, during and after the event
- Strong relationships with key stakeholders, regulating authorities, suppliers and service providers
- Well trained staff in incident management techniques and their individual roles in managing incidents. Incident scenarios are conducted for staff training and the testing of plans.

- Adequate equipment and resources
- Ongoing review and improvement of the response system
- Commitment by Senior Management
- The right corporate culture, with a high level of staff involvement in developing and implementing the response system

## 5.4 Capital Works

Capital works to improve post-event LOS should be identified. They should consider works to:

- Reduce exposure of the network to potential hazards caused by a seismic event, e.g. relocating underground utilities in areas susceptible to lateral spread, fault ruptures or landslides to areas where better ground performance is expected.
- Enable provision of a rapid response by:

  » Improving ease of repair by realigning utilities including:

  – Utilities below buildings or other locations that are difficult to access
  – Deep utilities, particularly those with deep connections, (e.g. laterals connecting at depths greater than 2.5m)
  – Utilities in ground likely to make repair difficult (e.g. where liquefaction is likely to occur)

  » Reducing impact of damage by realigning utilities to avoid:

  – Disruption or damage to lifeline roads
  – Damage to other major utilities
  – Washouts causing slips or property damage
  – Overflows of wastewater into environmentally sensitive areas
  – Damage to buildings and key facilities

  » Installation of isolation valves on pressure systems (whether automated or manually activated) to isolate damaged sections from less damaged sections or to isolate reservoirs to conserve water (Refer Section 6.6.4).

- Ensure the system is flexible by:

  » Installing facilities for alternative supplies, e.g.

  – Installing connections to enable potable water to be provided to community buildings via tankers
  – Installing connection points for bypass pumping, e.g. where trunk mains cross faults

  » Installing additional utilities to increase redundancy

  – Constructing additional storage capacity
  – Increasing tolerance to damage through use of ring mains, emergency supply points, and using systems that have low dependency on external power (e.g. through battery backup or manual override)

- Increase utility robustness to reduce the likelihood of underground utilities being damaged:

  » Replacing utilities that are susceptible to damage with more robust modern systems
  » Replacing specific vulnerable components with more resilient components (e.g. replacing relatively rigid connection systems with more flexible ones)

Longer term strategies could include harmonising systems by eliminating non-standard or rarely-used components to reduce stockholding or training needs. This increases resilience by decreasing the time and cost of maintenance or repair. While systems could be targeted individually, for more substantial parts of the network, this is probably best addressed through prioritisation of renewals works within existing asset management practices.

## 5.5 Supplementary Material

Technical Note 12 – Post-Event Damage Assessment

Technical Note 13 – Improving Seismic Resilience in New and Existing System

# 6 Providing New Utilities that are Seismically Resilient

## 6.1 Why Provide New Utilities that are Seismically Resilient?

To provide new utilities that deliver an acceptable level of resilience by:

- Limiting the amount of damage sustained
- Reducing the potential impact on levels of service
- Enabling repairs to be made as easily as possible to reduce the impact of seismic events on communities
- These measures enable communities to bounce back quickly from earthquakes

## 6.2 What to do to Provide New Utilities that are Seismically Resilient

Consider earthquake shaking and induced ground damage hazards in the design of new underground utilities, as follows:

1. Establish design earthquake parameters:
   - » Importance level of new utility (Table 4-1)
   - » Recurrence interval (Table 4-2)
   - » Design PGA (Equation 1). Assess ground performance under design earthquake conditions (Section 4.2)
2. Assess how the ground will perform during and after an earthquake (Section 4.1 and 4.2)
3. Locate utility to:
   - » avoid areas of poor ground performance (Section 6.3.4)
   - » improve ease of repair (Section 6.3.6)
   - » avoid consequential damage to other utilities and features (Section 6.3.5)
4. Establish maximum tolerable break rates (Table 6-1)
5. Establish design method (Table 6-2 )
6. Design the utility so that expected break rates are less than the maximum tolerable rates, considering:
   - » redundancy (Section 4.5.3.1)
   - » robustness (Section 6.4 to 6.8)


**Figure 6-1. Design of seismically resilient, buried utilities**

This process is shown in Figure 6-1. Note that the Guidelines specify increasing levels of design sophistication based on the importance level assigned to the utility. Acceptable solutions which do not require any further specific design to be undertaken are defined for Importance Level 1 and 2 utilities. These utilities will make up most the systems.

## 6.3 How to Provide New Utilities that are Seismically Resilient

### 6.3.1 Introduction

Earthquakes may damage underground utilities to some extent no matter how well the utilities are designed or installed. The aim is therefore to reduce damage to acceptable levels that will enable communities to quickly bounce back. When installing new utilities the focus, in order of priority, is:

1. Reducing exposure – ground performance significantly impacts on underground utility performance. Underground utilities should be in areas less susceptible to damage, e.g. avoiding wherever feasible areas of potential lateral spread, fault rupture or landslides and wherever practical areas of potential liquefaction.
2. Reducing the impact of damage – locating underground utilities such that if they are damaged they will not cause further damage to roads, other services, or buildings or cause slips or washouts.
3. Locating underground utilities where damage can be repaired without undue difficulty, e.g. considering the depth of the utility, the ground around the utility and proximity of buildings.
4. Reducing the likelihood of damage by installing robust utilities.
5. Reducing the impact on service of utility outages by providing appropriate redundancy.

### 6.3.2 Establish Importance Level and Design Earthquake Parameters

Establish the importance level of the utility in accordance with Section 4.1.3.1 based on the number of properties and type of facilities that the utility serves. Use the importance level to determine the:

- Peak Ground Acceleration which is used to assess ground performance and for design of new utilities
- Maximum tolerable break rates- Design new utilities so that damage resulting from the design earthquake is expected to be below the rates specified in Table 6-1. The maximum tolerable break rate defined in Table 6-1 can also be used to assess the positive benefits of improvement works on post-earthquake levels of service, as outlined in Section 3. Note that these are average break rates over the community considered, and individual lines may experience higher or lower break rates.
- Design method – structural design is generally only required for utilities assigned Importance Levels 3 or 4. Utilities assigned Importance Levels 1 and 2 will typically be installed in accordance with the acceptable solutions outlined in the Guidelines.

**Table 6-1. Maximum Tolerable Break Rates (breaks/10 km)**

| Importance Level | Seismic Importance | Return Period[1] | Maximum Tolerable Break Rate [2] | |
|---|---|---|---|---|
| | | | Pressure [3] | Gravity [4] |
| IL1 | Low importance facilities | 1:250 | 2 | 5 |
| IL2 | Normal facilities | 1:1,000 | 1 | 2 |
| IL3 | Important facilities | 1:2,500 | 0.5 | 1 |
| IL4 | Facilities with post-disaster functionality | 1:>2,500 | 0.2 | 0.5 |

**Notes:**

1. From Table 4.2
2. The break rates shown are average break rates across the entire system, and individual lines may have higher or lower break rates.
3. Most modern pipeline systems will meet the requirements of IL2 and IL3 after accounting for differences in design and installation practices. Flexible continuous pipeline systems will usually be required to meet IL4 requirements, but other modern systems may also be suitable with appropriate design detailing including seismically tolerant joints. The break rates for IL3 and IL4 lines are slightly higher than ALA figures which are all based on an event with 1:475 year return period.
4. Based on restoration of service following shaking only rather than reinstatement to pre-event condition. Where liquefaction occurs, rates may substantially exceed these targets. While any well-installed modern system should meet the requirements of IL2, reinforced concrete may need special design and construction considerations to meet IL3 and IL4 requirements, and other systems usually need special design and construction considerations to meet IL4 requirements.

### 6.3.3 Assess Ground Performance

Assess the ground performance under the design earthquake conditions as outlined in Section 4.2 to identify potential faults, landslides and areas of liquefaction or lateral spread.

The way that the ground behaves because of an earthquake has the greatest influence on the performance of utilities, as discussed in Section 4.4.

### 6.3.4 Locate Utilities to Avoid Areas of Poor Ground

Avoid installation of utilities across potential faults, landslides or areas of lateral spread wherever practical, and areas of liquefaction wherever feasible. Utilities installed in these areas are more likely to be damaged and the damage is often difficult to repair.

Where it is not practical to avoid faults, landslides or areas of lateral spread utilities should be:

- Designed to withstand the additional forces and movements that are likely to occur. Section 6.7 provides guidance on suitable design methods
- Identified as being likely to be damaged by the earthquake so that suitable mitigation and management practices can be applied

Consideration should therefore be given to:

- Installing additional utilities away from the area of poor ground performance to provide redundancy
- Installation of isolation valves on pressure systems each side of the affected area to enable isolation of the damaged section
- Installation of fittings to assist in provision of temporary (and probably limited) supply through alternative routes or temporary systems if the pipeline does fail

- Installation of instrumentation and telemetry at critical points to provide information on the state of the pipeline after an event

### 6.3.5 Locate Utilities to Avoid Consequential Damage

Avoid installing utilities where the damaged utilities may cause consequential damage such as:

- Undermining roads or other services
- Generating landslides
- Flooding buildings and other facilities

### 6.3.6 Ease of Repair

Generally, deeper utilities require more time and effort to repair should they be damaged. For gravity systems in particular, there is a trade-off between the operational cost benefits of deeper systems operating under gravity and shallower systems that may require greater pumping costs but are more readily repaired.

Options for shallower wastewater systems include vacuum or pressure sewer systems and more frequent use of pumping stations to minimise use of deep gravity sewers (sometimes described as sawtooth designs from the appearance of the long section).

Other practical steps include ensuring new constructions use standard systems and designs where possible, minimising use of special sizes. For new constructions, warning tapes and detector wires should be properly installed to enable utilities to be easily located. In addition, construction drawings and location plans should, where possible, be referenced to features that are likely to remain undamaged and unmoved in an earthquake.

For valves and controls, using simple information aids such as ensuring that valves include an identification plate in the chamber to confirm which line they relate to and clear operating instructions ("This way to open") can also help. Locating some systems above ground can improve ease of testing and operation in an emergency.

## 6.4 Installation Practices

Good installation practice has been shown to maximise the service life under normal operating conditions (Morris & Black, 2008). Technical Note 14 - Effect of Installation Practice on Seismic Response of Buried Pipeline Systems shows that installation practice also influences response of pipelines to earthquake loads. The following installation practices will improve seismic performance of underground utilities under both normal service conditions and under seismic conditions:

- Provide embedment of concrete pipes in accordance with *AS/NZS 3725:2007* (Standards New Zealand, 2007) or alternatively *Selecting Materials for Bedding Steel Reinforced Concrete Pipe* (Concrete Pipe Association of Australasia, 2017)
- Provide embedment of flexible pipes in accordance with *AS/NZS 2566.1:1998* (Standards New Zealand, 1998).
- Backfill trench in accordance *SNZ HB:2002:2003* (Standards New Zealand, 2003)

The above requirements provide well graded and free-draining backfill which should allow dissipation of pore water pressures.

It is particularly important to ensure that embedment should be properly placed to ensure that the pipe is evenly supported. Good compaction will ensure that densification or consolidation does not occur during an earthquake. Refer Technical Note 14 - Effect of Installation Practice on Seismic Response of Buried Pipeline Systems.

- Allow clearance between flexible pipes and fixed structures (for example where a pipe passes through a bridge abutment or a plastic pipe exits a more rigid sleeve) so that there is space to move without making unintended contact with the structure

Damage reports from earthquakes around the world and specifically from Canterbury showed that modern pipeline systems that have been properly installed are reasonably tolerant to earthquake damage, particularly where subject to only shaking or liquefaction. This was also demonstrated by physical testing undertaken under MBIE project ID OPS X1202. Several specific ways claimed to improve overall system resilience have been reviewed as part of this work and the results are summarised below:

- Testing showed that rubber inserts in the sockets of reinforced concrete pipes either reduced compressive failure load or had no effect. Their use is not recommended
- Use of unreinforced concrete haunching and bearing slabs is not recommended because under compressive loads bending failure can increase the risk of failure of the supported service. Refer Technical Note 14 - Effect of Installation Practice on Seismic Response of Buried Pipeline Systems.
- Longer socketed PVC pipes may provide some benefits but they are minor compared to other factors such as good installation practice and positioning of utilities to avoid areas of poor ground performance. More extensive use of longer socket joints is therefore not recommended.
- Testing showed that use of inserts for mechanical joints in PE pipes to provide fully end-load resistant joints is a cost effective way of improving seismic resilience in service pipes (Morris, McFarlane, Cook, & Hughes, 2015). Using inserts also provides benefits in normal service conditions. Inserts can also increase end-load resistance in larger pipe sizes

## 6.5 Design of New Underground Utilities

Design new utilities using the design methods outlined in Table 6-2.

**Table 6-2. Design Methods for New Underground Utilities**

| Importance Level | Design Method | | |
|---|---|---|---|
| | Acceptable Solution | Equivalent Static Load | Finite Element Analysis |
| Level 1 & 2 (Connections and Distribution) | √ | √[1] | |
| Level 3 (Trunk) | | √ | |
| Level 4 (Lifelines) | | √ | √[2] |

**Notes**

1. Use the equivalent static load method for Importance Level 1 and 2 utilities installed across potential faults, landslides or areas of lateral spread. Refer Section 6.7.
2. For critical sections of utilities with complex ground conditions finite element analysis should be used to supplement design. Refer Section 6.8.

## 6.6 Acceptable Solutions – Importance Level 1 and 2 Services

### 6.6.1 Ground Shaking

Utilities installed in accordance with *NZS 4404:2010* (Standards New Zealand, 2010) are acceptable solutions for installation in areas where liquefaction, lateral spread, faults or landslides are not expected to occur under the design earthquake, subject to the following additional requirement:

Where mechanical couplings are used on PE water pipe it is recommended for an insert or stiffener be used to support the internal diameter of the PE pipe. Refer Figure 6-2.

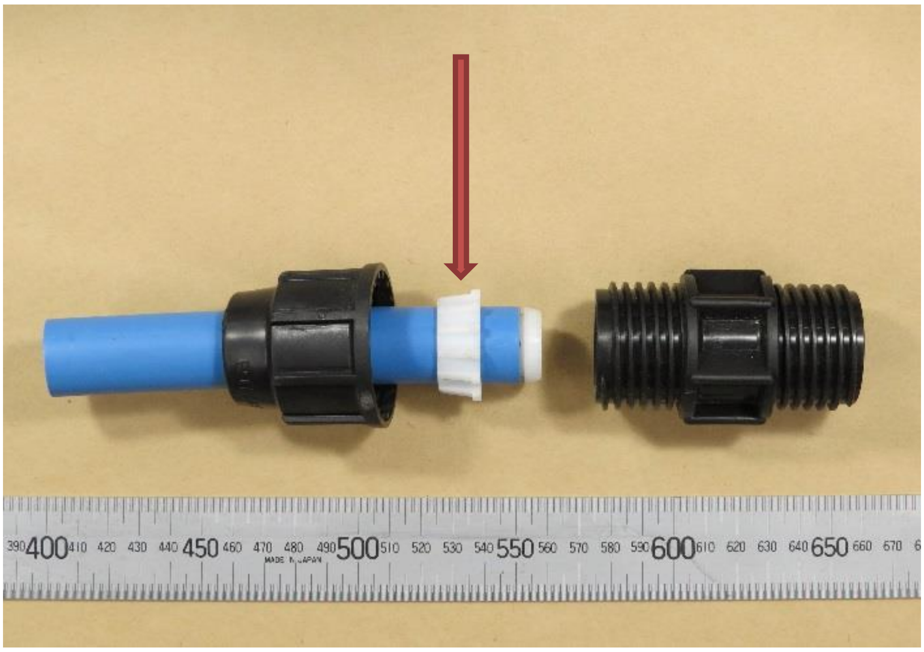


Figure 6-2. Insert (arrowed) installed in PE pipe

### 6.6.2 Liquefaction

Avoid installation of utilities through areas where liquefaction may occur under the design earthquake. Where this is not practical the following requirements in addition to those specified in Section 6.6.1 apply.

#### 6.6.2.1 General

- Locate utilities where they can be easily accessed for repair, e.g. avoid installing utilities below or close to buildings or other structures.
- Do not install utilities deeper than 3.5m to invert due to difficulty of making repairs at depth in liquefied ground.
- Do not install connections deeper than 2.5m to reduce the need to repair junctions at depth. 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.

#### 6.6.2.2 Gravity Pipes

- Wrap pipe joints in areas where liquefaction may occur, including those on laterals, with Class C geotextile to reduce ingress of silt if joints open up under seismic loading.

- Install pipes as steep as practical to reduce the likelihood of differential settlement resulting in disrupted or negative grades. However, additional pump stations may be needed to comply with the depth restrictions stated earlier. This may limit the practicalities of installing pipes on steeper grades.
- Consider using other technologies such as pressure or vacuum sewer systems to avoid the need to install gravity pipes in areas subject to liquefaction as they can be installed in shallow ground and therefore easier to repair after a seismic event.

#### 6.6.2.3 Discussion

Pressure pipes – the requirements covered under Section 6.6.2.1 apply to pressure pipes as well as gravity pipes. No additional measures are necessary for pressure pipes.

Trenchless – additional measures are not considered necessary for pipes installed by trenchless methods. In the case of pipes installed by horizontal directional drilling or pipe bursting the pipeline will typically be a flexible continuous system such as coiled or fusion-jointed PE, fusible PVC or welded steel which are less susceptible to damage. Pipes installed by microtunnelling will be more robust than standard pipes as they need to withstand the compressive forces imposed during installation loads.

### 6.6.3 Fault Crossings, Landslides and Areas of Lateral Spread

Avoid installing utilities across faults, landslides or areas where lateral spread may occur under the design earthquake. Where this is not feasible, assume that there is a high probability of pipes being damaged, no matter how well they are designed or installed. The following requirements in addition to those specified in Section 6.6.1 apply.

#### 6.6.3.1 General

- Use flexible continuous pipelines (welded steel or fused PE).
- Specifically design pipes to withstand the expected seismic loads using the equivalent static method as per Section 6.7.
- Ensure the utilities can be readily located, the damage can be identified and repaired in a reasonably practical manner in an acceptable timeframe.
- Ensure that the resources, materials and skills required for repair will be accessible after an earthquake.
- Locate utilities as far away as practical from other services or structures. Preferably ensuring a clear separation of at least 2m to reduce the possibility of damage occurring from utilities coming in contact with other services or structures during an earthquake.
- Locate utilities where they can be easily accessed for repair, e.g. avoid installing utilities below or close to buildings or other structures.
- Do not install utilities deeper than 3.5m to invert due to difficulty of making repairs at depth in poor ground.
- Do not connect laterals to main pipes in areas subject to faults, landslide or lateral spread due to the higher likelihood of damage.
- Consider installing flexible couplers on the more vulnerable side of isolation valves to provide a weak point that might fail during an earthquake without damaging the pipe itself. However, careful consideration is needed since a continuous flexible pipeline might remain operational even when exposed to substantial overall tensile deformation of the order of 5% for steel and 10% or more for PE, and a weak link could result in preventable failures occurring under some conditions.

- Ensure that the couplers are located in areas where repairs can be undertaken easily and consequential damage will not occur, e.g. damage from burst pipes. This approach may avoid damage occurring in areas that are more difficult to repair.
- Installing additional services away from the area of high vulnerability to provide redundancy (refer Section 4.5.3.1).

#### 6.6.3.2 Pressure Pipes

- Install isolation valves on pressure pipelines at the transition between areas of higher and lower vulnerability to earthquake damage. Ensure that the valves are located outside the zone of the expected faults, landslides or lateral spread and are positioned where they can be accessed easily.
- Consider installing tee-offs for connection of temporary lines to bypass the area of high vulnerability.

#### 6.6.3.3 Gravity Pipes

- Where possible, avoid installing manholes in areas subject to lateral spread, landslides or fault rupture.
- Install a manhole upstream of the transition between high and lower vulnerability areas. Provide provision to isolate flow in the manhole, e.g. through installation of a shutoff weir or by sand bagging. Ensure that the manhole is sized and located to enable by-pass pumping to be installed in the manhole so that flows can be pumped across the area of high vulnerability.
- Consider using other technologies such as pressure or vacuum sewer systems to avoid the need to install gravity pipes in areas subject to liquefaction.

#### 6.6.3.4 Fault Crossings

In addition to the above:

- Consider locating the pipeline above ground, and allowing for the pipeline to slide on top of the ground for a suitable distance either side of the fault crossing.

#### 6.6.3.5 Slope Failures or Landslides

In addition to the above:

- Locate underground utilities on the uphill side of the road, where overslips are unlikely to affect the underground pipelines, and avoid locating them on the downhill side of roads where the road embankment could be prone to underslips and slope movement in earthquakes.

### 6.6.4 Isolation Valves

Provide valves on pressure systems to enable damaged sections to be isolated from undamaged sections, thus reducing the time required to restore service to the majority of the network. Install valves to divide potable water networks into zones and at the transition between areas of ground that are less vulnerable to damage and those that have a higher susceptibility to damage, e.g. either side of fault crossings. Pressure management zones may provide sufficient isolation although some additional valves may be required to fully address seismic considerations.

Periodically inspect and exercise valves to confirm that they are accessible and to provide confidence that they will operate should a seismic event occur.

Consider placing labels in the valve chamber to show which line they control and to show the opening and closing directions to assist operators in an emergency.

Isolation valves may be manually operated or automatically operated or remotely operated . The decision to install manual or actuated valves depends on:

- Cost – manually operated valves are generally cheaper
- Availability of secure power supply for actuating valves in case of emergency
- Consequence of the utility not being turned off for a period of time. On small pipes it might be acceptable for water to leak for a period of time but this might not be acceptable for large pipes where breaks could cause significant flooding or result in considerable loss of water. Automatic and remotely operated valves will be able to cut off a water supply faster than a manually operated one as there is no transport delay for an operator to get to site.
- Consequence of the supply being automatically shut down. In some cases, it may be desirable for the supply to continue to be provided through damaged utilities, e.g. for fire fighting

If actuated valves are installed ensure that actuation will not generate water hammer that could adversely affect the system.

Generally, avoid seismic-only actuation; instead actuate based on both seismic activity and high flow or a pressure drop to avoid undamaged sections being unnecessarily shutdown and removing fire fighting capacity. The exception would be valves at reservoirs where it might be desirable to isolate the reservoir to conserve the stored water.

### 6.6.5 Connections to Structures

Connections to pump stations and other structures can be potential weak points due to differential movements (Gibson, 2015). Reduce the movement of the structure that the utility is being connected to by:

- Locating the structure in a position where it is not vulnerable to earthquake induced ground movements. Avoid areas subject to liquefaction where practical and areas prone to lateral spread, landslides or fault crossings, wherever feasible.
- Undertake ground improvements or found the structure on piles in areas subject to liquefaction. Consider buoyant uplift and differential settlements in the design of the structure.

In addition, where possible consider locating an isolation valve inside the structure itself and ideally a second isolation point located away from the structure on stable ground in order to isolate the system from the structure should it be damaged.

As a pipeline is generally easier to repair than a structure consider making the connection at the wall of the structure more robust than the connecting pipeline so that the pipeline breaks rather than the wall.

Provide a resilient connection, through (Gibson, 2015):

- Using flexible continuous pipelines to accommodate vertical and horizontal movements
- Making the connection as shallow as practical to improve ease of repair
- Over-steepening gravity inlet pipes to accommodate for differential settlement
- Undertaking ground improvements at the site of the structure, extending ground improvement to include the connecting services

- Installing “fuses” designed to break but which can be replaced easily. For example, install a gibault joint on the downstream side of the terminal manhole to encourage breaks to occur at a known and readily accessible position.
- Locating the terminal manhole outside the area of vulnerability if possible and locating it in a position where inspection and repair can be easily undertaken.
- Installing rocker pipes or proprietary flexible expansion joints in critical connections where high ground movement may occur. Often these can be considered as alternatives to the above but can be complementary.

### 6.6.6 Manholes

Install manholes in accordance with *NZS 4404:2010* (Standards New Zealand, 2010).

Technical Note 15 - Manhole Floatation discusses factors that affect manhole floatation and methods of preventing floatation.

There were many observed instances after the CES and the Japanese Tohoku event of 2011 where manholes protruded above ground level after an earthquake, particularly in areas where liquefaction occurred. However, in most cases the differences between manhole cover levels and ground levels that were observed were due mainly to ground settlement rather than manhole floatation except in areas of severe liquefaction. This view is further supported by the relatively low break rates between manholes and services.

Settlement of the surrounding soil may not cause much differential movement of the pipeline system components, whereas flotation could potentially result in substantial differential movements between pipes and manholes.

Important factors covered in *NZS 4404:2010* (Standards New Zealand, 2010) that reduce the risk of manhole floatation are:

- A manhole base that extends beyond the manhole riser – this increases the factor of safety against floatation by more than 20%
- Permeable backfill to reduce pore water pressures and therefore the risk of floatation
- Rocker pipes at each side of the manholes to accommodate movement

While all manholes are potentially liable to float in soil that can liquefy, the likelihood and severity of flotation is greater in structures with a lower net density than in a system with overall higher density. Larger manholes have a larger internal volume and are therefore potentially more ‘buoyant’, while cast-in-place manholes tend to have thicker, heavier walls and a correspondingly lower ‘buoyancy’. Conversely, plastic manholes are lighter and are more likely to float in liquefied soil, so they are more reliant on the presence of flanges and well-placed free draining embedment materials to minimise flotation risk.

## 6.7 Acceptable Solutions for Level 3 Services

For Importance Level 3 utilities, use the Equivalent Static Method (ESM) (see below) to predict the amount of force, strain and displacement that the utility will be subjected to under the design earthquake. Design the utility so that it can withstand these seismic response quantities.

The ESM is described in Section 7.3 of *American Lifelines Alliance Seismic Guidelines for Water Pipelines* and the *IITK-GSDMA Guidelines for Seismic Design of Buried Pipelines* (American Lifelines Alliance, 2005)

Technical Note 16 – Equivalent Static Method provides a worked example of the design calculations undertaken using the ESM method.

## 6.8 Acceptable Solutions for Level 4 Services

For Importance Level 4 utilities, use the Finite Element Method (FEM) to analysis and design the utility to withstand the design earthquake. Design the utility so that it can withstand these seismic response quantities. FEM is described in Section 7.4 of *American Lifelines Alliance Seismic Guidelines for Water Pipelines* (American Lifelines Alliance, 2005).

Refer Technical Note 16 - Equivalent Static Method for a worked example

## 6.9 Supplementary Material

Technical Note 14 - Effect of Installation Practice on Seismic Response of Buried Pipeline Systems

Technical Note 15 - Manhole Floatation

Technical Note 16 – Equivalent Static Method

# 7 Future Work

While the guidelines were being produced, a number of areas that may justify further investigation were studied. In addition, the Kaikoura and Seddon events of November 2016 have provided a further source of information.

We have therefore identified areas where further work may be of value, whether to improve current guidance, to promote awareness of the guidelines or to evaluate the results of other events and maintain currency of the guidelines.

Because there is a substantial body of ongoing work that would rapidly render a detailed list obsolete, and also to avoid giving the impression that this list is definitive, we have only provided a brief overview of the issues identified.

## 7.1 Promotion of awareness

Industry guidelines and studies are of minimal value if potential users are not aware of them. The Advisory Group has previously discussed some options for making information accessible in a variety of media and formats and also for promoting awareness of the guidelines. Water New Zealand has (as at January 2017) proposed the use of regional seminars as well as a dedicated session at their annual conference.

Many seismic improvement technologies developed elsewhere could be applied effectively, even where some adaptation is required for New Zealand conditions. Independent assessment to spread awareness of technology and support for adoption and adaptation of systems developed for overseas use could be a cost-effective way to extend the availability and awareness of cost effective solutions. While individual larger service providers can probably do this themselves, a practical means of assisting smaller bodies with fewer resources and less technical depth could be useful.

## 7.2 Lessons learnt

Whenever damaging earthquakes occur in future, it would be useful to review what factors assisted response and recovery along with identifying a list of actions that would have been useful if they had been in place.

While the focus would probably be on the higher level systems, it is also valuable to understand the contribution of local knowledge and independent initiative. The objective should be to help appreciate what kind of organisational structures are effective, but also to look at whether different approaches would have been effective in most circumstances or if there were specific local factors that contributed to their success.

The ability to identify rapid, cost effective and low-risk solutions would assist in improving resilience nationwide.

## 7.3 Further research topics

A number of seismic improvement projects were exposed to the Kaikoura and Seddon events of November 2016. A review of their effectiveness would be of interest.

Similar work could be of value for any future event affecting an area where works to improve resilience had been completed.

While other factors appear to dominate in failure of the more numerous smaller pipeline systems larger, more critical pipelines are likely to include features (such as length and operating pressures) that could make transients more of a problem, while also having much greater consequence of any failure.

Good quality information on the seismic performance of any system is hard to obtain, but there appears to be a particularly severe shortfall in systems other than water supply. Topics of interest could include:

- Good quality break rate data for other services with an objective of preparing more robust fragility functions;
- Improved understanding of how to classify gravity pipe defects and to develop improved fragility functions for damage prediction;

Development of repair and stabilisation systems for addressing specific defects that are currently difficult to address.

Development of innovative systems that improve seismic resilience, preferably while providing other operational or cost benefits.

# 8 References


American Lifelines Alliance. (2005). *Seismic Guidelines for Water Pipelines*. American Lifelines Alliance.

Brabhaharan, P. (2010). Characterisation of Earthquake Geotechnical Hazards for Engineering and Planning in New Zealand. *11th IAEG Conference*. Auckland.

Concrete Pipe Association of Australasia. (2017). *Selecting Materials for Bedding Steel Reinforced Concrete Pipe*. Retrieved from Concrete Pipe Association of Australasia: http://www.cpaa.asn.au/Latest-News/selecting-materials-for-bedding-of-steel-reinforced-concrete-pipe.html

Cubrinovsk, M., Hughes, M., Bradley, B., Noonan, J., Hopkins, R., McNeil, S., & English, G. (2014). *Performance of Horizontal Infrastructure in Christchurch City through the 2010-2011 Canterbury Earthquake Sequence*. Christchurch: Unversity of Canterbury.

Davis, C. A. (2011). Water System Services and Relation to Seismic Performance. *7th Japan-US-Taiwan Workshop on Water System Seismic Practices* (p. 12). Niigata, Japan: JWWA/WRF.

Gibson, G. N. (2015). Design Philosophy of Improving Horizontal Intrastructure Siesmic Resilience. *6th International Conference on Earthquake Geotechnical Engineering*. Christchurch.

IPCC. (2011). *Special report on managing risks of climate extremes and disastersto advance climate change adaption*. Geneva: IPCC.

Kameda, H. (2000). Engineering Management of Lifeline Systems Under Earthquake Risk. *12WCEE2000*.

Kestral Group Ltd. (2011). *Resilience Lessons:Orion's 2010 and 2011 Earthquake Experience*. Kestrel Group.

Langridge, R. (2016). The New Zealand Active Faults Database. *New Zealand Journal of Geology and Geophysics*, 86-96.

Misko Cubrinovski, M. H. (2011). *Liquefaction Impacts on Pipe Networks*. Christchurch: University of Canterbury.

Mitroff, I. (2005). "From my perspective: Lessons from 9/11: Are companies better prepared today?". *Technological Forecasting and Social Change*, 375-376.

Morris, J. (2002). The effect of pipeline design on response to natural hazards. *NZWWA Conference*. Auckland, New Zealand.

Morris, J., & Black, J. (2008). Piped systems - 100 year design life: fact or fiction? *Water New Zealand*. Christchurch, New Zealand.

Morris, J., McFarlane, P., Cook, S., & Hughes, M. (2015). Understanding Service Pipe Resilience. *Water New Zealand 57th Annual Conference 2015*. Hamilton.

National Infrastructure Unit. (2012, March). *Infrastructure Update*. New Zealand Government.

National Infrastructure Unit. (2015). *The Thirty Year New Zealand Infrastructure Plan*. Wellington: New Zealand Government.

New Zealand Geotechnical Society. (2010). Guideline for the identification, assessment and mitigation of liquefaction hazards.

New Zealand Government. (2002). Civil Defence Emergency Management Act 2002. New Zealand Government.

New Zealand Government. (2002). Local Government Act 2002. New Zealand Government.

New Zealand Government. (2011). *National Infrastructure Plan 2011*. New Zealand Government.

New Zealand Government. (2015). Health and Safety at Work Act 2015. New Zealand Government.

NZTA. (2016). *Bridge manual (SP/M/022)*. NZTA.

Pan American Health Organization. (2006). *The Challenge in Disaster Reduction for Water and Sanitation Sector: Improving quality of life by reducing vulnerabilities*. Washington, D.C: PAHO.

PIPA. (2009). *POP205 Water jet cleaning of plastic pipes*. Plastics Industry Pipe Association of Australia .

SCIRT. (2011, December 06). *Infrastructure rebuild plan adopted*. Retrieved from Stronger Christchurch: http://strongerchristchurch.govt.nz/article/infrastructure-rebuild-plan-adopted

Sheffi, Y. (2007). Building a Resilient Organisation. *The Bridge - Linking Engineering and Society, 37*(1), 30-36.

Standards New Zealand,. (2010). *Land Development and Subdivision Infracture (AS/NZS 4404:2010)*. Standards New Zealand.

Standards New Zealand. (1998). *Buried Flexible pipelines - Structural Design (AS/NZS 2566.1:1998)*. Standards New Zealand.

Standards New Zealand. (2002). *AS/NZS 2566 - Buried Flexible Pipelines*. Wellington: Standards New Zealand.

Standards New Zealand. (2002). *Structural design actions - Part 0: General Principles (AS/NZS 1170.0:2002)*. Standards New Zealand.

Standards New Zealand. (2003). *Code of Practice for Working in the Road (SNZ HB 2002:2003)*. Standards New Zealand.

Standards New Zealand. (2004). *Structural design actions - Part 5: Earthquake actions - New Zealand (NZS 1170.5:2004)*. Standards New Zealand.

Standards New Zealand. (2007). *Design for installation of buried concrete pipes (AS/NZS 3725:2007)*. Standards New Zealand.

Swiss Re Ltd. (2015, March 25). *Sigma 2/2012: Natural catastrophes and man-made disasters in 2011*. Retrieved from www.swissre.com: http://www.swissre.com/clients/Sigma_22012_Natural_catastrophes_and_manmade_disasters_in_2011.html

The Department of Internal Affairs. (2009). *Information on Local Government Water Network Infrastructure*. The Department of Internal Affairs.

The United Nations Office for Disaster Risk Reduction. (2015). *Global Assessment Report*. Geneva: United Nations.

Tromans, I. (2004). *Behaviour of buried water supply pipelines in earthquake zones*. London: University of London.

United Nations Office for Disaster Risk Reduction. (2011). Chengdu Declaration for Action. *2nd World Cities Scientific Development Forum* (p. 1). Chengdu: United Nations Office for Disaster Risk Reduction.

Water New Zealand. (n.d.). *Levels of Service Performance Measures for the Seismic Resilience of Three Waters Network Delivery*. Retrieved from Quake Centre: https://12240-console.memberconnex.com/Folder?Action=View%20File&Folder_id=438&File=3WaterLoS_Final.pdf

Wimmers, A. (2013). Building the business case for resilience investment. *Insight, The Global Infrastructure Magazine*, 30-31.

Wotherspoon, L., Pender, M., & Orense, R. (2010). Relationship between observed liquefaction at Kaiapoi following the 2010 Darfield earthquake and former channels of the Waimakariri River. *Engineering Geology, 125*, 45-55.

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