

Seismic Assess and Design of Underground Utilities

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ABSTRACT: This paper describes research into the seismic response of underground infrastructure following the Canterbury earthquakes which has been sponsored by the Ministry of Business, Innovation and Employment. The research findings are being incorporated into a set of guidelines that will enable practitioners to assess and improve the resilience of existing and new buried utilities in order to limit damage to manageable levels that enable communities to bounce back from seismic events.

The paper describes the key findings of the research and provides an overview of the guideline documents. Guidance is provided that will 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 levels of service expected after an earthquake.
- Identify measures to improve resilience of existing networks. This includes the development of response plans and capital works to improve the robustness and redundancy of the system and to make it easier to restore service after an event. Direction is given as 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 infrastructure that provides an acceptable level of resilience.

1 INTRODUCTION

1.1 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 which disrupted supply to households and businesses and cost several billion dollars to repair.

After the CES and the initiation of the subsequent rebuild, it was clear that further research was required to better understand why some underground utilities failed and others did not and to understand the impact of failures on overall resilience. A set of guidelines was needed to communicate the findings of this research to practitioners so that it could be used in a New Zealand context.

This paper describes the *Underground Utilities – Seismic Assessment and Design Guidelines* that have been developed by Opus International Consultants Limited and GNS Science. The guidelines are provided as a user-friendly framework for asset managers, designers and local councils to integrate seis-

mic resilience into the design and management of buried utilities. The guidelines help organisations comply with the Civil Defence Emergency Management Act (2002), Local Government Act (2002) and Health and Safety at Work Act (2015) and will help deliver the Government's aspiration to improve the resilience of New Zealand's infrastructure, as defined in the National Infrastructure Plan

The Guidelines enable practitioners to:

- Assess the vulnerability of existing underground utilities to seismic events.
- Identify and prioritise measures to improve the resilience of current networks.
- Design and install new utilities that have an acceptable level of resilience to earthquake events.

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, 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 components included information gathering, physical testing and finite element analysis, refer Figure 1. Specifics include:

- Reviewing national and international research and guidelines.
- Collating the findings assembled in a database of Christchurch's underground utilities' damage.
- Enhancing the findings from the damage database and literature review by undertaking 3D finite element analysis and large scale physical testing.

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 and fragility functions. These can be used to assist in forward planning to understand the likely scale and form of damage caused by an earthquake and to assist in post-event management.

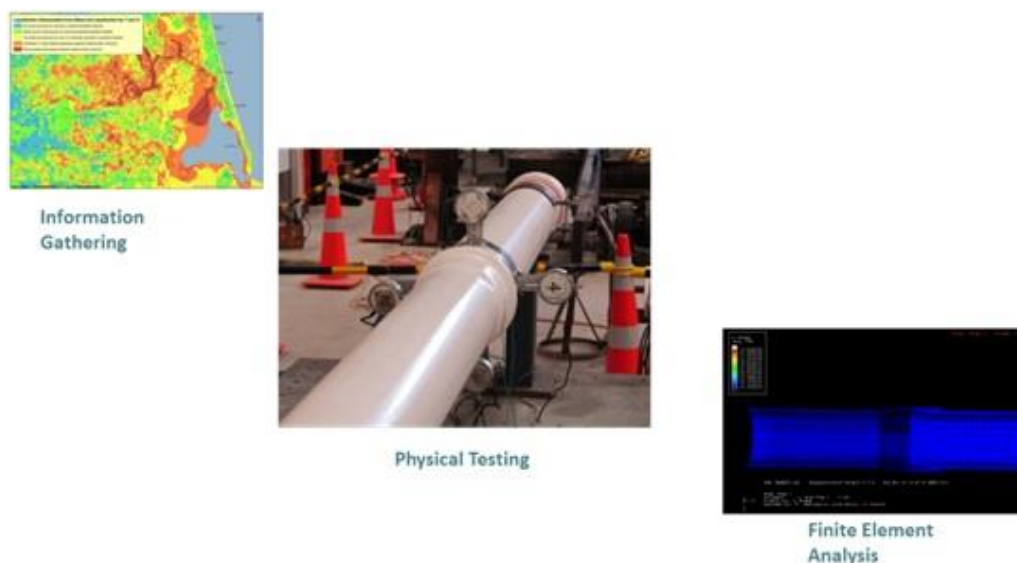


Figure 1. Research Components

1.3 Guideline Objectives

Guidance is provided on how to assess and improve the resilience of existing and new underground utilities.

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.

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 level of service expected after an earthquake.
- Identify measures to improve resilience of existing networks. This includes the development of response plans and capital works 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 provides an acceptable level of resilience.

The Guidelines have been tailored for New Zealand conditions. They complement standards for designing and installing underground utilities under normal operating conditions.

1.4 Scope of Guidelines

The Guidelines cover the following underground networks:

- Potable water
- Wastewater
- Stormwater
- Telecommunication, power and gas networks

The research was focused mostly on the three waters (potable, waste and storm) as a large amount of damage occurred in these systems when compared to the other systems. However, most of the recommendations in the Guidelines are also relevant to other utility systems.

2 STRUCTURE & CONTENT OF THE GUIDELINES

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.

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 assess and evaluate measures to improve infrastructure resiliency to seismic events through the consideration of post-event Levels of Service (LOS). LOS 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. Considering 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 (e.g. hospital, fire service) to determine appropriate post-event LOS and alternate services (such as supply of tankered water, pumping sewage into rivers) that balance cost, risk and the community's ability to adapt.

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. This is an iterative process that reviews and balances the various issues, once the current resilience has been assessed.

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.
- Predicting how the ground may respond during and after an earthquake. Observations from the CES and elsewhere indicate that permanent ground deformations significantly influence the type and amount of damage sustained by underground utilities, 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 the conditions expected from the earthquake.

- Predict how underground utilities will behave. Estimating the extent of damage likely to be sustained, 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 and 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.

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 improvement to post-event levels of service generated for each dollar spent.

It is considered that, through a combination of response planning, renewals prioritisation and capital expenditure works, the resilience of existing systems can be improved significantly. 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, to avoid consequential damage to other utilities and features and to 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. Acceptable solutions which do not require any further specific design to be undertaken are defined for Importance Level 1 & 2 utilities. These utilities make up the majority of most systems. More sophisticated methods such as the equivalent static design method and finite element modelling are proposed for utilities with Importance Level 3 or 4.

3 KEY LEARNINGS INCORPORATED INTO THE GUIDELINES

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

- The cost to benefit ratio of resilience infrastructure has been estimated by the United Nations to be up to 1:10. In New Zealand, electricity company Orion spent an estimated \$6 million on seismic strengthening which saved \$30-\$50 million in direct asset replacement costs following the Canterbury earthquakes.

- The performance of the ground and associated ground damage has far more influence on damage than shaking and forces resulting directly from earthquakes.
- Axial forces along utilities cause the majority of damage. Most of the damage occurs at pipe joints. Bending and other transverse loading tend 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 sustained less damage than smaller pipelines. Service pipe connections sustained 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.
- Gravity pipes located in areas where liquefaction or lateral spread occurred experience significant differential deformation, causing their grade to be reduced and dips to occur. This affects all pipe materials.
- 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. This is because of sand and silt entering through gully traps and manholes even where pipelines were undamaged.
- The time it takes to restore service is affected by both the amount of damage sustained and by the ground conditions. For example after the CES in areas where the ground liquefied both earthenware and PVC pipes tended to become blocked, however service through PVC pipes was able to be reinstated much quicker than was the case for earthenware pipes as these pipes tended to re-block due to silt entering into the pipes through pre-existing or earthquake related damage.
- The quantum of damage sustained to non-critical pipes often controls the time it takes to restore service. For example the lifting of the boil water notice on the potable water system in Christchurch 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.

4 CONCLUSIONS

The Canterbury Earthquake Sequence demonstrated a clear need for further research to better understand why some underground utilities failed and others did not and to understand the impact of failures on overall resilience. The research undertaken by Opus International Consultants Limited and GNS Science under the research project titled *The Seismic Response of Underground Services* funded by the Ministry of Business, Innovation and Employment enhanced understanding of the performance and resilience of underground utilities under seismic loading.

The findings of this research have been incorporated into the *Underground Utilities – Seismic Assessment and Design Guidelines*. These guidelines provide as a user-friendly framework for asset manag-

ers, designers and local councils to integrate seismic resilience into the design and management of underground utilities. The guidelines help organisations comply with the Civil Defence Emergency Management Act (2002), Local Government Act (2002) and Health and Safety at Work Act (2015) and will help deliver the Government's aspiration to improve the resilience of New Zealand's infrastructure.

The Guidelines provide a consistent approach which enables practitioners to:

- Assess the vulnerability of existing underground utilities to seismic events.
- Identify and prioritise measures to improve the resilience of current networks.
- Design and install new utilities that have an acceptable level of resilience to earthquake events.

The research project demonstrated that the performance of the ground has far more influence on utility damage than the shaking forces that may result directly from earthquakes. It also showed that modern utility materials provide a reasonable degree of resilience. By understanding the vulnerabilities in the system it is possible to make significant improvements in resilience through a combination of response planning, renewals prioritisation and some capital expenditure works. In many cases the amount of capital expenditure required to improve resilience is not significant.

5 REFERENCES

Opus International Consultants & GNS. (2017). Underground Utilities – Seismic Assessment and Design Guidelines.