Decision Support Framework for Post-earthquake Restoration of Sewerage Pipelines and Systems

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by

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Abstract

Sewerage systems convey sewage, or wastewater, from residential or commercial buildings through complex reticulation networks to treatment plants. During seismic events both transient ground motion and permanent ground deformation can induce physical damage to sewerage system components, limiting or impeding the operability of the whole system. The malfunction of municipal sewerage systems can result in the pollution of nearby waterways through discharge of untreated sewage, pose a public health threat by preventing the use of appropriate sanitation facilities, and cause serious inconvenience for rescuers and residents.

Christchurch, the second largest city in New Zealand, was seriously affected by the Canterbury Earthquake Sequence (CES) in 2010-2011. The CES imposed widespread damage to the Christchurch sewerage system (CSS), causing a significant loss of functionality and serviceability to the system. The Christchurch City Council (CCC) relied heavily on temporary sewerage services for several months following the CES. The temporary services were supported by use of chemical and portable toilets to supplement the damaged wastewater system. The rebuild delivery agency -Stronger Christchurch Infrastructure Rebuild Team (SCIRT) was created to be responsible for repair of 85 % of the damaged horizontal infrastructure (i.e., water, wastewater, stormwater systems, and roads) in Christchurch.

Numerous initiatives to create platforms/tools aiming to, on the one hand, support the understanding, management and mitigation of seismic risk for infrastructure prior to disasters, and on the other hand, to support the decision-making for post-disaster reconstruction and recovery, have been promoted worldwide. Despite this, the CES in New Zealand highlighted that none of the existing platforms/tools are either accessible and/or readable or usable by emergency managers and decision makers for restoring the

CSS. Furthermore, the majority of existing tools have a sole focus on the engineering perspective, while the holistic process of formulating recovery decisions is based on system-wide approach, where a variety of factors in addition to technical considerations are involved. Lastly, there is a paucity of studies focused on the tools and frameworks for supporting decision-making specifically on sewerage system restoration after earthquakes.

This thesis develops a decision support framework for sewerage pipe and system restoration after earthquakes, building on the experience and learning of the organisations involved in recovering the CSS following the CES in 2010-2011. The proposed decision support framework includes three modules: 1) Physical Damage Module (PDM); 2) Functional Impact Module (FIM); 3) Pipeline Restoration Module (PRM). The PDM provides seismic fragility matrices and functions for sewer gravity and pressure pipelines for predicting earthquake-induced physical damage, categorised by pipe materials and liquefaction zones. The FIM demonstrates a set of performance indicators that are categorised in five domains: structural, hydraulic, environmental, social and economic domains. These performance indicators are used to assess loss of wastewater system service and the induced functional impacts in three different phases: emergency response, short-term recovery and long-term restoration. Based on the knowledge of the physical and functional status-quo of the sewerage systems post-earthquake captured through the PDM and FIM, the PRM estimates restoration time of sewer networks by use of restoration models developed using a Random Forest technique and graphically represented in terms of restoration curves.

The development of a decision support framework for sewer recovery after earthquakes enables decision makers to assess physical damage, evaluate functional impacts relating to hydraulic, environmental, structural, economic and social contexts, and to predict restoration time of sewerage systems. Furthermore, the decision support framework can be potentially employed to underpin system maintenance and upgrade by guiding system rehabilitation and to monitor system behaviours during business-as-usual time. In conjunction with expert judgement and best practices, this framework can be moreover applied to assist asset managers in targeting the inclusion of system resilience as part of asset maintenance programmes.

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Please detail the nature and extent (%) of contribution by the candidate:

For the above papers with the PhD candidate as the first author, she gathered 100 % of the data, carried out 100 % of the analysis, and prepared 100 % of the paper draft. The co-authors provided a review, comments, and corrections. Overall PhD candidate contribution was 95 %.

For the one paper where the PhD candidate is one of the co-author, she assisted in data collection, drawing conclusions, and draft preparation. Overall PhD candidate contribution was 20 %.

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Name: *Eric Scheepbouwer* Signature: Date: *31/3/2016*

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Abbreviation and Acronym

AFT	Accelerated Failure Time
AIC	Akaike Information Criterion
ALA	American Lifelines Alliance
BART	Bayesian Additive Regression Trees
CART	Classification and Regression Trees
CCC	Christchurch City Council
CCR	Correct Classification Rate
CERA	Canterbury Earthquake Recovery Authority
CES	Canterbury earthquake sequence
CONC	Concrete
CPH	Cox Proportional Hazard
CSN	Christchurch Sewerage Network
CSS	Christchurch Sewerage System
DR	Damage Ratio
DSHA	Deterministic Seismic Hazard Assessment
EW	Earthenware
EQC	Earthquake Commission
FIM	Functional Impact Module
GIS	Geographical Information System
HAZUS-MH	Hazards U.S. Multi-Hazard
IRMO	Infrastructure Rebuild Management Office
IRTSG	Infrastructure Recovery Technical Standards and Guidelines
LRI	Liquefaction Resistant Index
LS	Lift Station
MAE	Mean Absolute Error

MARS	Multivariate Adaptive Regression Splines
MGS	Maximum Ground Strain
MLR	Multiple Linear Regression
MMI	Modified Mercalli Intensity
PDM	Physical Damage Module
NZTA	New Zealand Transport Agency
PGA	Peak Ground Acceleration
PGD	Permanent Ground Deformation
PGDH	Permanent Ground Deformation Hazards
PGV	Peak Ground Velocity
PI	Performance Indicator
PRM	Pipeline Restoration Module
PS	Pump Station
PSHA	Probabilistic Seismic Hazard Assessment
PVC	Polyvinyl chloride
RCRR	Reinforced concrete rubber ring
RF	Random Forest
RMSE	Root Mean Square Error
RR	Repair Rate
RSF	Random Survival Forest
SCADA	Supervisory Control and Data Acquisition
SCIRT	Stronger Christchurch Infrastructure Rebuild Team
SDC	Selwyn District Council
SGP	Sewer Gravity Pipeline
SPP	Sewer Pressure Pipeline
UPVC	Unplasticized polyvinyl chloride
WDC	Waimakariri District Council

WPH	Wave Propagation Hazards
WPP	Water Pressurized Pipeline

CHAPTER 1

INTRODUCTION

1.1 Motivation

A sewerage system is a major component of municipal infrastructure systems. It conveys sewage, or wastewater, from residential or commercial buildings through complex reticulation networks to treatment plants. The majority of sewerage systems worldwide are gravity-fed. Most pipelines are buried underground up to 15 m deep at a slight downward angle to enable the gravitational force to transfer sewage. The systems can be particularly vulnerable to earthquakes as they are generally not designed to resist peak ground velocities that occur near the epicentre of earthquakes, rather they are designed for average static and hydraulic soil loading. During seismic events both transient ground motion and permanent ground deformation can induce physical damage to wastewater system components and thereby cause dysfunction of the system components, limiting or impeding the operability of the whole system. The malfunction of municipal sewerage systems can result in the pollution of nearby waterways through discharge of untreated sewage, pose a public health threat by preventing the use of appropriate sanitation facilities, and cause serious inconvenience for rescuers and residents. Effective restoration of sewerage systems subject to existing financial and time constraints is needed post-earthquake to avoid or limit the associated consequences (e.g., environmental and/or health issues) that might arise from a limited sewerage service.

Christchurch, the second largest city in New Zealand, was seriously affected by the Canterbury Earthquake Sequence (CES) in 2010-2011. The sequence started with the September 4, 2010 earthquake (Mw=7.1), and the subsequent major shocks, including the ones on February 22, 2011 (Mw=6.2), June 13, 2011 (Mw=6.0) and December 23, 2011 (Mw=5.8) were each followed by a large number of aftershocks. The CES imposed widespread damage to the Christchurch sewerage system (CSS), causing a significant loss of functionality and serviceability to the system. The Christchurch City Council (CCC) relied heavily on temporary sewerage services for several months following the February 22, 2011 earthquake. The temporary services were supported by use of chemical and portable toilets to supplement the damaged wastewater system. The CCC, working alongside other agencies, coordinated the distribution of 42,000 chemical toilets to city homes and 2,900 portable toilets on city streets to provide temporary sewerage services (SCIRT, 2012). The rebuild delivery agency -Stronger Christchurch Infrastructure Rebuild Team (SCIRT) was created by the CCC, Canterbury Earthquake Recovery Authority (CERA) and New Zealand Transport Agency (NZTA), in accordance with the Canterbury Earthquake Recovery Act 2011 (Hartevelt, 2011). The SCIRT is responsible for repair of 85 % of the damaged horizontal infrastructure (i.e., water, wastewater, stormwater systems, and roads) in Christchurch.

Numerous initiatives to create platforms/tools aiming to, on the one hand, support the understanding, management and mitigation of seismic risk for infrastructure prior to disasters, and on the other hand, to support the decision-making for post-disaster reconstruction and recovery, have been promoted worldwide. Despite this, the CES in New Zealand highlighted, once again, that none of the existing platforms/tools are either accessible and/or readable or usable by emergency managers and decision makers for restoring the CSS. Furthermore, the majority of existing tools have a sole focus on the engineering perspective, while the holistic process of formulating recovery decisions is based on system-wide approach, where a variety of factors in addition to technical considerations are involved. Lastly, there is a paucity of studies focused on the tools and frameworks for supporting decision-making specifically on sewerage system restoration after earthquakes.

In view of the contribution undertaken by the SCIRT and the limited literature regarding frameworks/tools supporting the decision-making on sewerage systems recovery after earthquakes available in literature, the following key questions have been identified:

1) How to document and reuse the practices and experience that have been deployed in support of the post-earthquake recovery of the sewerage system in Christchurch;

2) How to provide rapid yet reliable information requirements for decisions on sewer recovery for future earthquakes.

1.2 Aims and objectives

Based upon the key questions, the aim of this thesis is to develop a decision support framework for sewerage network restoration after earthquakes, building on the experience and lessons learnt by the organisations involved in the CSS recovery following the CES in 2010-2011. This framework is intended to support decision making processes in terms of physical damage assessment, functional impact evaluation, and restoration time estimation in the move towards managing an effective and informed post-earthquake restoration of sewerage networks. Towards that, the objectives of this PhD research are:

- Objective 1: To investigate, document and review the decision making process that was conducted for sewerage network recovery in Christchurch;
- Objective 2: To identify information requirements for the decisions in relation to post-earthquake sewerage network restoration;
- Objective 3: To provide tools to: a) assess earthquake-induced physical damage to sewerage pipelines; b) evaluate functional impacts on hydraulic, environmental, structural, economic and social contexts that have arisen from the malfunction of sewerage systems; c) predict the time needed to restore the damaged sewerage systems; and
- Objective 4: To develop a framework for supporting decision making on sewerage system restoration after earthquakes.

1.3 Expected significance

By achieving the objectives listed in Section 1.2, this research will be of value for: 1) enriching the bodies of knowledge in recovery management and the decision making process for post-earthquake recovery for sewerage systems; and 2) helping asset managers make effective and informed decisions on sewer recovery in the event of future earthquakes and on system upgrades for seismic risk mitigation.

By documenting and reviewing the decision making process during the post-earthquake recovery of the CSS after the CES, this research summarises the lessons learnt and suggests best practice in terms of post-earthquake reconstruction of sewerage systems. The knowledge regarding the identified effective post-earthquake response and decision making procedures provide references as well as valuable know-how for recovery authorities worldwide facing decisions in relation to sewer recovery after disasters.

The development of a decision support framework for sewer recovery after earthquakes enables decision makers to assess the physical damage, evaluate the functional impacts relating to hydraulic, environmental, structural, economic and social contexts, and to predict the restoration time of sewerage systems. Furthermore, the decision support framework can be potentially employed to underpin system maintenance and upgrade by guiding system rehabilitation and to monitor system behaviours during business-as-usual time. In conjunction with expert judgement and best practices, this framework can be applied to assist asset managers in targeting the inclusion of system resilience as part of asset maintenance programmes.

1.4 Scope

The focus of this research is on decision making in regard to the recovery of sewerage pipelines and systems. The sewerage pipelines can also be called a sewer network or wastewater pipelines, which contain gravity, pressure pipelines and council-owned laterals. The sewerage system, in other words, wastewater system, is comprised of sewerage pipelines, pumping stations, treatment plants and other functioning appurtenances. In this thesis, the physical damage module (Chapter 6) and serviceability restoration module (Chapter 8) of the decision support framework proposed are exclusively developed for sewerage pipelines. Other sewerage assets, such as manholes, pump stations (PS), and treatment plants are usually treated as stand-alone structures in literature for risk mitigation and post-disaster recovery and, therefore, excluded in this research as well. In addition, there is limited relevant information and data concerning these assets in Christchurch available for analysis. However, the functional impact module (Chapter 7) does include post-earthquake performance indicators established for manholes and PSs.

The primary focus of this research is on earthquake hazards because of the vulnerability of sewerage systems to this hazard. Some of the research findings may have the potential to be applied to other natural hazards (e.g., flood).

1.5 Outline of the thesis

The thesis consists of nine chapters, organised into three main parts.

The first part, consisting of Chapters 1 and 2, provides the introduction to the thesis and the literature review on pertinent concepts and methodological contexts relating to the topic. Chapter 1 introduces the motivations behind choosing this topic and the objectives identified for this research. In Chapter 2, the elementary concepts in relation to the taxonomy of sewerage systems and earthquake-induced physical damage and functional failures of the system components are presented. The in-depth literature reviews on the relevant methods/approaches adopted by the research for developing the decision support framework and the modules embedded in the framework for post-earthquake recovery of sewerage networks are provided.

The second part corresponds to Chapters 3 and 4. Chapter 3 delineates the CSS, the CES 2010-2011, and the seismic performance of the system following the CES, with the focus on the physical damage and functional impacts observed in the aftermath of the earthquakes. The organizations involved in the Canterbury recovery and the decision-making process on sewer recovery conducted by the responsible reorganisations are also presented in Chapter 3. In Chapter 4, critical success factors for post-earthquake infrastructure recovery are identified and categorised into governmental, technical, and information requirements for decision making.

Chapters 5, 6, 7, 8, 9 constitute the third part of the thesis, proposing a decision support framework for the post-earthquake restoration of sewerage networks. Chapter 5 provides an overview of the proposed decision support framework and database and the seismic hazard parameters that have been implemented. Chapters 6, 7, 8 respectively delineate three modules embedded in the framework, namely: 1) physical damage module (PDM); 2) functional impact module (FIM); and 3) pipeline restoration module (PRM). Key conclusions from this research are drawn in Chapter 9, followed by discussions regarding the future work foreseen.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews the state-of-the-art knowledge and existing literature in relation to pertinent concepts and methodological contexts of this research. Section 2.2 introduces the classification and taxonomy of municipal sewerage systems. In Section 2.3, seismic hazards affecting sewerage systems, or infrastructure systems, in general, are presented, with emphasis on seismic hazard parameters implemented in earthquake-related studies for distributed underground pipelines. In accordance with the three main modules embedded in the proposed decision support framework (Chapter 5), the literature regarding the physical damage assessment, functional impact evaluation and restoration time estimation are reviewed respectively in Section 2.4, 2.5, and 2.6. The decision support frameworks for post-disaster recovery and the systems designed underpinning post-earthquake decision making for infrastructure systems are surveyed in Section 2.7.

2.2 Classification and taxonomy of municipal sewerage systems

Sewage, which is also called wastewater, is the fluid disposed from toilets, kitchens, bathrooms, and laundries after use. Most of the sewage stems from domestic, commercial, and industrial usage (Grigg, 2003). A sewerage system (also a wastewater system) is composed of sewer pipelines, manholes, pumping/lift stations, wastewater treatment plants, and appurtenances (Figure 2.1). The sewerage systems transfer the sewage from residential and non-residential buildings through complex underground reticulation to treatment plants for treatment and disposal.

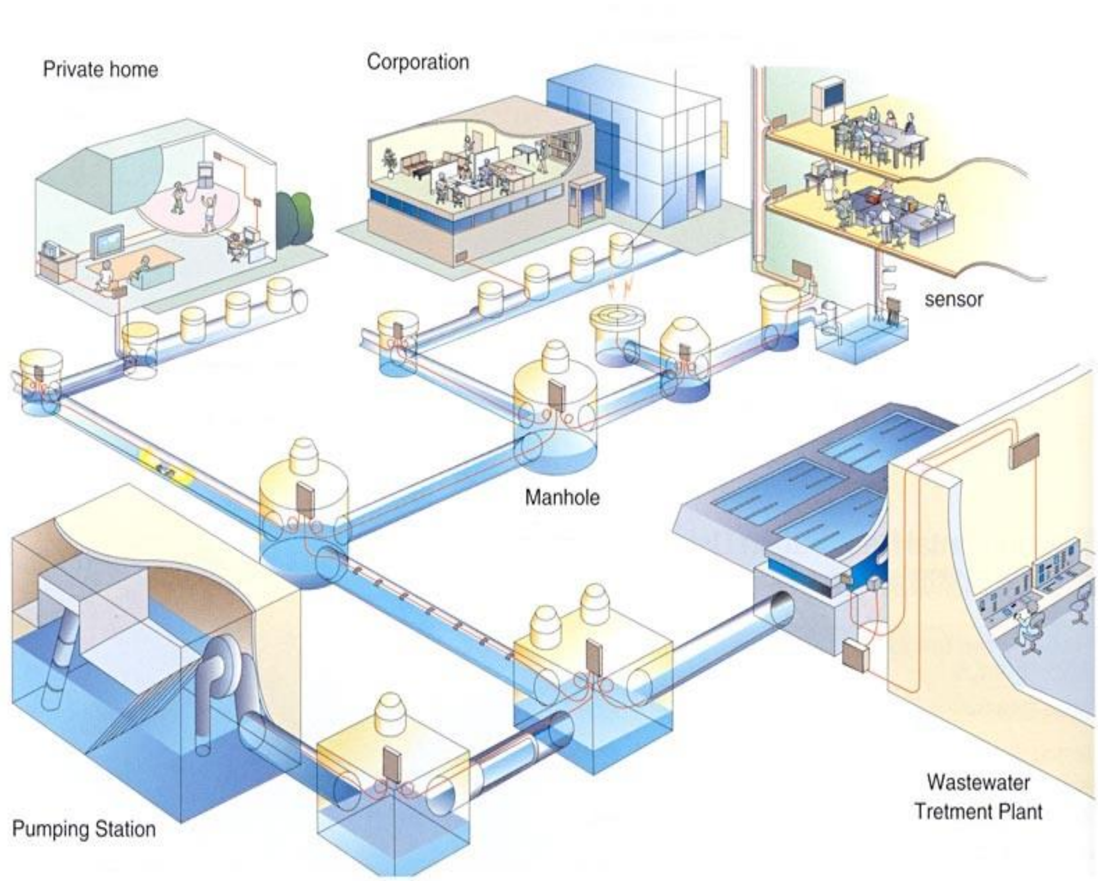
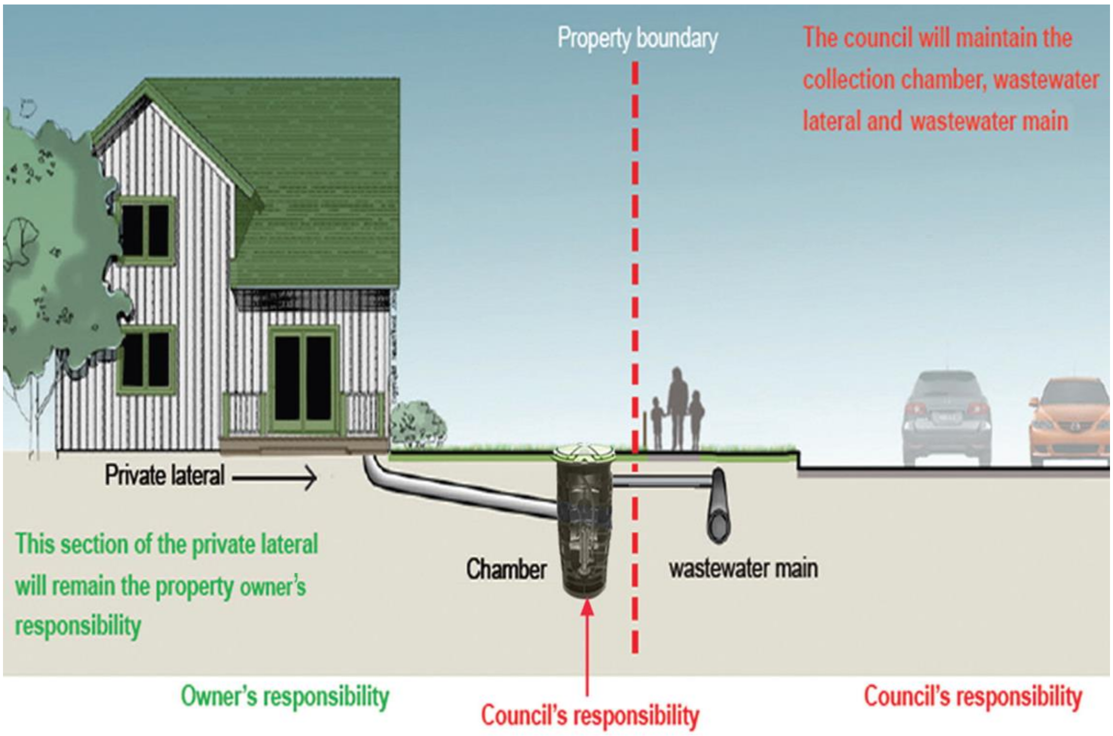


Figure 2.1 Schematic representation of a sewerage system (JSWA, 2002)

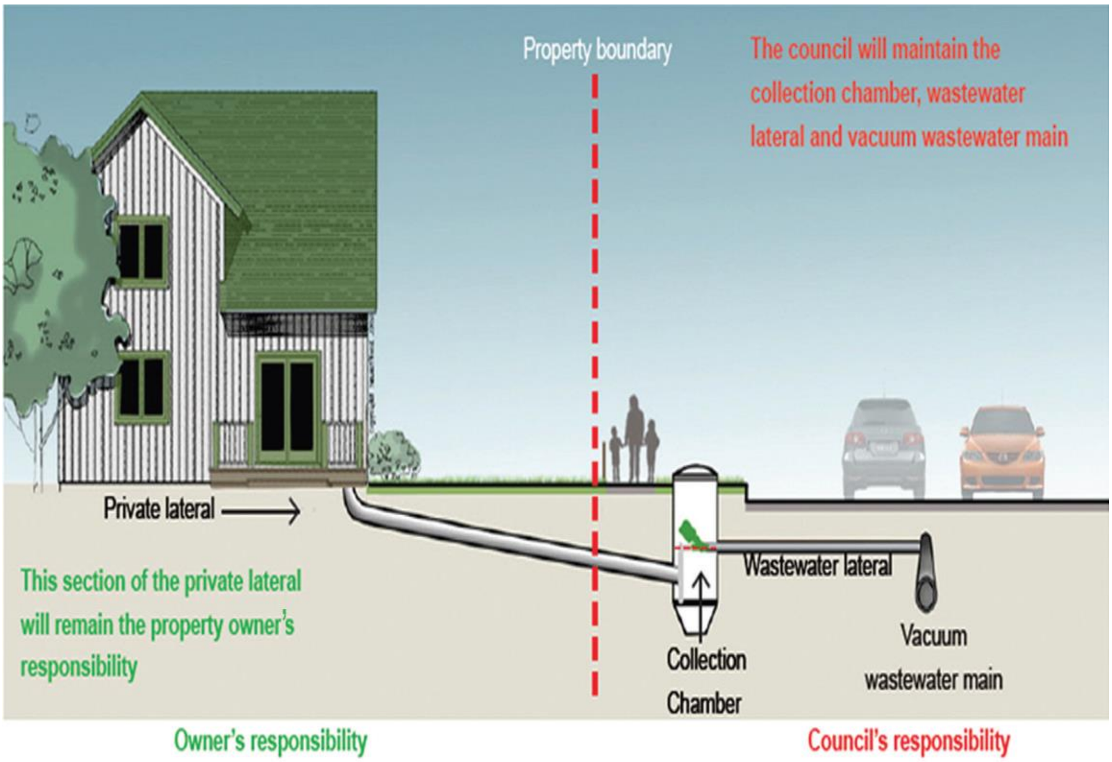
There are two types of sewerage systems, namely: combined and separate sewerage systems. The combined sewerage systems use the same pipeline reticulation to transport both sewage and surface runoff (e.g., rain, meltwater) to treatment plants. In wet weather, the seasonally increased runoff volumes can result in pipe overflow, causing water pollution issues. Therefore most of these combined sewerage systems have been replaced by separate sewerage systems. The separate sewerage systems only convey sewage itself and stormwater systems are built to transfer and drain surface runoff into watercourses without processing or with limited treatment and management. The separate sewerage system is the predominant type of sewerage system adopted worldwide.

The majority of sewerage systems worldwide are gravity-fed. These gravity pipelines are buried underground up to a depth of 15 m with a slight downward angle to enable the gravitational force to transfer sewage. Compared to other underground infrastructure systems (e.g., water supply pipes), the sewerage pipelines are normally buried deeper so as to make better use of the gravitational force. Although the force of gravity is the main driver of the sewerage systems, pressure pipes are still needed to connect to PSs where sewage is pumped to a certain elevation for further conveyance.

Advanced sewerage systems, such as pressurised and vacuum sewerage systems, are drawing increasing attention. In pressurised sewerage systems, an individual property has a collection tank buried in the garden and a control panel to supply and operate the pump equipped in the tank. When the tank is full, the wastewater is pumped to the public pipelines on streets. Vacuum sewerage systems use collection chambers for collecting wastewater from a number of properties located in nearby areas. Once the amount of liquid in the chambers reaches a certain level, the chambers are emptied by use of suction. The wastewater is conveyed to vacuum pumping stations where it is pumped into normal gravity or pressure systems. Figure 2.1 illustrates the main components and responsibilities of the pressurised and vacuum sewerage systems in Christchurch.



a) Pressurised sewerage systems



b) Vacuum sewerage systems

Figure 2.2 Main components and responsibilities of a) pressurised and b) vacuum sewerage systems (SCIRT, 2012)

Taxonomy is the practice of classifying elements into larger groups based on their similarities and differences (Resnik, 1999). Defining a taxonomy of sewerage systems offers an opportunity to fully understand the constituent components within the system, thereby facilitating asset management and data management. For instance, according to ALA (2004), sewer mains, conduits, and laterals are all categorised as parts of a sewer collection system. The asset management plans and database organisation for the sewer collection system are uniformly applied to the three pipe types, which is more effective and efficient than managing them individually. Furthermore, the taxonomy allows for the comparison of functionality and performance of a type of sewerage system assets across different cities and countries.

A comparative study regarding the taxonomy of sewerage systems was conducted for this research using a few well-known frameworks/platforms in lifeline earthquake engineering worldwide: ALA (2004), HAZUS (NIBS, 2003), Syner-G (Pitilakis et al., 2014a, b) (details in Section 2.3.2). ALA (2004) and HAZUS (NIBS, 2003) were conceived in the United States (US) and widely applied for lifeline performance assessment and social-economic loss estimation. Syner-G (Pitilakis et al. 2014a, b) is a European collaborative research project focusing on systematic seismic vulnerability and risk analysis of buildings, transportation, utility networks and critical facilities in Europe. Table 2.1 compares the taxonomy of sewerage systems proposed in the aforementioned frameworks/platforms and the one used in New Zealand.

Table 2.1 The taxonomy of sewerage systems in literature

Source	Taxonomy	Key facilities/categories
ALA (2004)	Collection system	Sewage collection, sewage interceptor, manhole
	Lift station	Power supply, valve, pump, building, electrical equipment
	Reclamation plant	Sedimentation tank, clarifier, digester tank, building, control system, Supervisory Control and Data Acquisition (SCADA) system
HAZUS (NIBS, 2003)	Collection sewer	Smaller diameter pipe (4 to 42 inches)
	Interceptor	Larger diameter pipe (≥ 42 inches)
	Lift station	Small: < 10 mgd, medium-large: ≥ 10 mgd
	Treatment plant	Small: < 50 mgd, medium: 50-200, large: ≥ 200 mgd
Syner-G (Pitilakis et al. 2014a, b)	Conduit	Pipe, tunnel
	Lift station	Electric power, vertical/horizontal pump, building, equipment,
	Treatment plant	Electric equipment, chlorination equipment, sediment flocculation, chemical Tanks, elevated pipe, building
	SCADA system	System control, storage, administration, customer service
New Zealand (CCC, 2004)	Pipeline	Minor sewer collector (diameter < 300 mm), trunk mains (diameter ≥ 300 mm)
	Pumping/lift station	Pump, electrical equipment, building, system control
	Manhole	Vented/unvented manhole
	Treatment plant	Building, SCADA, screening, pre-aeration and grit removal, primary sedimentation

2.3 Seismic hazard characterisation for underground pipelines

2.3.1 Seismic performance of sewerage systems in past earthquakes

The daily functioning of modern societies rely heavily on engineered sewerage systems. The functionality of sewerage systems are subject to disruption caused by natural disasters. Hazards like earthquakes can induce physical damage which then results in functional impacts on the services. This, in turn, can affect community wellbeing by means of posing health and safety threats; causing environmental concerns; triggering short-term and long-term impacts on local businesses and wider economy.

Examples of partial or total loss of functionality for sewerage systems following earthquakes can be identified worldwide. Approximately 150 km of sewer pipes and 2700 manholes were damaged to a varying level in the Hanshin event, Japan (1995). The moment magnitude (Mw) 7.4 Turkey earthquake (Izmit, Oct. 19. 1999) had serious impact on the Izmit wastewater system, which used to have capacity of 10,500 litres per second but reduced to 30,000 litres per day due to the seismic effects (Erdik, 2001). Tohoku earthquake (Mw= 9.0) and Tsunami in 2011 damaged 63 treatment plants, of which 48 totally lost functionality and seriously affected 101 sewer PSs, of which 79 were out of service immediately after the event (Eidinger and Davis, 2012). The Canterbury earthquake sequence (CES) 2010-2011 caused significant damage to the Christchurch wastewater network. As of January 2014, 659 km of sewer pipelines, accounting for 41 % of the total reticulation network, and 136 pumping stations (83 %) were identified as damaged to a varying extent (Liu et al., 2015c). Two months after the February event, the Christchurch wastewater treatment plant was operating at 30% of its normal capacity, and the wastewater system was leaking 40 million liters per day into backyards and water courses due to earthquake-induced damage to pipes (Tang 2016). 42,000 chemical and 2,900 portable toilets were deployed for the provision of a temporary sanitation service in Christchurch to relieve the strain on the wastewater system (Liu et al., 2013).

2.3.2 Seismic hazard analysis

During seismic events, underground sewer pipelines can sustain physical damage caused by wave propagation hazards (WPH), or permanent ground deformation hazards (PGDH), or a combination of both (O'Rourke and Liu, 1999). Even in one earthquake event, it is common to find the induced pipeline damage is caused by different hazards; that is, some damage occurred in areas where the WPH is the predominant hazard while others are triggered by the PGDH. The PGDH tends to affect pipelines in localised areas and the pipeline damage rates are averagely higher, whereas the WPH (causing transient ground shaking) often damages underground pipelines in a relatively large scale region yet with lower damage rates (O'Rourke and Liu, 1999).

Seismic waves traveling through the earth cause transient ground motion to a varying degree along the paths of the waves. The WPH can be characterised by use of transient strain and curvature in the ground resulting from ground shaking. Permanent ground deformation (PGD) commonly occurs from liquefaction, landslide, lateral spreading, ground settlement and fault rupture. Since the PGD occurs in a geographical area, the amount, geometry and spatial extent of the PGD zone are utilised to characterise the PGDH (O'Rourke and Liu, 1999). In particular, the fault-crossing PGDH is characterised by the permanent horizontal and vertical offset at the fault and the pipe-fault intersectional angle.

The magnitude (M_w), location and depth of earthquakes can significantly influence the extent of the earthquake-induced physical damage that the structures may sustain (Erdik et al., 2011). Seismic hazard assessment aiming to capture and estimate the earthquake ground movement is often conducted for developing earthquake hazard scenarios and as a further step for seismic fragility analysis (Wen and Ellingwood, 2005).

There are two widely recognised approaches for seismic hazard assessment, namely: Deterministic Seismic Hazard Assessment (DSHA) and Probabilistic Seismic Hazard Assessment (PSHA) (Kramer, 1996). The DSHA uses a sole earthquake event as an input for seismic scenarios, the magnitude, location of the earthquake and its distance from study structures are determined (Reiter, 1991). The earthquake scenarios can be chosen from existing geological faults where their pertinent characteristics are explicitly documented and mapped, or from historic earthquake events that have caused destructive consequences. In either case, the expected ground shaking that structures might experience can be estimated. PSHA assesses seismic effects on the structures of interest which are subjected to a whole range of earthquake scenarios in a probabilistic fashion. The PSHA of engineered pipelines defines the earthquake hazard scenarios by combining all possible earthquakes that could potentially damage the pipes, accounting for all feasible combination of magnitude, distance and the occurrence frequency of seismogenic sources (Cornell, 1968). The PSHA is conducted through a recurrence relationship to characterise the seismicity of the considered earthquakes and where information is sufficient, examines probabilistically the resultant consequences (e.g., societal, economic). However, this method consumes extensive time and resource (e.g., trained engineers, computation facilities).

The selection between the DSHA and PSHA depends on, among others: the purposes of study, the availability of necessary inputs, and the constraints on budget and time. In the case of the establishment of proactive risk mitigation plans, the PSHA is preferable because it holistically evaluates the seismic effects of all possible earthquakes and elicits underlying risk and issues on the structures of interest. On the other hand, the

DSHA could more promptly analyse the data available and compose with a range of seismic consequences upon which reactive actions for infrastructure planning and emergency response can be drawn.

In line with the research questions as to how to provide rapid yet reliable information requirements for decision makers and practitioners on restoring sewerage systems post-earthquake, DSHA is chosen in the thesis. Among all the earthquakes that occurred during the CES, the February quake caused the most severe damage to buildings and infrastructure in Christchurch (Cubrinovski et al., 2011a). Therefore, this quake is selected as an input for a deterministic seismic damage scenario in this thesis.

2.3.3 Seismic hazard parameters

Seismic hazard parameters are used to qualitatively or quantitatively measure seismic hazard intensity. They represent observational or mechanical aspects of either the WPH or PGDH of seismic events. Among others Modified Mercalli Intensity (MMI), peak ground acceleration (PGA), peak ground velocity (PGV) and maximum ground strain (MGS) are commonly used seismic parameters of the WPH as, for instance, fragility function arguments in fragility analysis. As for the PGDH, permanent ground deformation (PGD) is a widely recognised parameter to characterise the severity of ground displacement.

2.3.3.1 Modified Mercalli Intensity

MMI or seismic hazard intensity, represented as a Roman numeral, describes the severity of an earthquake in accordance to its effects on the earth's surface as well as on the community and engineered structures existing on it. MMI developed by seismologists Wood and Neumann in 1931 is one of the most common descriptors for assessing seismic effects at a specified location (Richter, 1958). The MMI qualitatively measures the observational effects of earthquakes based particularly on people's experience and the observed structural damage. There are ten levels in the MMI scale ranging from imperceptible shaking as the lowest level to catastrophic destruction which is defined as the extreme level. Due to the extensive usage of the MMI as a seismic parameter in evaluating earthquake-induced damage to aboveground structures, it was adopted to correlate damage to underground pipelines in the 80s and 90s (Pineda and Ordaz, 2012). However, along with the increasing development of quantitative indicators (such as PGV and PGA), the MMI has been gradually replaced by the parameters that can quantitatively measure seismic effects on distributed pipelines.

2.3.3.2 Peak ground acceleration and peak ground velocity

The installation of seismic stations around the world especially in seismic-prone areas or countries leads to the increase in the application of PGA and PGV as seismic hazard descriptors. The two descriptors have become the most popular seismic parameters for developing fragility functions for pipelines in the last 30 years (Lanzano et al., 2014). Equipped with strong ground motion sensors, seismic stations can record ground motion accelerations caused by seismic waves. Before 2000, the PGA was widely used in the development of fragility functions for underground pipelines (Katayama et al., 1975; Isoyama et al., 2000). This is because the PGA can be directly estimated from the sensor records whereas the obtainment of the PGV requires advanced mathematic computation (e.g., integral) which could be difficult due to the lack of PGV attenuation laws before 2000.

Since 2000, the PGV has become the most widely adopted earthquake intensity measure when creating seismic fragility functions for buried pipelines (O'Rourke and Ayala, 1993; Eidinger, 1998; ALA, 2001, 2004; NIBS, 2003). A number of studies show PGV correlates empirically better with earthquake-induced damage to pipelines than the

PGA (O'Rourke at al., 1998; Isoyama et al., 2000; Pineda and Ordaz, 2003). The underlying reason is that the PGV is related to ground strain which is the main inducer of the WPH-triggered pipeline damage, whereas PGA is more related to inertia forces which affects stand-alone structures but not geographically distributed pipelines (Pineda and Ordaz, 2012).

Pineda and Ordaz (2007) propose PGV^2/PGA as a new seismic parameter and show a higher correlation with damage to pipelines than PGV or PGA alone using the damage data on the Mexico City's Water System observed after the 19 September 1985 Mexico City earthquake (M_w=8.0). Although the PGV^2/PGA is found numerically related to ground displacement in the study, it is only composed of seismic intensity parameters related to seismic wave propagation. The validity of the parameter in areas where both the WPH and PGDH occurred like Christchurch city has not been investigated.

2.3.3.3 Maximum ground strain

Earthquake-induced ground strain is considered the main cause of physical damage to pipelines as a result of WPH (Kramer, 1996). Therefore, maximum ground strain (MGS) has been utilised to characterise the effects of the WPH for analysing seismic performance of buried pipelines (O'Rourke and Liu, 1999). The MGS (ε_g) can be calculated using Eq. (2.1) as below:

$$\varepsilon_g = \max\left|\varepsilon(t)\right| = \max\left|\frac{\partial D(t)}{\partial x}\right| \qquad (2.1)$$

Where x is a space variable, ε(t) is ground strain time history and D(t) is the displacement time history. There are three limitations when using this equation to compute ε_g. First, the displacement time histories D(t) are computed by use of double integration of acceleration time histories, which can lead to loss of information and accuracy, thereby resulting in ambiguous outcomes. Second, the derivation involved in obtaining ε_g, due to the presence of a space variable x, requires the same time reference and preferably the close geographical locations for the seismic records analysed in the Eq. (2.1). Since pipelines are often spread over large-scale zones, the requirement reduces the adoptability of this equation. The last one is the availability of necessary ground information and the feasibility of sufficient seismic sensors installed in a large zone covering the entire pipeline networks (Pineda and Ordaz, 2012).

Assuming a simple seismic wave with a constant wave shape, Newmark (1967) proposes a simplified equation to estimate the MGS (Eq. 2.2).

$$\varepsilon_g = \frac{PGV}{C} \tag{2.2}$$

Where the PGV is the maximum horizontal particle velocity in the direction of wave propagation and C is the propagation velocity of the seismic wave. However, the estimation of C could be hard and problematic (Singh et al., 1997; O'Rourke and Deyoe, 2004).

Some researchers propose seismic fragility functions using ε_g (O'Rourke et al., 2004, 2012, 2014). However, the adoption of infrequent seismic parameters normally requires extra analytical calculations, thus leading to added time and resource for practitioners to rapidly gain understanding of seismic effects on underground pipelines (Liu et al., 2015).

2.3.3.4 Permanent ground deformation

The PGDH tends to cause more severe physical damage to the structures and pipelines in localised areas. The PGDH can be caused by surface faults, landslide, seismic settlement and lateral spreading associated with soil liquefaction (Kramer, 1996). In view of the extensive liquefaction hazard after the CES, this thesis will only focus on the ground deformation caused by liquefaction.

To measure soil liquefaction, liquefaction-induced ground settlement is deployed as an intensity indicator. Some researchers devised analytical approaches to estimating ground settlement by multiplying volumetric strain of liquefaction layers with the layer thickness (Tokimatsu and Seed, 1987; O'Rourke et al., 1999; Pradel, 1998; Zhang et al., 2002). Empirical regression equations are developed based on historical observations in the field by Takada and Tanabe (1988) and Yan et al. (2004). The Liquefaction Resistance Index map (LRI) was created by Cubrinovski et al. (2011c) after the CES in 2010-2011. The map was produced by use of extensive field mapping conducted by professional geotechnical engineers after the February Earthquake. The average lateral displacement and ground settlement estimates from the map were combined using vector addition to create PGD values for each region of the map.

During the CES in Christchurch, extensive liquefaction occurred and led to variable damage to underground pipelines. In this thesis, the PGDH is considered and represented by use of the LRI zones (Section 5.4).

2.4 Physical damage assessment

2.4.1 Earthquake-induced damage mechanism and damage measurements

Earthquake events can cause physical damage and functional impacts on sewerage system components. Sewerage gravity systems are particularly vulnerable to earthquakes as they are generally designed to only resist static and hydraulic soil loading. During seismic events both transient ground motion and permanent ground deformation could induce physical damage to system components and thereby cause dysfunction of the components, limiting or impeding the operability of the whole system.

The damage mechanisms of sewerage system components describe the types of earthquake-induced physical failures or incidents that occur on the components, such as leakage and cracking.

Damage measurements qualitatively or quantitatively assess the extent of the damage/defects/failures to the system components. The most widely recognized measures of damage for underground pipelines are the Damage Ratio (DR) and Repair Rate (RR) expressed as numerical incidents (fault for DR, repair for RR) per pipe length (Toprak and Taskin, 2007). Available empirical fragility formulae generated by use of historical data on physical damage to sewer pipes are based on either DR (Naba, 2012; Nagata, 2011), or RR (ALA, 2004; Alexoudi et al., 2010; NIBS, 2003; O'Rourke et al., 2014). For stand-alone structures like lift stations (LSs) or treatment plants, measures such as different damage states or operability are often employed for damage assessment.

In line with the taxonomy of sewerage systems defined in ALA (2004), HAZUS (NIBS, 2003), Syner-G (Pitilakis et al., 2014a, b), the damage mechanism and damage measurements pertinent to each type of asset are presented in Table 2.2. This table compares the same type of components that are expected to experience similar physical damage after earthquakes and be measured using qualitative or quantitative criteria. Furthermore, it shows that the taxonomy of sewerage systems adopted in New Zealand is comparable and adaptable to other taxonomies available in the international literature.

Table 2.2 Damage mechanism and measures adopted in literature

Reference	System component	Damage mechanism	Damage measures
ALA (2004)	Collection system	Axial pull-out, joint rotation, tensile and bending deformations of the pipe barrel	Repair rate
	Lift station Reclamation plant	Loss of power and communication, asset structural failures, damage to building,	Three levels of damage state: low, medium, high
HAZUS (NIBS, 2003)	Collection sewer Interceptor	Leakage and breakage	Repair rate
	Lift station Treatment plant	Loss of electric power, damage to equipment, buildings, connecting pipes	Serviceability state, type and extent of structural damage
Syner-G (Pitilakis et al., 2014a, b)	Conduit	Leakage and breakage	Repair rate
	Lift station Treatment plant SCADA system	Loss of electric power, damage to equipment, buildings, connecting pipes	Extent of damage, serviceability state
New Zealand (CCC, 2004)	Pipeline	Cracks, Joint breakage, Breaks, Collapses, Loss of gradient	Damage ratio
	Pumping/lift station	Pump-related facility damage, building damage	Extent of damage and operability
	Manhole	Uplifting, settlement	Extent of damage and operability
	Treatment plant	Treatment facility damage, building, SCADA damage	Extent of damage and operability

2.4.2 Simplified fragility assessment approach: Fragility matrices

A fragility assessment could serve as a pivotal tool for predicting potential damage to infrastructure. Fragility assessment approaches link quantitative measures of the seismic hazard (e.g. in terms of peak ground velocity or permanent ground deformation) to the potential physical/functional damage that might be sustained by the system components. A fragility matrix is a simplified method for evaluating seismic fragility of sewerage pipelines. It provides a basis upon which preliminary screening of existing pipelines for pre-event risk mitigation could be performed. Moreover, they have the potential to facilitate reconstruction prioritization of the impaired pipes in the aftermath of disasters.

Fragility matrices have been used as approximate indicators to interpret the relationship between seismic hazard and seismic response of a given building/system. For buildings, the Building Ministry of China (BMOC, 2001) publishes seismic fragility matrices for infrastructure and buildings. For a given level of seismic intensity, the matrices indicate the probability that the system/building of interest might experience five damage states, namely: intact, slightly damaged, moderately damaged, seriously damaged, and destroyed. In Europe, Grunthal (1998) proposes six vulnerability classes for various building typologies, categorised by commonly used European structural materials (e.g., masonry, reinforced concrete). The vulnerability classes have been widely used for developing damage scenarios and risk assessment in different territorial scales, like, urban and regional (Okada and Takai, 2000; Giovinazzi and Lagomarsino 2004; Roca et al., 2006; Pitilakis et al., 2014a, b)

The fragility matrices can also be of use for formulating asset maintenance and rehabilitation plans as part of business-as-usual programs. Park et al. (2010) develop fragility matrices in terms of likelihood and consequence of failure for water pipelines based on physical conditions (e.g., pipe age), failure history and capacity performance. The fragility matrices are fed into a risk-based asset prioritization tool aiming to guide water asset repair and upgrade in the City of Tampa (US) to accommodate the increasing population.

Seismic fragility matrices designed for sewer pipelines could serve as a simplified approach to providing rapid judgements regarding seismic behaviours of underground sewer pipes to be used for post-earthquake recovery, especially when the information needed for making sophisticated decisions is not yet available.

2.4.3 Advanced fragility assessment approach: Fragility functions

Fragility functions, graphically illustrated as fragility curves, are a well-established tool to assess seismic risk to buried pipelines, including water supply pipelines (ALA, 2001; NIBS, 2003; Alexoudi et al., 2010; Eidinger, 1998; O'Rourke and Ayala, 1993, 2014; Toprak and Taskin, 2007) and sewerage pipelines (ALA, 2004; Alexoudi et al., 2010; NIBS, 2003; Nagata et al., 2011; O'Rourke et al., 2014). Fragility functions correlate physical representations of ground motion intensity and system damage/repair, represented as numerical incidents per pipe length (Toprak and Taskin, 2007) expressed either as a Repair Ratio (RR) (ALA, 2004; Alexoudi et al., 2010; NIBS, 2003; O'Rourke et al., 2014) or as a Damage Rate (DR) (Nagata et al., 2011; Shoji et al., 2011).

One of the underlying reasons that DR appears to be less-developed than RR in the literature is the lack of available damage data. This is for the simple reason that repair data can be collected more conveniently because it can be accomplished during repair operations after the disasters. Damage evaluation requires ancillary support in terms of trained staff and inspection equipment at a time of high demands on these resources. Additionally, the short time frame available for assessment under emergency situations hampers the collection of damage data. Damage evaluation that occurs at the time that repairs are recorded can impede restoring services to customers. Alternatively, damage evaluation could be executed prior to repairs as part of assessment of the network condition using various evaluation methods (e.g., Liu et al., 2013). However, this could significantly prolong the restoration process. In either case, the additional effort required for the collection of damage data has meant less damage data are available. Improvements in technologies such as CCTV are increasing the efficiency of collecting and using damage data in post-earthquake restoration.

Fragility curves are used within different platforms for seismic risk assessment, e.g. HAZUS (NIBS, 2003) and Syner-G (Pitilakis et al. 2014a, b), to estimate the earthquake-induced damage to pipes. In particular, Syner-G implements ALA (2001), backbone vulnerability curves for water distribution networks considering variations in pipe materials and joint types. HAZUS (NIBS, 2003) uses fragility functions proposed by O'Rourke & Ayala (1993) for brittle and ductile water pressurized pipes for post-earthquake loss estimation. Pitilakis et al. (2014a, b) validate the fragility algorithms available in Syner-G, also proposing fragility functions developed by O'Rourke and Ayala (1993) for water supply pipelines when subject to wave propagation and those proposed by Honegger and Eguchi (1992) when water pipelines experience permanent ground deformation. The ALA, HAZUS and Syner-G approaches recommend extending the use of the fragility algorithms specifically derived for water supply pipelines, when subjected to PGV and PGD, to sewerage pipelines. However, recent seismic events, including 1994 Northridge (America) earthquake (Schiff, 1995), 2004 Niigata (Japan) Earthquake (Scawthorn et al., 2006) and 2010-2011 Canterbury earthquake sequence (Giovinazzi et al., 2011) highlighted that pressurized pipes and sewerage unpressurised (gravity) pipes behave differently under seismic loadings.

A limited number of fragility functions have been specifically defined for sewerage pipelines. Nagata et al. (2011) develops fragility curves for polyvinyl chloride (PVC) sewer pipes within liquefaction and non-liquefaction sites and at various burial depths based on the physical damage data on four cities in Japan after four earthquakes. Shoji et al. (2011) derives a set of fragility curves for sewerage pipelines based on the damage data on the Kobe wastewater system after the 1995 Kobe (Japan) earthquake. They utilize a trust region method for obtaining regression coefficients of the assumed log-normal distribution of fragility curves. O'Rourke et al. (2014) correlates lateral ground strain with RR for earthenware (EW), PVC and unplasticized polyvinyl chloride (UPVC) wastewater pipes; and proposes correlation between the angular distortion, expressed as the differential vertical movement between two adjacent LiDAR points over the horizontal distance, and RR for EW, reinforced concrete rubber ring (RCRR), and concrete (CONC) wastewater pipelines. These fragility functions were generated by processing the data on the earthquake induced damage to the Christchurch sewerage system after the Canterbury earthquakes in 2010-2011.

There are different shortcomings affecting fragility curves specific to sewerage pipes. The sewerage fragility functions, either only refer to a limited number of pipe types and material categories, or adopt infrequent parameters (e.g. angular distortion) which require extra analytical calculations for practitioners worldwide to obtain and thus lead to added time and resource in assessing seismic performance of sewerage pipelines. Furthermore they use RR as parameters to estimate earthquake-induced incidents to sewer pipes, while DR would provide more reliable and accurate assessment as found by Liu et al., (2015d) when comparing and analysing the databases of the damaged pipes and repaired pipes in the Christchurch sewerage network. Finally, levels of liquefaction extent are not considered in the process of developing fragility functions for sewer pipelines.

2.5 Functional impact evaluation

2.5.1 Functional failure classification of sewer components

The functions of system assets are what utilities and customers want the assets to do. After earthquakes, the seismic-induced physical damage to sewerage system components might lead to various function failures, thus resulting in partial or total loss of functionality of the sewerage systems. This, in turn, can affect community wellbeing by posing health and safety threats; causing environmental concerns; triggering short-term and long-term impacts on society and wider economy.

The function failures, effects and resultant impacts are presented in Table 2.3 in accordance to the functions of sewerage system assets. Table 2.3 lists the functions of each type of assets, expected function failures, and potential consequences on the hydraulic, environmental, structural, economic and social contexts caused by the malfunction of the systems. For example, one main function of sewer pipelines is to transfer sewage. Pipe collapse and/or cracks induced by seismic events could cause partial or total malfunction in terms of conveying wastewater. The broken pipes might leak sewage into the environment and obstruct the functionality of neighbouring pipes. As a result, restrictions on domestic usage have to be issued. This results in a series of consequences such as hydraulic, environmental, structural, economic and social impacts. These impacts should all be accounted for when, on one hand, assessing seismic performance to seek improvement opportunities and, on the other hand, when measuring the success of recovery practices according to community demands.

Table 2.3 Breakdown of function failures, failure impacts, and resultant impacts according to the functions of sewerage system assets

Asset	Function	Function failure	Failure effect	Resultant impacts
Pipeline	Transfer sewage	Partially or fully fail to transfer	Restricted domestic usage	Social impact
			Sewage leakage to environment (e.g., soil, waterways)	Environmental impact
			Effects on the functionality of neighbouring pipes	Hydraulic impact
	Store sewerage	Fail to store	Restricted toilet usage	Social impact
			Sewage leakage to environment (e.g., soil, waterways)	Environmental impact
Pumping/ lift station	Pump/lift sewage	Fail to pump	Sewage well overflow	Hydraulic impact
	Store sewage	Fail to store	Sewage leakage in pumping stations	Structural impact
	Transfer sewage	Partially or fully fail to transfer	Sewage flow cannot go through pumping stations	Hydraulic, social impacts
Manhole	Personnel access	Fail to enter	Restricted accessibility	Structural, social impacts
	Transfer sewage	Partially or fully fail to transfer	Sewage flow cannot go through manholes	Hydraulic, social impacts
	Odour release	Fail to release	Odour backflow to properties	Social impact
Treatment plant	Treat sewage	Partially or fully fail to treat sewage	Sewage discharged to waterways without treatment	Social, environmental impacts
	Discharge sewage	Fail to discharge sewage	Sewage storage well overflow	Social, economic, environmental impacts

2.5.2 Performance evaluation of sewerage systems at the business-as-usual time

Performance evaluation of sewage systems allows for a holistic review of system performance by use of criteria or indicators that intend to qualitatively and quantitatively measure the system performance against pre-defined targets. It could disclose the weaknesses of the systems and investigate potential solutions in an effort to improve the performance and functionality of the examined sewerage systems.

Specific performance evaluation tools able to measure sewerage facility behaviours for business-as-usual asset management do exist. Two main types of performance evaluation tools available, designed for water and wastewater systems include: 1) performance assessment tool; and 2) performance indicator (PI) (Cardoso et al., 2004). The first one solely concentrates on technical aspects of system performance (Cardoso et al., 2004). The second one is adopted to measure such relevant aspects of system performance as environmental, operational, personnel, physical, quality of service and financial domains (Marques and Monteiro, 2011; Matos et al., 2003). In particular, Cardoso et al. (1999) evaluates wastewater system performance in hydraulic, environmental, structural, economic and social domains. Following this, the abovementioned domains have been applied in the wastewater system field in terms of operation and maintenance issues and rehabilitation planning.

Cardoso et al. (2005) measure hydraulic performance of a separate sewerage system and a combined system by use of hydraulic PIs, namely: water level and flow velocity. The use of the PIs, graphically presented in event and system performance charts, assists in disclosing the strengths and weaknesses of the system in terms of hydraulic capability by comparing the PIs during dry weather period and rainfall events. It also highlights the importance of the usage of PIs for asset performance management and where possible for comparative analysis across counties. Hosseini and Ghasemi (2012) develop a fuzzy model for performance evaluation of sewer systems in the hydraulic domain, accounting for pipe attributes, discharge features and uncertainties (e.g., infiltration rate) as well as expert judgement. The developed hydraulic model can act as a performance assessment tool for decision makers to plan asset maintenance and rehabilitation programme.

Korving et al. (2009) propose a risk-based approach for sewer rehabilitation, with a special emphasis on environmental impacts. Considering the probabilities and consequences of overflow issues of sewer systems, the approach uses economic cost functions that model pollutant concentrations in overflow volume to optimise in-sewer storage environmental impacts. ALA (2004) proposes PIs for evaluating sewerage system performance in the context of environment and public health for 100-year and 500-year return periods, respectively.

Aiming to assess the performance of sewerage services and service providers, IWA (2003) presents a set of PIs including environmental, personnel, physical, operational, quality of service and economic and financial indicators, exclusively designed for wastewater services at the business-as-usual time.

The aforementioned PIs applied for sewerage systems/services in business-as-usual times, however, may not be able to deal with earthquake-induced issues as they do not account for:

- The severity and peculiarity of structural damage to sewerage facilities caused by earthquakes, which significantly shorten asset service life (e.g., collapsed pipes caused by caving road surface);

- The various damage modes, mechanism and functional failures that are sustained by sewerage systems and components after earthquakes (e.g., uplifted manholes due to ground settlement); and
- Resultant and interventional consequences that result from the earthquake-induced functional failures on sewerage service, thus interfering with normal operability (for example, volume of direct wastewater discharged into waterways).

2.5.3 Post-earthquake performance evaluation of infrastructure systems

Holistic evaluation and quantitative measurement of functional impacts caused by earthquake-induced physical damage is needed in the aftermath of destructive earthquakes (Harvey and Reed, 2002; Davis, 2014a, b). It is useful for decision makers to gain full knowledge of residual functionality of the damaged sewerage systems in order to formulate recovery plans leading to more robust sewerage systems (Liu et al., 2013). This can be achieved through performance evaluation with the help of indexes/indicators.

Two commonly used dimensions for post-disaster performance evaluation for infrastructure networks are connectivity and serviceability. Connectivity indicates the remaining connection status between two points in a system. Serviceability is the capacity of the system to provide satisfied services to meet the demand and expectations of the customers (Pitilakis et al., 2014a). Pre-defined performance indexes/indicators are deployed in preceding studies to measure system connectivity (Argyroudis et al., 2011; Poljanšek et al., 2012) and serviceability (Adachi and Ellingwood, 2008; Dueñas-Osorio and Rojo, 2011; Wang et al., 2010). The performance evaluation tools could disclose the susceptibility of the examined systems and potential solutions for improving system performance and, where possible, for the inclusion of resilience into the as-built systems.

A few studies have been conducted to evaluate post-disaster performance of different types of infrastructure systems. For water supply systems, Kawakami (1990) uses a service ratio to indicate the connectivity of the water transmission system in the City of Tokyo. The service ratio indicates the ratios of connected properties after earthquakes to the total number of connected houses under normal condition, which is expected to rise along with the post-earthquake restoration process. ALA (2002) develops a simplified evaluation method for estimating the system connectivity by the use of connectivity matrices and reachability matrices. Shi et al. (2006) and Wang (2006) propose a system serviceability index (SSI) to measure seismic performance of water supply systems. The SSI is calculated as the ratio of the sum of the satisfied customer demand nodes before earthquakes to that after the earthquakes. The index is then applied to a build damage consequence index and an upgrade benefit index by Wang et al., (2010). Adachi and Ellingwood (2008) propose a serviceability ratio for evaluating system serviceability which is defined as the percentage of the number of water distribution nodes in the network which are still accessible after earthquakes over the total number of distribution nodes. The serviceability ratio can also be used to estimate the number of customers who can still access the water service from the network after seismic events by multiplying by the total number of customers served. In the study, the serviceability ratio is then applied to an electrical power system in order to examine the dependence of the functionality of water systems to the presence of electrical power systems. In Syner-G, graph analysis was used to model functionality and undertake connectivity analysis for water supply systems (Pitilakis et al. 2014a, b).

As for electrical power systems, Ang et al. (1996) use a network connectivity model for system connectivity analysis whereby the connectivity between pairs of nodes is captured by the connectivity or reachability matrices of the network which can be attained by summing up adjacency matrices. The adjacency matrix between two nodes is determined as 1 if the two nodes are connected and 0 otherwise. Albert et al. (2004)

introduce connectivity loss (CL) to measure the reduction in terms of the number of generators connected to distribution substations, assuming that every substation is linked to all generators in the system. Kim et al. (2007) use the CL as a system performance measure to quantify the functional loss of a lifeline system for evaluating the seismic performance of interdependencies between water supply and electronic power systems. Poljanšek et al. (2012) advance the concept of CL by counting the real number of generators that each distribution substation is connected to and then find out the number of damaged nodes.

A gap is evidenced in relation to well-established performance indexes/indicators for post-earthquake performance evaluation of sewerage systems. The performance evaluation tools should have the potential to:

- Evaluate the severity and proportion of the earthquake-induced structural damage to sewerage facilities on both component and system levels, based on the typology of sewerage systems;
- Consider the various damage mechanism and functional failures caused by earthquakes;
- Assess the resulting consequences that have arisen in hydraulic, physical, structural, environmental, social, and economic contexts; and
- Speculate on the actions/strategies to be undertaken in the post-earthquake recovery process.

2.6 Restoration time estimation

2.6.1 Restoration models for infrastructure systems

Further to the assessment of the physical damage and functional impacts on the impaired sewerage systems that support the understanding of the reduced capability and loss of serviceability of the system, a post-earthquake recovery is vital. A timely and effective post-earthquake recovery is able to minimise societal, environmental, and economic impacts that have arisen from a limited sewerage service. In addition, post-earthquake restoration of wastewater systems should be seen as an opportunity to enhance the system's performance in general terms and to increase their resilience to future disaster events.

It is of benefit to acquaint both decision makers and local community with the restoration time. Based on the sewer restoration time, decision makers could better allocate rebuilding resources (e.g., crew, budget) for action and distribute portable and chemical toilets for providing temporary sanitation service. The logistical arrangement (e.g., number, location) of the distribution of the temporary sanitation facilities, to a certain extent, depends on the estimated reconstruction time. From serviceability viewpoints, local community can be better informed of the time needed to restore their service so that they can better prepare for the lack of sanitary service. Hence, it is imperative to estimate restoration duration of the impaired sewerage systems subjected to earthquakes.

Restoration models (or restoration curves when presented graphically) are used to predict overall restoration time of buildings or infrastructure systems caused by disasters (natural or man-made). For a damaged infrastructure system, the restoration models estimate the outage time that this system needs to recover its normal serviceability for meeting end-users' expectation in the aftermath of a disaster (e.g. earthquakes). Restoration curves, represented as percentage of serviceability vs time, could therefore be used to visualise system performance and resilience over time and determine indirect losses during the system downtime where necessary information is available.

Much research into developing post-disaster restoration models has been conducted for various infrastructure systems. The developed restoration models are used to estimate electrical power outage after hurricanes (Guikema and Quiring, 2012; Kwasinski, 2010; Liu et al., 2007; Nateghi et al., 2011; Quiring et al., 2011) and ice storms (Liu et al., 2007). There are some studies on modelling restoration process of water supply systems after earthquakes (Brink et al., 2012; Tabucchi et al., 2010).

Many approaches have been utilized to model restoration process of infrastructure systems and estimate outage duration, including empirical curve fitting, deterministic resource constraints, Markov processes, optimization, simulation and statistical regression. Cagnan (2005) and Liu (2006) summarise the international literature related to the abovementioned restoration modelling approaches in detail. The contents are not repeated herein. This thesis, however, explicates the advancements that have been made since then.

The empirical curve fitting method uses historical restoration data collected after previous events to fit restoration models and/or curves for representing future restorations. The parameters of the models normally include system characteristics (e.g., asset material), physical damage (e.g., number of breaks), and functional damage (e.g., number of disconnected customers). MacKenzie and Barker (2012) use a large dataset in relation to electrical power outage occurring from January 2002 to June 2009 in the US to fit a dynamic inoperability input-output model. The parameters include the time and date of power outage and the power that was recovered, the companies and states that suffer the outage, the number of disconnected customers, and the type or cause of outage. In this method, however, such variables regarding restoration decisions and implemented strategies that are directly related to actual restoration process, such as repair priority, are not captured.

Xu et al., (2006) present an optimization approach to producing construction project schedules for restoration tasks for electrical power systems post-earthquake. The schedules pertain to damage inspection and assessment, and repair team allocation. The aim of the optimisation operation is to minimise the average time for each customer disconnected from the power grid. The developed restoration curves are compared with the original working schedules. Guikema et al., (2006) optimise different groups of recovery crews participating in the post-earthquake restoration of electrical power systems, applying the project priorities recommended by Xu et al., (2006). This study computes the number of crews to be assigned for each type of recovery tasks for crew allocation.

Cagnan and Davidson (2007) model the post-earthquake restoration of electrical power systems and estimate restoration time and spatial sequence of the recovery operations through a discrete event simulation. The model uses information and data pertaining to real life reconstruction operations, such as personnel allocation and repair material usage in different restoration phases. Quantitative restoration curves with uncertainty bounds are produced, together with a series of maps representing spatially distributed changes in power outage along with the restoration time. The approach is then applied by Tabucchi et al., (2010) to simulate water supply systems and by Brink et al., (2012) to evaluate recovery strategies for reducing service downtime for the Los Angeles water supply system after earthquakes. Luna et al., (2011) improve the discrete event simulation model by using a coloured Petri nets (CPN) approach that describes the actual restoration process. The CPN can model a system's behaviour and analyse all possible states of the systems during the recovery process. The simulation model can be used for forecasting restoration time and resource used (e.g., material, crew), allocating resources, and prioritising construction projects. Gay Alanis (2013) utilises a stochastic simulation model for assessing resilience of water supply systems during disruptive events. Hydraulic analysis is conducted to calculate performance ratio which is indicated as water volume of demand nodes under the condition of failure divided by normal operational water quantity. The stochastic simulation aggregates all performance ratios under different failure scenarios, accounting for the network model, to generate performance levels for the whole system to be compared with pre-defined resilient performance targets.

Survival analysis is a type of statistical approach to analysing epidemiological and other data where outcome variables are time recorded from the start of study until the occurrence of a specified event. The event of interest can be, among others, disease occurrence, death and recovery from the disease and relapse from remission (Kleinbaum, 2005). Accelerated failure time (AFT) and Cox proportional hazard (CPH) models are respectively parametric and semi-parametric models that are commonly deployed in survival analysis for estimating specified event duration by use of time-to-event data.

The CPH model is used especially when assigning an appropriate parametric model is uncertain. The CPH is defined as:

$$h(t, X) = h_0(t)e^{\sum_{i=1}^{p} \beta_i X_i}, X = (X_1, X_2, \ldots, X_p) \tag{2.3}$$

where h(t) is hazard function, expressed for the probability of the occurrence of an event at time t for an individual object with a vector of explanatory or predictor variables symbolised by X. The hazard function is the product of a baseline hazard function, $h_0(t)$, which is a non-parametric function with all covariate values of zero, and an exponential expression e to the linear sum of $\beta_i X_i$ where β is the vector of parameters, assuming X is independent of t. The CPH method can be adapted to capture the probability that a pipe will be repaired after a specified time.

The AFT model is a parametric survival model utilised for modelling survival data as a function of predictor variables. Unlike the CPH model, the AFT model directly relates covariates to survival time through a linear relationship shown as below:

$$\ln(T_i) = X^T \beta + \varepsilon_i \tag{2.4}$$

where T_i denotes survival time (outage duration) and εi is error vector which is assumed to be independently distributed. The survival time is assumed to follow a known distribution which is commonly one of the Weibull, exponential, log-logistic, or lognormal distributions. The AFT model requires distributional assumptions for the survival time in advance of survival analysis. The error term ε is determined correspondingly using an extreme-value, logistic or normal distribution. The AFT model is able to directly model pipe restoration time.

Liu et al. (2007) compare the AFT and CPH models by use of a large dataset collected from three power companies regarding six hurricanes and eight ice storms, finding that the AFT model outperforms the CPH model when modelling electrical power restoration time after ice storms and hurricanes. In the developed model, hazard characteristics, such as maximum gust wind speed and ice thickness, outage features (e.g., total number of outages and outage start time), and exposure data including number of affected customers and population density are considered. The values of log-likelihood and Akaike information criterion (AIC; Akaike, 1970) are calculated for model and variable selection. The number of model coefficients is chosen by a stepwise selection, minimizing the AIC. In the end, the Weibull AFT models are the best fit model to estimate power outage duration ahead of hurricanes and ice storms.

In view of the spatial nature of distributed infrastructure systems and relevant data, Reed (2008) uses a statistical-geographical approach to examining empirical data regarding an urban power distribution system in the Pacific Northwest of the US that experienced three hurricanes between 1995 and 1996, in order to identify the main causes of system failures geographically. The data are used to fit fragility functions and restoration curves, assuming a shape of log-normal and Gamma distributions respectively. The R^2 measure is employed as a goodness-of-fit measure herein. A spatial restoration model is developed by Maliszewski and Perrings (2012) to measure system resilience by modelling the outage duration of a residential power distribution system in the City of Phoenix (US) after an accidental outage. The model aims to estimate the time that a system needs to re-operate after a disruption, taking into account the spatial interaction between the system and the biophysical environment and using adjusted R^2 for non-spatial models and the pseudo R^2 for spatial models for comparing the prediction accuracy. This study concludes that the correlation of the variable of vegetation abundance and infrastructure, specifically overhead lines, is statistically significant to the system outage duration.

Nateghi et al. (2011) compare five statistical approaches, namely: AFT, CPH, Bayesian additive regression trees (BART), multivariate adaptive regression splines (MARS), and classification and regression trees (CART) and showed that the BART provides the highest predictive accuracy when predicting the electricity outage duration of the electricity utility triggered by disruptive hurricanes. To advance the previous work, Nateghi et al. (2014) apply a random forest (RF) method to predict the electricity outage duration and improve the accuracy of statistical models over those available in the international literature. Both studies use the root mean square error (RMSE) and the mean absolute error (MAE) to measure the prediction power of the proposed methods/models.

The RF method, developed by Breiman (2001), is an ensemble machine learning method for understanding and making predictions on the data. As the RF is an ensemble tree method, therefore, there is no predictive equation proposed using this method. The RF is robust to noise and outliers, mathematically accurate, and computationally efficient, which is ideal for complex data (Hastie, 2011; Nateghi et al., 2014). This is because a combination of regression trees is generated instead of a single tree so that the forest is relatively stable in spite of any noise in the datasets.

Ishwaran et al., (2008) extended the RF method to survival analysis and created a Random Survival Forest (RSF). The RSF randomly selects a number of variables at each node and splits the node based on a survival criterion involving survival time and censoring status information to grow individual trees and then build ensemble forests for regression. Furthermore, it conducts survival analysis without making the proportional hazard assumptions. The applicability of the RSF to predict system downtime has not yet been examined.

Although many advancements have been made on statistical modelling of restoration time or service downtime for infrastructure after disasters, some gaps are still evidenced. In particular, there is little research available on restoration models or curves for estimating the restoration time of sewerage systems following natural disasters, specifically earthquakes. Additionally, the literature has not identified the key factors that play important roles in influencing the duration of sewerage recovery post-earthquake, while accounting for the peculiarities of sewerage pipelines. For example, the type of sewer pipelines may have an effect on the restoration time due to the different repair procedures and techniques of sewerage gravity and pressure pipes. Lastly, there are no restoration curves (empirical or analytical) for sewerage systems that can be deployed as a reference for comparing the recovery performance and efficiency undertaken by other recovery practices, for instance, post-flooding restoration of sewerage systems.

2.7 Decision support frameworks and systems

2.7.1 Decision support frameworks for post-disaster recovery

The process of restoring impaired sewerage systems post-earthquake to regain normal capability and serviceability presents both opportunities and challenges. The opportunities are for decision makers to upgrade the system facilities and enhance system resilience while rebuilding/repairing the system components. The challenges are to make rational decisions under pressure and thus take efficient and effective actions to implement them for accomplishing predefined recovery targets. Decision support frameworks and systems intend to inform and assist decision makers by providing a framework/platform for collating, organising, processing the data and information available and by composing a range of possible alternative solutions on which asset management strategies and plans can be developed (Liu et al., 2013).

A number of well-developed frameworks for disaster risk reduction and post-event service recovery do exist, including, among others: Hyogo Framework for Action 2005-2015, HFA (UNISDR, 2005), Sendai Framework for Disaster Risk Reduction 2015-2030, Sendai Framework (UNISDR, 2015), National Disaster Recovery Framework, NDRF (FEMA, 2011) and Civil Defence & Emergency Management (CDEM) framework (MCDEM, 2005). An exemplary example is the HFA (UNISDR, 2005) proposed and agreed by 168 countries during the 2005 World Disaster Reduction Conference in Japan. It is recognized as the first plan with detailed explanation and description regarding required tasks of distinct sectors and actors, aiming to reduce disaster losses and, where possible, to accomplish disaster resilience. It formulates directive principles and actable approaches for institutional (i.e., organisation, legislation, and finance issues) preparedness and community engagement to achieving efficient post-event recovery (UNISDR, 2005). The Sendai Framework serves as the successor instrument to the HFA (UNISDR, 2005), aiming for largely mitigating disaster risk and the consequences that may occur on "the lives, livelihoods, and health and on the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries" (UNISDR, 2015). NDRF was developed by the Federal Emergency Management Agency (FEMA) in the U.S. to guide and promote effective and efficient post-event recovery, especially for large-scale events. The NDRF establishes recovery principles, defines roles and responsibilities of parties involved, and guides recovery planning as well as communication structuring (FEMA, 2011). In New Zealand, the CDEM framework has been developed by the Ministry of CDEM for guiding recovery planning and management undertaken by local governments, government departments and Civil Defence Emergency Management Groups. The framework defines goals of CDEM in a national scale and plans recovery activities in relation to social, building, natural and economic environment, with special focus on community (MCDEM, 2005).

The abovementioned frameworks highlight the importance for fundamental elements (e.g., organisation, finance, and community factors) identified for post-disaster recovery. However, a paucity is recognized in terms of the identification of technical factors that look into practical operations in the field for structural reconstruction and in particular, for infrastructure systems, including sewerage systems.

2.7.2 Post-earthquake decision support systems for infrastructure systems

Decision support systems that predict possible infrastructure damage and social-economic losses due to earthquakes can effectively support and inform emergency response and recovery planning. Moreover, the same systems can be effectively used for mitigation planning purposes. The understanding of the local seismic risk and potential effects of an earthquake of various intensities and probabilities of occurrence on infrastructure, economy, and societal activities, is a fundamental pre-requisite for the development of adequate plans for the protection of communities. The developed plans can reduce inherent vulnerability of the infrastructure, economy, society, and community and increase their resilience. Significant progress has been made in developing software platforms that integrate the components of seismic risk and interactive environment to provide decision-makers with tools to assess the impact. Table 2.4 presents the most well-known and internationally used ones including, among others: HAZUS (NIBS, 2003), MAEviz (MAE Centre, 2007), RiskScape (Reese et al., 2007), Syner-G (Pitilakis et la., 2014a, b).

The Hazards U.S. Multi-Hazard (HAZUS-MH; NIBS, 2003) methodology aims to assess potential losses of residential and commercial buildings, schools, critical facilities, and infrastructure given a type of natural hazards, including floods, hurricanes, and earthquake. The HAZUS-MH earthquake model can compute earthquake-induced physical damage to infrastructure, for instance, wastewater systems by using damage functions for system components (i.e., collection sewers, interceptors, LSs, and treatment plants) as a function of, respectively, PGA and PGD. The economic loss analysis inbuilt in the model is performed to calculate damage ratios of the aforementioned components, indicated as the fraction of the cost to completely replace the component. Additionally, the HAZUS-MH earthquake model has the function of social impact analysis that is used to measure casualties and shelter requirements that normally emerge from building collapse. In particular, the needs of shelter is contingent on displaced households and the number of community disconnected to water and power services.

The Mid-America Earthquake Centre Seismic Loss Assessment System (MAEViz; MAE Centre, 2007) uses a consequence-based risk management methodology where spatial data and information are integrated and analysed in order to determine structural damage, social vulnerability, economic losses and population dislocation. In the MAEViz, there is no stand-alone module specifically designed for sewerage systems; instead, buried pipeline damage analysis could be applied to sewer pipelines. The data inputs as a format of shapefile include pipe material, joint type, diameter, length, and soil type. The system calculates RR of pipelines based on the abovementioned pipe attributes and generates pertinent tables, graphs, and reports according to the results for visualisation and analysis purposes.

Table 2.4 Platforms for seismic risk assessment in literature

Platform	Hazard	Simulation type	Application
HAZUS (NIBS, 2003)	Flood, hurricane, earthquake	Deterministic, probabilistic	Building, school, critical facility, infrastructure
MAEViz (MAE Centre, 2007)	Earthquake	Deterministic	Building, bridge, hazard, lifeline, socioeconomic
Syner-G (Pitilakis et al., 2014a, b)	Earthquake	Probabilistic	Building, transportation, utility network and critical facility
Riskscape (Reese et al., 2007)	Earthquake, flooding, storm-tide inundation, tsunami, volcanic ash fall, wind storm	Deterministic, probabilistic	Agriculture, building, electricity cable, network junction point, open space, pipeline, road, telecommunication cable, waterway

SYNER-G (Pitilakis et al., 2014a, b) is a European collaborative research project focusing on systemic seismic vulnerability and risk analysis of buildings, transportation and utility networks and critical facilities. The SYNER-G develops an innovative methodological framework for assessment of physical as well as socio-economic seismic vulnerability at both the urban and regional levels. The framework encompasses in an integrated fashion all aspects in the chain that go from the regional hazard to fragility assessment of components to the social impacts of an earthquake. This framework can furthermore model interactions between multiple systems of interest, accounting for all relevant uncertainties within an efficient quantitative simulation scheme.

RiskScape (Reese et al., 2007) is an area-specific risk analysis platform that is specifically developed and operated for the agriculture, buildings, electricity cables, network junction points, open space, pipelines, roads, telecommunication cables, and waterways in New Zealand, incorporating local historical knowledge and information related to previous events. The software platform intends to estimate the economic losses due to physical damage to structures of interest based on vulnerability functions/curves. In addition to this, the platform is able to quantify social impacts on community caused by natural hazards, for example, casualties, affected population, and transportation interruption.

Despite this, the CES in 2010-2011 in New Zealand highlighted that none of the existing platforms/tools are either accessible and/or readable or usable by emergency managers and post-disaster recovery decision makers. Furthermore, the majority of existing tools have a sole focus on the engineering perspective, while the holistic process of formatting recovery decisions is based on a system-wide approach, where a variety of factors are involved. Lastly, there is a paucity of studies focused on the tools and frameworks for supporting decision-making specifically on sewerage system restoration after earthquakes.

2.8 Chapter summary

This chapter reviewed the state-of-the-art literature in relation to the key concepts and methodological contexts of this research topic. Research gaps were identified as follow:

- Effective yet fast tools for seismic fragility analysis to estimate physical damage to sewer pipelines are needed, using relatively common variables while accounting for different seismic hazards;
- A set of PIs to evaluate seismic impacts on hydraulic, structural, environmental, social, and economic contexts that have arisen from the impaired sewerage system components;
- Restoration models and curves for predicting the restoration time of sewerage networks after earthquakes are needed whereby the unique characteristics of sewer pipes and relevant decision variables in terms of reconstruction process are taken into account; and
- A framework for supporting decision making process of sewerage system restoration after earthquakes.

CHAPTER 3

POST-EARTHQAUKE DECISION MAKING ON SEWER RECOVERY IN CHRISTCHURCH

3.1 Introduction

This chapter provides an overview of the seismic performance of the CSS during the CES in 2010-2011 and explicates the decision making process used in the restoration of the sewerage system after the CES.

The chapter starts with the background information in relation to the CSS (Section 3.2) and the CES (Section 3.3). The seismic performance of the CSS following the CES is presented in Section 3.4, with particular emphasis on the technical details regarding physical damage and functional impacts observed. Section 3.5 introduces the organizations involved in the Canterbury recovery after the CES and Section 3.6 discusses rebuilding strategies undertaken for sewer recovery. In Section 3.7, the post-earthquake decision-making on sewer recovery following the CES is explicitly demonstrated.

This chapter is based on the following papers:

Liu, M., Giovinazzi, S., MacGeorge, R. and Beukman P. (2013). Wastewater network restoration following the Canterbury (NZ) Earthquake sequence: Turning post-earthquake recovery into resilience enhancement. Technical Council on Lifeline Earthquake Engineering Publications and Monographs No.38:

International efforts in lifeline earthquake engineering. (ASCE). pp. 160-167. (ISBN 978-0-7844-1323-4).

Liu, M., Milke, M., Heiler, D. and Giovinazzi, S. Post-earthquake decision-making on sewer recovery and the roles of damage and repair data. Journal of Infrastructure Systems (in review).

3.2 The Christchurch sewerage system

Christchurch, the largest city in the South Island of New Zealand, has a population of nearly 376,700 living in roughly 1426 km^2 (Statistic New Zealand, 2010). Christchurch resides on the Canterbury Plains, a fan deposit formed by numerous rivers flowing eastward from the foothills of the Southern Alps. Soils beneath Christchurch are comprised of a complex sequence of gravels inter-bedded with silt, clay, peat, and shelly sands (Forsyth et al., 2008). Most Christchurch soils are classified as soft and/or fine grained soil (Elder et al., 1991). The main surface layers in the west and east of Christchurch are the Springston formation (containing alluvial gravels, sands and silts) and the Christchurch formation (estuarine, lagoon, beach, dune, and coastal swamp deposits of sand, silt, clay and peat) (Forsyth et al., 2008).

The CSS covers 99.9% of Christchurch city, leaving the remainder served by septic tanks and other sanitary systems in remote dwellings. Since construction started in the 1870s, the system has been a gravity system, independent (generally) from the stormwater system. Lying on the Canterbury plains, the CSS is flat. Therefore, PSs have been critical to the operation of the gravity-fed systems. Some pressure pipes had been installed in Christchurch, often to connect directly to PSs. There were more than 42,100 pipes, 25,900 manholes, 120 PSs, 239 pumps and one treatment plant functioning in the CSS before the CES in 2010-2011 (CCC, 2011).

Table 3.1 presents the taxonomy of components for the Christchurch sewerage system in line with the CCC asset classification for the Christchurch sewerage system (CCC, 2004). It is noted that the treatment plant is included herein for the completeness of information provided although treatment plants are beyond the scope of the thesis.

Table 3.1 Taxonomy for the Christchurch sewerage system (CCC, 2004)

Component	Description
Pipelines	Convey sewage between system components.
PS/LS	Pump sewage to specific elevations to facilitate wastewater conveyance. Pumps are equipped to transfer sewage.
Manhole	Access to buried sewers for maintaining/repair purposes.
Treatment plant	Where buildings, tanks, and basins are installed to treat wastewater for further usage and/or disposal.

3.2.1 The sewer reticulation

The Christchurch sewer reticulation connects approximately 165,000 households throughout Christchurch city with a daily average flow of 185 million litres per day (CCC, 2015). The length of public sewer reticulation was 1857 km, comprised of 1682 km of gravity pipelines, 154 km of pressure pipelines (Figure 3.1). There are also other appurtenances functioning in the sewer network in Christchurch, such as valves and joints. The sewer pipelines with diameters of 300 mm or greater are classified as trunk sewer mains while others are defined as minor reticulation pipes (CAE, 1997). Figure 3.2 illustrates the length of gravity and pressure pipes in these two categories, showing that smaller diameter (<300 mm) gravity pipes play principal roles in the CSS.

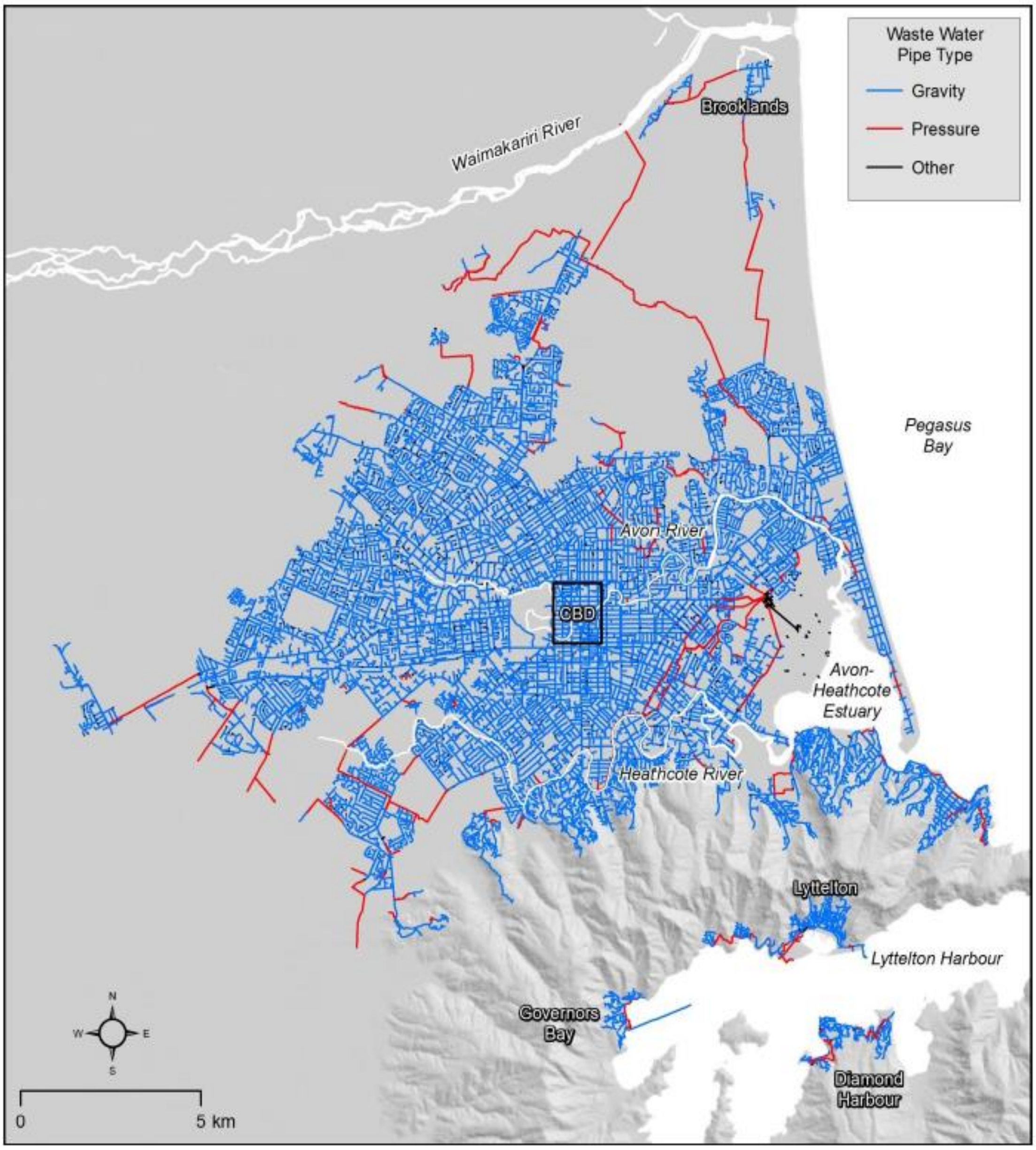


Figure 3.1 The Christchurch wastewater network according to pipe type (i.e., gravity, pressure) (Bradley et al., 2014)

The Christchurch sewerage system has a variety of pipe materials. The network was first introduced to Christchurch city in 1880 and pipes were made of Earthenware (EW) and brick barrel. The EW pipes were often jointed with mortar and more recently, elastomeric rings for more flexibility. Cast Iron (CI) is one of the oldest pipe materials; it has been used in Christchurch since 1906. Asbestos Cement (AC) pipelines started to be used for construction from 1970. AC and CI pipelines are often jointed by lead. Reinforced

Concrete Rubber Ringed (RCRR) jointed pipes were commonly installed since 1930's and in particular for large pipelines installed after the earthquakes. Since 1980's, ductile materials such as Polyvinyl Chloride (PVC) and Polyethylene (PE) became commonly installed and variations have been developed to provide better structural performance. For instance, UPVC is an unplasticised version of PVC and is subsequently more rigid. MPVC is further modified for improved toughness. It is stiffer than standard PVC, however it is not as stiff as UPVC (Vinidex, 2011). The standard PE pipe with the lowest density is the most flexible. Medium Density PE (MDPE) and High Density PE (HDPE) pipes are modified with higher density for stiffness.

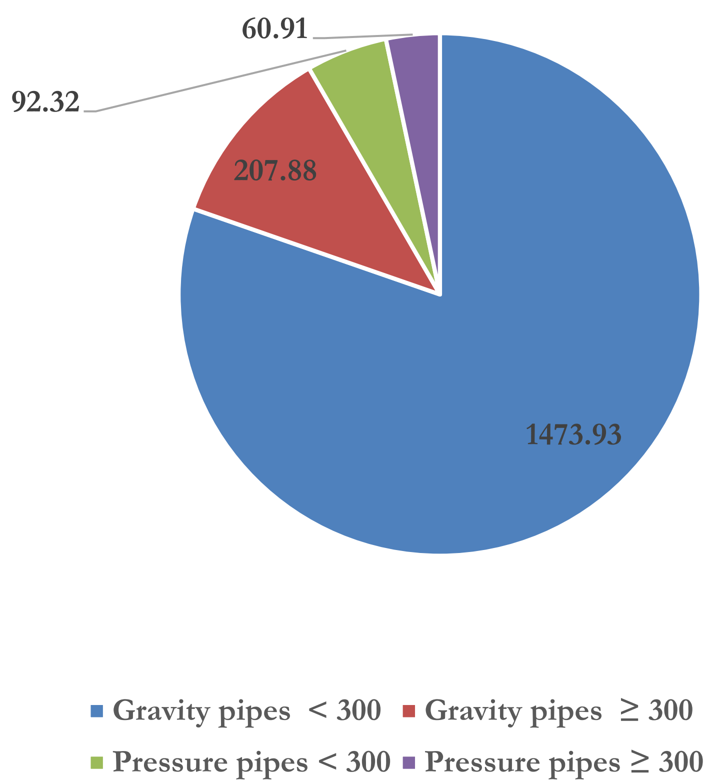


Figure 3.2 Length proportions (km) of gravity and pressure pipes in diameter (mm) categories

Table 3.2 presents the breakdown of the pipe material distribution of the Christchurch sewer network. RCRR is the most common pipe type in the Christchurch sewerage network. PVC pipes with welded joints accounted for a large proportion, followed by EW pipes. AC and CONC pipelines are still present in the network, yet before the earthquakes they were being gradually replaced by more seismically resistant materials (e.g., PE).

3.2.2 PSs/LSs

PSs or LSs are engineered structures aiming to lift fluids to higher elevations by use of pumps operated via electricity. A PS comprises PS buildings, pumping facilities, interior pipes, supervisory control and data acquisition equipment and electronic equipment. In Christchurch, the total capacity of terminal PSs to the Bromley treatment plant (central treatment plant) is 6,610 l/s (CCC, 2015).

The wastewater PSs in Christchurch are grouped into: 1) dry well PS; and 2) wet well PS. Dry-well PSs place pumps in an enclosed pump room or underground structure while the wet well ones install submersible pumps inside the reservoirs. Dry well PSs were more common until the middle of the 20th century. The PSs built before 1966 only have dry wells (Zare, 2010). The advantage of dry wells is easy accessibility for visual inspection and routine maintenance. However, wet well PSs, due to the low cost, small landscape and simplified maintenance, had been widely utilised more recently (EPA, 2000).

There were 120 PSs pumping sewage to higher elevations for further transference in Christchurch before the earthquakes. Figure 3.3 presents the number of PSs based on installation years. The number of PSs built every twenty years increased steadily until 2000. Nearly 25 % of the PSs (around 40) were built between 1981 and 2000. Only 15 were newly constructed from 2001 to 2009.

Table 3.2 Breakdown of pipe distribution of the Christchurch sewerage network

Abbreviation	Material	Minor reticulation		Trunk main		Types (length, km)
		Diameter range (mm)	Length (km) (proportion)	Diameter range (mm)	Length (km) (proportion)	
AC	Asbestos Cement	50-250	146.2 (88.47%)	300-600	19.06 (11.53%)	–
CI	Cast Iron	80-250	13.91 (75.6%)	300-675	4.49 (24.4%)	–
CONC	Unreinforced Concrete	100-250	95.1 (77.86%)	300-1800	27.04 (22.14%)	–
EW	Earthenware	100-255	369.66 (96.23%)	300-825	14.49 (3.77%)	–
PE	Polyethylene	25-280	37.2 (89.14%)	300-1800	4.53 (10.86%)	High density PE (HDPE) (19.65), Medium density PE (MDPE) (6.72), Low density PE (LDPE) (2.09), PE (13.27)
PVC	Polyvinyl chloride	50-250	400.73 (91.78%)	300-675	35.91 (8.22%)	PVC (53.57), Unplasticised (UPVC) (362.93), Modified (MPVC) (20.14)
RCRR	Reinforced Concrete Rubber Ringed	100-250	493.29 (75.96%)	300-1600	156.12 (24.04%)	–

Others	—	50-250	10.19 (58.8%)	300-1800	7.14 (41.2%)	ABS (Acrylonitrile butadiene styrene), CLS (Concrete Lined Steel), DI (Ductile iron), Steel, VC (Vitrified clay), etc.
Sum	—	25-280	1566.26 (85.35%)	300-1800	268.78 (14.65%)	—

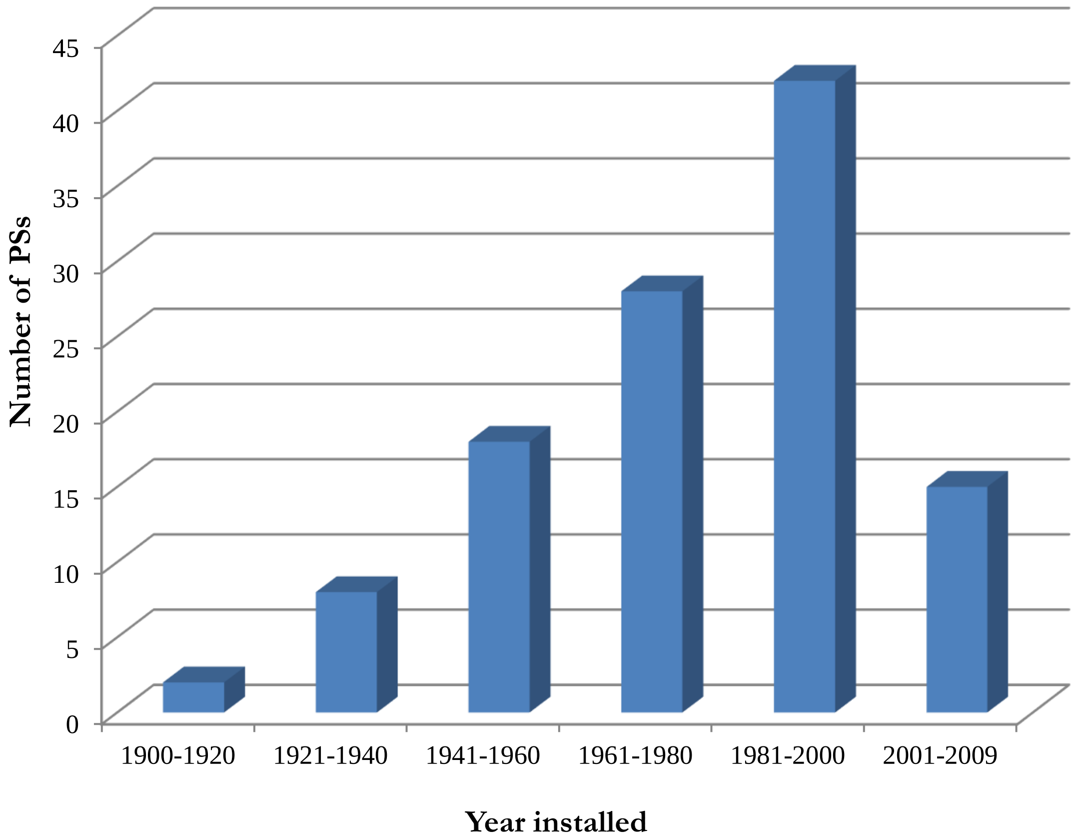


Figure 3.3 Number of PSs by year installed

LSs are also used to transfer sewage from lower elevations to higher elevations via pressure provided by embedded pumps. In Christchurch, LSs are smaller than PSs, functioning with lower capability. There were no LSs in the CSS before the CES. So far, 56 LSs have been built close to residential and/or commercial buildings to lift sewage from the upstream side for better conveyance (SCIRT, 2014).

3.2.3 Manholes

Before 1925, wastewater manholes installed in Christchurch were built by use of bricks and mortar on site after surveying and excavation. The introduction of cast in-situ square manholes happened in the 1920's. This type of manhole is made of concrete and widely used for pipes with diameters in excess of 400 mm and is particularly adopted where irregular geometry requires (Menefy and Scally, 2013). Since the 1970's, circular pre-cast concrete manholes were increasingly installed for relatively small pipes (dia. < 400 mm) in Christchurch. The cast in-situ square and circular pre-cast manholes had become the two predominant manhole types in Christchurch (Cubrinovski et al., 2014).

There are vented and unvented manholes in the CSS. For odour release purpose, vented manholes are extensively installed in the system, in particular, near waterways and public green zones.

3.3 The CES in 2010-2011

The CES in 2010-2011 includes four major events, namely September 4, 2010 earthquake (Mw=7.1), February 22, 2011 (Mw=6.2), June 13, 2011 (Mw=6.0), and December 23, 2011 (Mw=5.9), and thousands of associated aftershocks (Figure 3.4). The first main event (4th September 2010) and aftershock sequence struck near the town of Darfield in the South Island of New Zealand, 30 km west of Christchurch. The Darfield earthquake was the first large earthquake striking close to an urban centre in New Zealand since the Hawke's Bay earthquake in 1931 (Giovinazzi et al., 2011). There were no fatalities and only two serious injuries (Wood et al., 2010). PGAs were in the range of 0.3 g to 0.8 g and PGVs exceeded 1 m/s. On 22nd February 2011, another quake hit Christchurch City with a shallow epicentre at about 5-6 km under the ground, causing high ground accelerations across the city. The earthquake caused 185 causalities, 8,600 injuries and widespread physical damage to buildings and lifelines. This event occurred while the Canterbury region was still recovering from the Darfield earthquake on 4th September, with many structures suffering from compounded damage. The February earthquake produced large ground accelerations and the highest PGA recorded was 1.41g (Bradley and Cubrinovski, 2011). Another two notable earthquakes

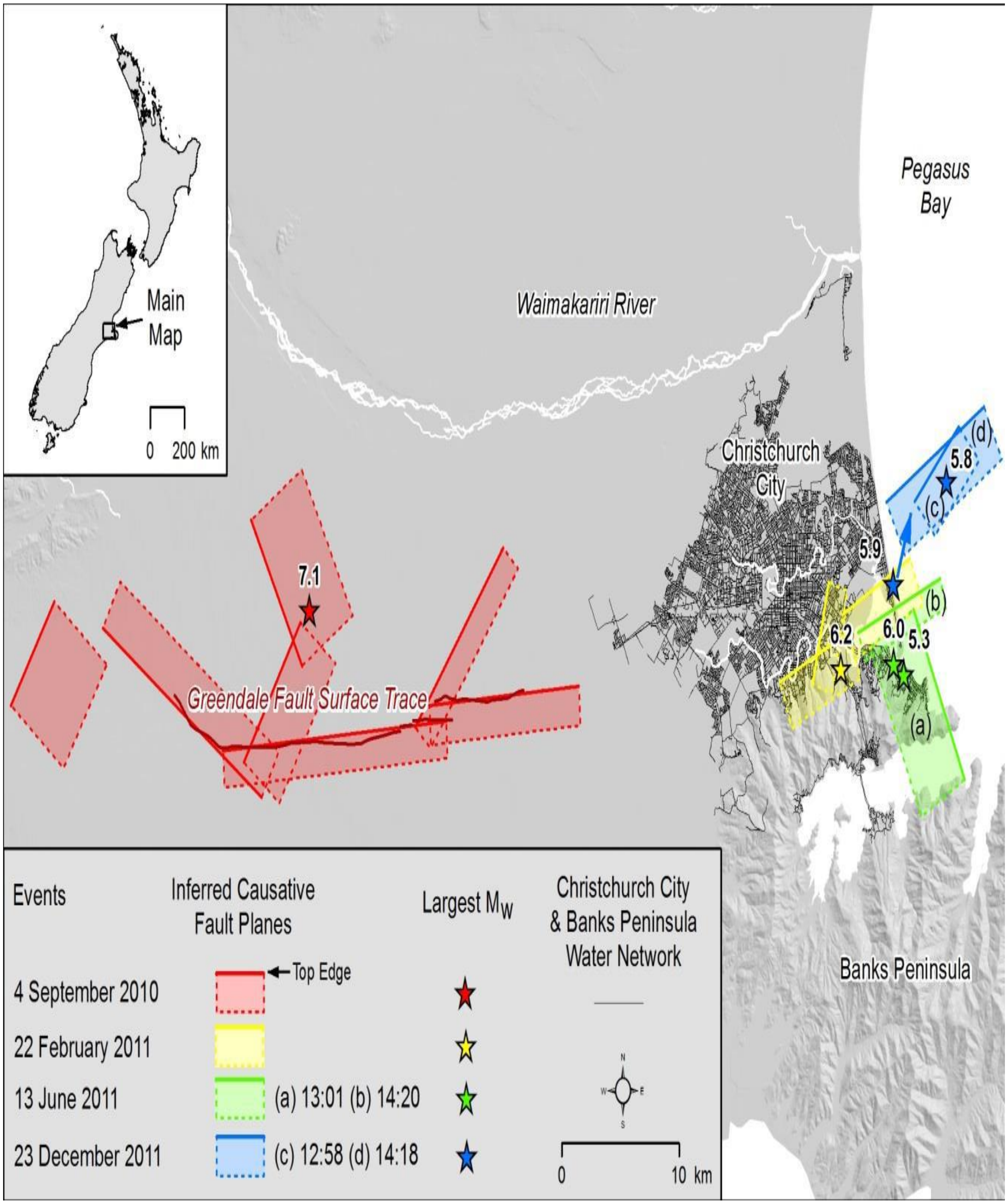


Figure 3.4 Locations of the CES causative fault planes (Bradley et al., 2014). Largest Moment Magnitudes (Mw) for the four major events and Greendale Fault surface trace (4 September 2010) are also shown. The fault plane for the 23 December 2011 Mw 5.9 event is indicated

with a blue arrow. Also shown is the wastewater network for Christchurch City and Banks Peninsula.

(on 13 June and 23 December) did not cause death or injures, yet they exacerbated the physical damage sustained and additionally hindered the post-earthquake recovery that had occurred since the September quake. The CES, in particular the February earthquake, caused unprecedented levels of liquefaction throughout the southern and eastern suburbs of Christchurch alongside the Avon River (Yamada et al. 2011). The liquefaction resulted in settlement, lateral spreading, sand boils, and a large quantity of ejected silt mud and water ponding on the ground surface.

3.4 Seismic performance of the CSS following the CES

3.4.1 Physical damage to the Christchurch sewerage components

As a result of the CES, the CSS experienced extensive damage. Figure 3.5 shows examples of the physical damage to sewer pipes. 659 km of sewer pipelines, accounting for 41 % of the total reticulation network throughout Christchurch, suffered physical damage to some extent (SCIRT, 2014). A large amount of fracturing and collapse of brittle pipelines, especially in EW and RCRR pipelines, was observed. Compression failures caused by strong ground shaking and/or land movement occurred mostly at pipe joints. PVC and PE pipes performed reasonably well.

The damage ratio (DR), expressed as the number of faults per km, and the repair rate (RR), which is defined as the number of repairs per km, are deployed to evaluate the physical damage to buried pipelines (Toprak and Taskin, 2007). Represented as the numerical incidents per pipe length, the DR and the RR facilitate an understanding of the average damage levels of underground pipelines. Figure 3.6 presents the DR of the sewer pipelines classified by the pipe diameter and material.

a)

b)

Figure 3.5 Earthquake-induced damage to the sewerage system in Christchurch: a) damaged sewer pipes; b) physical damage to AC sewer pipes.

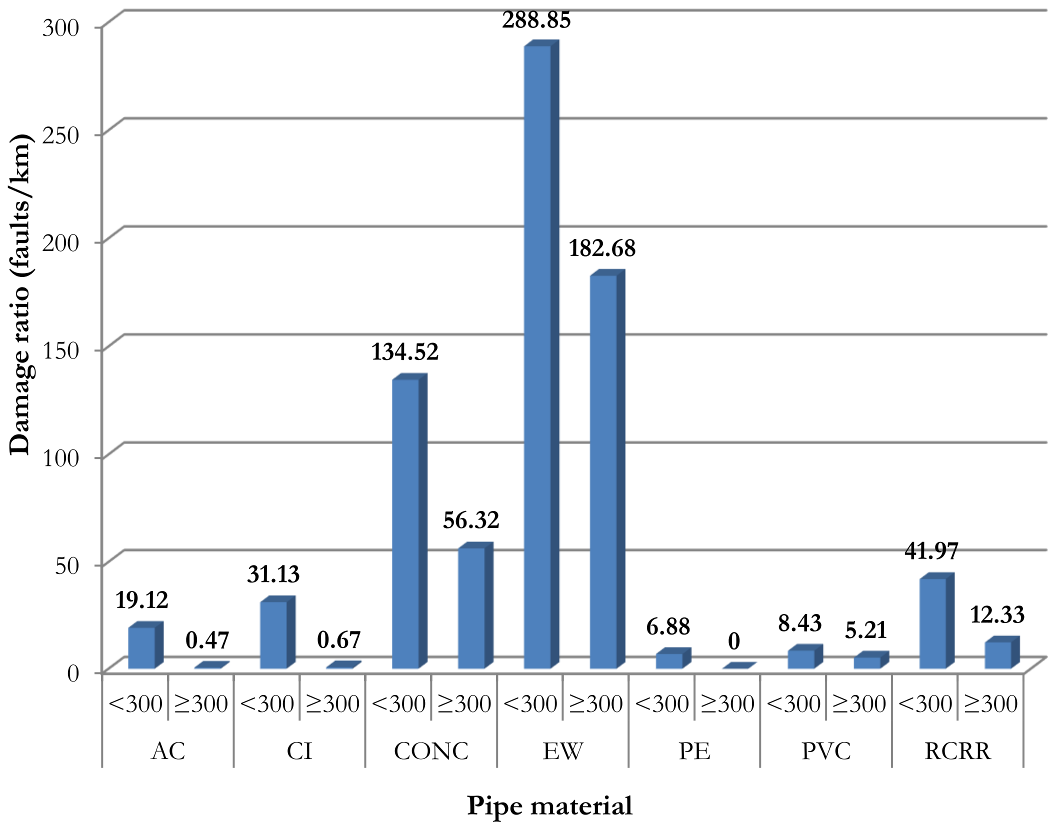


Figure 3.6 DR (number of faults/km) on sewer pipelines classified by pipe material and pipe diameter

Not only did the extensive liquefaction generated by the earthquakes damage the Christchurch sewer reticulation, but also it caused uplift and settlement of many PSs, in particular, in the badly damaged area. There were 136 PSs subjected to earthquake-induced damage during the CES, of which 22 were newly built after the September quake as part of the post-earthquake recovery program. Figure 3.7 demonstrates the earthquake-induced damage to PSs.

The faults of PSs vary from case to case and several PSs suffered from multiple faults. The most common damage was station uplift/subsidence owing to ground motions and liquefaction. Some LSs that had been installed near the Avon River after the September earthquake floated upwards and tilted towards the river during the subsequent seismic events, due to liquefaction and associated lateral spreading.

In many cases, land, pavement or concrete kerbs were uplifted while the buildings stood still, resulting in broken sewer connections outside the stations. It is worth mentioning that no flexible joints installed beforehand contributed to the rupture of pipes connected to PSs. As a result of these broken connections to pipes, some PSs totally lost functionality even though the PSs remained operable. Other common failures of PSs in Christchurch included outage of electrical power, cracking and leaking of pumps and equipment (e.g., valves) in the pump house and control kiosk. However, these types of facility defaults are out of the scope of the thesis.

The physical damage to manholes in the Christchurch sewerage system is not introduced herein due to the inability to obtain relevant information.

a)

b)

Figure 3.7 Earthquake-induced damages to PSs in Christchurch: a) PS differential movement; b) uplifted PS (Tang, 2016)

3.4.2 Functional impact of the CSS

The extensive physical damage from the CES caused a serious loss to the functionality of the CSS, affecting the wellbeing of the local community. Two weeks after the February earthquake, a leak rate of approximately 60 million litres per day was estimated by damage assessment teams working in the field. A reduced leakage volume of 40 million litres flowed out of the cracked/broken sewer pipes every day in early April of 2011. Silt and sand infiltrated the broken pipes, flowing soil to the treatment plant. It posed an underlying threat to the entire system by blocking pipes to the treatment plant and resulted in a longer restoration time. Until April of 2011, 1,000 tons of silts and sands were removed from the primary setting tanks in the Bromley treatment plant (Brears, 2012). Raw sewage continued to be disposed of in the rivers and estuaries as the heavily damaged Bromley wastewater treatment plant was unable to cope with the increasing inflows (Tang, 2016).

The sewer lines were so badly damaged that residents were not able to use showers or toilets from a couple of days to several months after the earthquakes depending on their locations. One month after the February quake, it was reported that 8 %, 31 % and 61 % of the entire sewerage network possessed no service, limited service and full service, respectively. It is reported that a total of 75,000 properties were identified with malfunctioned sewer facilities.

Effective emergency strategies and long-term reinstatement planning were implemented progressively in the aftermath of the seismic shocks. One remarkable emergency response was the provision of portable toilets. One day after the February Christchurch earthquake, 780 port-a-loos were distributed and installed around the affected areas of

Christchurch City and other 1213 were in transit to Christchurch from both nationally and overseas sources (Zare et al., 2011).

In addition, the council requested 30,000 chemical toilets for the purpose of addressing the sanitary issue. The Council, working alongside other agencies, coordinated the distribution of 42,000 chemical toilets to city homes and 2,900 portable toilets on city streets to provide temporary sewerage services (SCIRT, 2012). By 31 August, 2011, work to reinstate operable wastewater service was completed on all public sewer pipes, but around 800 houses were still out of sewer service due to damage to their private sewer pipes.

3.5 Organisations involved in the Canterbury recovery after the CES

Figure 3.8 shows the inter-relationship of organizations involved in the decision-making process for infrastructure recovery from the Canterbury Earthquakes. Three local councils comprising Greater Christchurch, namely CCC, Waimakariri District Council (WDC) and Selwyn District Council (SDC) own most of the three waters (potable water, sewerage, and storm water drainage) horizontal infrastructure damaged in the earthquakes (Figure 3.8). The WDC and SDC are currently carrying out the infrastructure rebuilding process separately, entering into contracts with construction companies in their districts. The CCC, where most of the damage was suffered, established an Infrastructure Rebuild Management Office to manage the large first response and temporary repair task of its infrastructure assets. However, after the February 2011 event it became clear that the infrastructure rebuild task would require significantly extra coordination and management to ensure this work could be delivered in a timely and cost effective manner.

The Canterbury Earthquake Recovery Authority (CERA) was established by law with the purpose of leading response and recovery so that Greater Christchurch, local authorities and their communities could respond and recover from the 2010 and 2011 earthquakes.

In April 2011, central government– through CERA– and CCC worked together to understand how to respond to the size of the infrastructure rebuild job, expected, in the short term, to be around tenfold the normal yearly maintenance programme of the local authority. This resulted in the establishment of a new delivery vehicle: the Stronger Christchurch Infrastructure Rebuild Team (SCIRT), with an agreed Scope of Works including much of the three waters and roads repair, bridges and retaining walls. SCIRT is effectively a delivery team managing the rebuilding activities for around 85% of the infrastructure, with three funding agencies (CCC, CERA and NZTA) – the clients– and five of New Zealand's largest contracting companies.

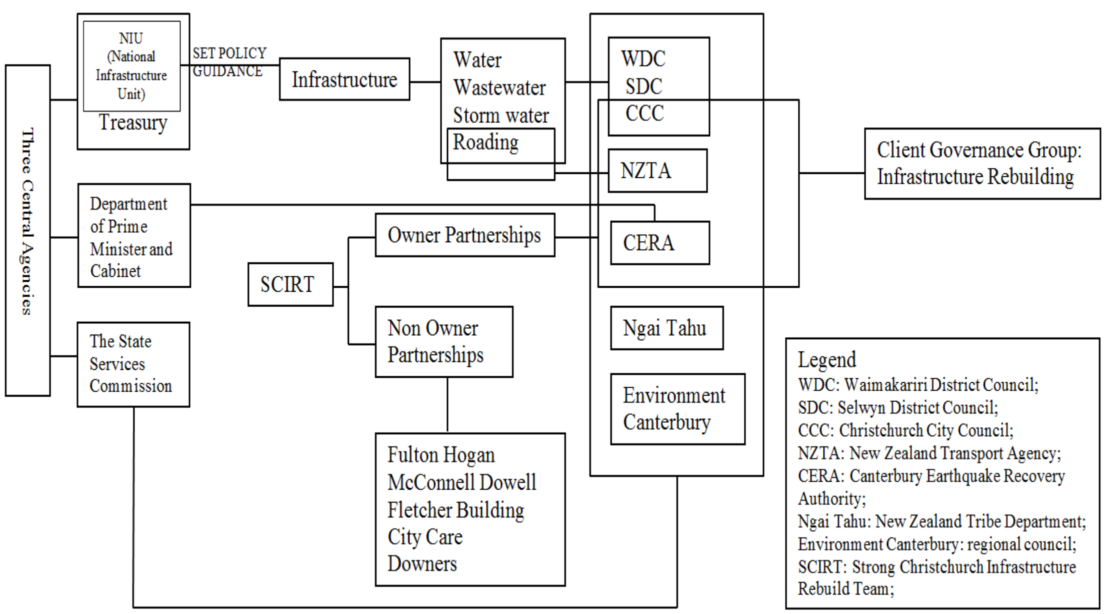


Figure 3.8 Organisational chart of the agencies and companies involved in the Canterbury Earthquake recovery

3.6 SCIRT's Strategies in the rebuilding programme

CCC, CERA, NZTA and SCIRT and other organizations involved in the infrastructure recovery are seeking metrics, performance indicators and tools to measure and compare the potential infrastructure resilience of alternative reconstruction strategies.

For the permanent repairs and reconstruction, alternative techniques and strategies are considered by SCIRT including: i) like-for-like repairs; ii) modified-gravity system with steeper gradient; iii) new materials, and/or modern construction methods; and iv) advanced sewer systems, including pressurized systems and vacuum systems.

For the "like-for-like" repairs (namely patch repairs), the damaged sewer components are repaired using the same existing pipe materials and joint types. This obviously implies that no further resilience is added in the repaired components which remain vulnerable to future seismic-induced damage and disruptions. On the other hand, like-for-like repairs are covered by infrastructure insurance policies; any deviation from this arrangement implies additional cost for the community.

Modified-gravity systems with steeper gradient are introduced while repairing damaged gravity systems, aiming to guarantee the functionality of the gravity system, even if the pipelines are raised and/or buckled by earthquake-induced ground deformations.

The use of more robust materials and newly developed construction methods are considered by SCIRT when possible. In the case of pipes, longer lasting and more robust polyethylene or PVC pipes are used to replace older materials (Figure 3.9a). Directional drilling machines are used for faster pipe installation without digging a trench (Figure 3.9b).

a) b)

Figure 3.9 Examples of alternative techniques adopted by SCIRT: a) installation of PVC rising main; b) directional drilling machines

The use of highly advanced technological sewerage systems, such as pressurized systems and vacuum systems, is a further alternative considered by SCIRT. These innovative systems might provide a more robust wastewater management and make restoration easier in the event of earthquakes. However, they depend on electricity and the system performance can be compromised in the event of electrical power outage. Moreover, their effective resilience to earthquakes has not yet been largely proved, considering that they are still seldom used worldwide. Pressure sewer pump systems have been installed in selected pioneer communities in Christchurch.

SCIRT has been valuing network resilience offered by the four different aforementioned reconstruction alternatives in monetary terms (Heiler, 2012), by jointly considering the Capital Expenditure, the Operating Expenditure costs, along with the Net Present Value for all the possible options.

3.7 Decision making process of SCIRT's sewerage pipelines rebuilding programme

The needs of decision making support in sewer repair vs. renewal during business-as-usual are identified by Selvakumar and Tafuri (2012). In the aftermath of destructive earthquakes, it is valuable to understand the physical damage to sewerage system pipelines as part of the decision-making on repair and rebuild. Figure 3.10 provides an overview of the decision-making process used by SCIRT. Pipes were selected for investigation because of customer complaints, obvious incidents, anticipated high damage (e.g. in a zone severely damaged above ground by earthquakes), their value to the network (e.g. connection to hospitals), their vulnerability based on database attributes (e.g. pipe age, material), or because of their geographical proximity to other infrastructure systems (e.g. adjacent water supply pipes were being replaced).

Three damage assessment methods were applied to the Christchurch sewerage reticulation system: 1) Manhole level survey; 2) Pipe profilometer assessment; 3) Closed Circuit Television (CCTV) inspection. The manhole level survey was a topographical survey conducted to identify directional movement of invert (i.e., the bottom of the inside of the existing pipe) and lid levels for wastewater network manholes throughout Christchurch City. A profilometer is a device that moves along a pipe section measuring vertical elevation by signal processing. For its use in Christchurch, the profilometer integrated the elevation measurements to find an average elevation at 1 m intervals (0.25 m intervals near manholes). CCTV inspection is a commonly used method for detecting damage to a gravity pipeline network. This involves running moveable equipment, mounted on a camera, through pipelines. The data are then analyzed and damage is classified.

Manhole level survey and pipe profilometer assessment were used early in pipe assessment process to identify the non-structural defects in Christchurch. The non-structural defects are of two types: 1) loss of gradient, caused by the vertical movements of the connected manholes leading to reduced flow velocity; 2) dips (almost exclusively in flexible piping) that resulted from the subsidence of solid objects and/or influent sand. These two failure modes may or may not associate with structural defects in pipes (e.g. cracks). Manhole level surveys have been mainly used for checking the loss of pipe grades. Pipe profilometer assessment has been predominantly deployed when a quantitative assessment of pipe profile was required for measuring dips, and when CCTV investigations could not be implemented. The identified non-structural defects (i.e. poor grades and dips) were directly addressed via repair/renewal operations without further evaluation.

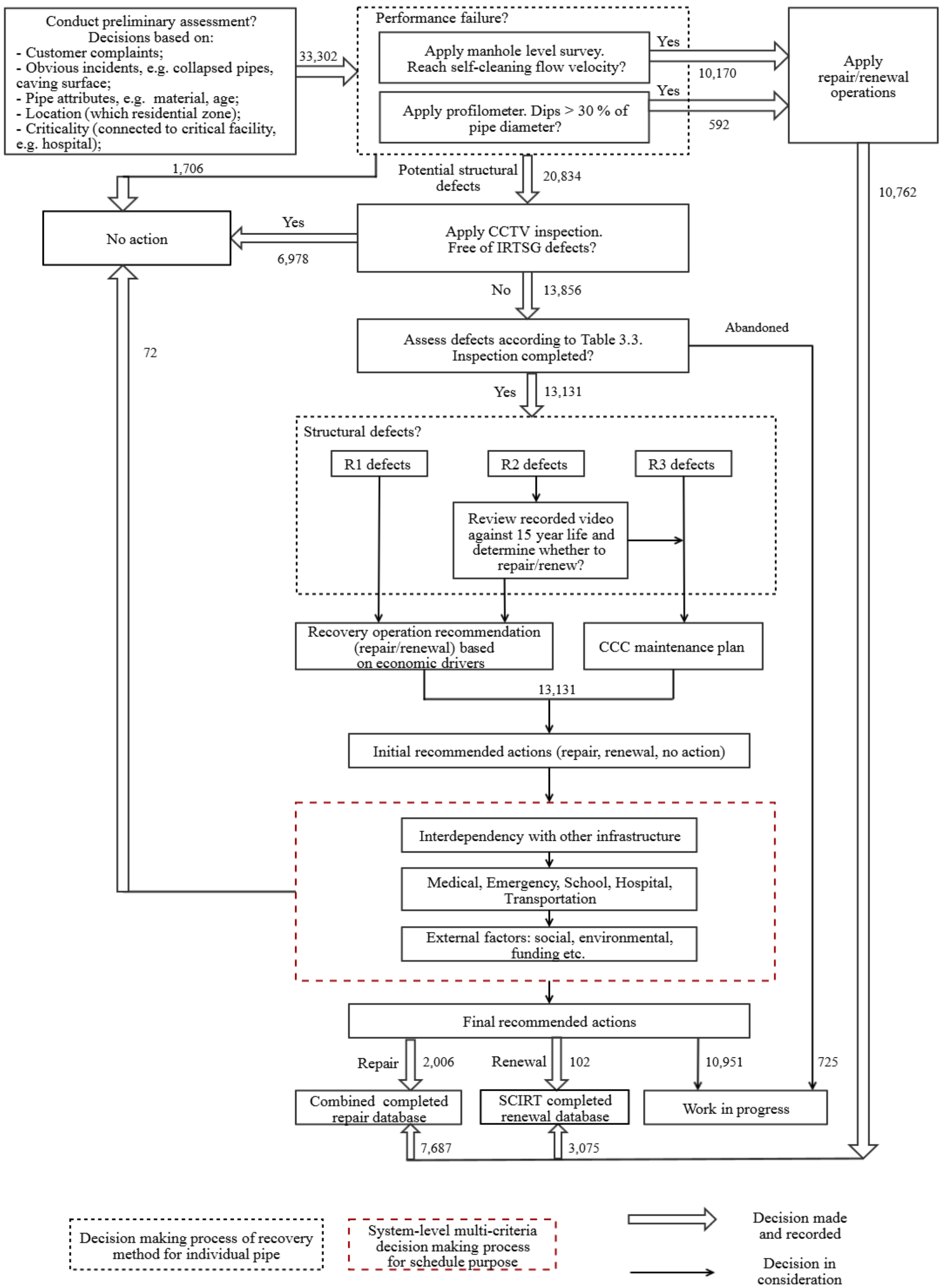


Figure 3.10 Diagram for decision-making process of post-earthquake reinstatement of the Christchurch sewerage system pipelines as of 21 January 2015. Numbers denote the number of pipes following each part of the decision tree.

In order to conduct CCTV inspections, silt and debris were cleared from the sewer pipes by use of hydro-jetting in a downstream direction with a pressure of 140 bar (for light cleaning) or 275 bar (for full cleaning). A few upstream cleaning cases occurred when necessary. Re-cleaning of silt commonly happened in the field because cleaning activities allowed soil and sand to re-enter sewer pipes through breaks or cracks in the pipe walls. In many cases, sewer pipes were cleaned two or even three times before a CCTV camera could be operated through the pipes. Whether pipe cleaning was necessary or not was mainly contingent on the purpose of CCTV inspections. Only when an assessment of small severity faults in the pipeline was desired would full pipe cleaning be conducted. There were many cases where a pipe was not fully cleaned because it was clear that the pipe needed repair or replacement without full cleaning. The database related to sewer physical damage used herein is established on the basis of only the CCTV inspections that were directly collected by the CCTV crew.

After physical defects in sewer pipes were recorded by CCTV surveys, trained assessors embarked on a coding program in accordance with New Zealand Pipe Inspection Manual (NZWWA, 2006). The NZPIM provides standard technical specifications for carrying out CCTV inspections when the structural condition of wastewater pipes is required, both during normal operation and after a disaster. It regulates good practice procedures for implementing CCTV inspections in New Zealand and provides a standardized set of codes for processing and analysing the observational information. Based upon the severity and location of the CCTV-recorded defects, assessors categorize them in accordance with Table 3.3. Table 3.3, modified from a table in the Infrastructure Recovery Technical Standards and Guidelines (IRTSG), provides defect categories and the corresponding suggestions on recovery actions (CCC, 2012a). The IRTSG, developed by CCC, has been specifically used to assess physical damage and to determine the design and construction of

Table 3.3 Defect categories for gravity sewer pipes and recommended recovery action classification (modified from IRTSG; CCC, 2012a). **R1**: critical defects requiring a recovery option; **R2**: case-dependent defects; **R3**: defects with no recovery action recommended; **OM**: operations maintenance; **N/A**: not applicable, defects of this type cannot have small or medium severity (for example, pipe collapses cannot be classed as a small or medium defect and must be a large defect, and so assessed as R1); **B**: decisions dependent on nearby recovery practice.

Categories	**Defect Type**	**Defect Severity**		
		Small	**Medium**	**Large**
Pipe wall	Crack: multiple	R3	R2	R2
	Crack: longitudinal	N/A	R2	R2
	Crack: circumferential	N/A	R3	R2
Interior pipe	Debris: silt	OM	OM	OM
	Deformed pipe	N/A	R1	R1
	Debris: greasy	OM	OM	OM
	Dipped pipe	further assessment needed		R1
	Encrustation deposits	OM	OM	OM
	Infiltration at pipe wall	N/A	R1	R1
Pipe joint	Joint displaced	N/A	R2	R1
	Joint faulty	N/A	R3	R2
	Joint open	N/A	R3	R2
Lateral	Lateral faulty	N/A	R2	R2
	Lateral protruding	OM	OM	OM
	Lateral problem	N/A	R2	R2
Pipe surrounding	Obstruction: permanent	OM	OM	OM
	Obstruction: temporary	OM	OM	OM
	Root intrusion	R2	R1	R1

	Surface damage	B	B	B
	Tomo (pipe cavity)	N/A	N/A	R1
Others	Deformed plastic pipe	R3	R3	R2
	Pipe holed	N/A	R2	R1
	Protective lining defective	N/A	N/A	R2
	Pipe collapsed	N/A	N/A	R1
	Pipe broken	R1	R1	R1

the repair/renewal operations being undertaken by SCIRT for the recovery. The recovery action classifications used in the table are defined and described as:

- Operational issue (OM): not a structural defect caused by the earthquakes but it is a defect that needs to be repaired by CCC as it has the potential to disrupt service (for example, a large root intrusion that is likely to have been present before the earthquakes). The defect will be treated as business-as-usual and the pipe will not be repaired by SCIRT unless the pipeline requires renewal due to the presence of other earthquake-related defects on it.
- Betterment (B): pipe will be repaired/renewed only when other nearby pipes are repaired, renewed or when reconstruction of roads occurs.
- Recovery (R1, R2 and R3):

  R1: critical defects that require recovery operations (repair/renewal) and do not require further assessment;

  R2: case-dependent defects that need further assessment to determine whether recovery operations are necessary;

R3: although defects have been found, no repair/renewal actions are recommended due to the absence of critical defects. Pipes with this classification are treated the same as the pipes classified as operational issue.

All the physical defects listed in Table 3.3 are recorded as “faults”. The R2 pipes were considered further to decide on whether to group them with the more serious cases (i.e. R1) to be managed by SCIRT, or to group them with the less serious cases (i.e. R3) that would be managed by the CCC as part of ongoing maintenance. To make this decision, SCIRT has been applying a “Level of service” approach by considering the estimated remaining asset life. Pipes that are not at a risk of collapse and at a low risk of compromised service within the next 15 years are classified as more appropriate for ongoing CCC maintenance planning rather than earthquake repair/renewal by SCIRT.

The faults on each pipe have been defined by SCIRT as the sum of the R1 defects and the R2 defects that had been re-assessed as more serious. The total number of faults on each pipe is then used to assign an initial recommended recovery action (either action recommended or no action recommended) to each pipe. The choice of initial recovery action has been driven by the number of faults, the fault types and the severity of the faults. The recommendations on renewal or repair were made using the IRTSG. The term ‘renewal’ is used instead of ‘replacement’ to clarify that any new pipe will not be a simple exchange and instead will be selected and installed based on revised design and construction rules. For example, badly damaged earthenware pipes would be replaced with new PVC pipes, and ‘renewal’ includes provision for completely lining an old pipe between manholes, and new trenching and pipe laying methods.

There are two main repair methods that have been adopted in Christchurch: trenched and trenchless repairs. The trenched repairs, also called dig-up repairs, are conventional methods for underground pipeline repair by means of excavating the trench. The trenchless repairs include small operations such as patch repairs or partial pipe lining. Trenchless repairs necessitate specific equipment (e.g. directional drilling machine) and distinct professionals. The choice between trenched or trenchless repairs depends on the type and location of faults. For example, partial pipe lining as one trenchless repair method applied in Christchurch has considerable merits in terms of adding structural integrity to pipes, reducing public inconvenience and lowering installation cost. However, it is not ideal for vertical pipe displacement and faults in pipe joints.

To help in the decision of renewal or repair, a rough guideline has been developed. For the purpose of simplification and standardization, the typical length between manholes (90 m) has been used by IRTSG to set the following guideline for trenched repairs:

- For pipes < 1.5 m deep, where there are in excess of 5 dig-up repairs, it is more economical to renew;
- For pipes > 1.5 m deep, where there are in excess of 6 dig-up repairs, it is more economical to renew.

In summary, the result of the process of assessing defects results in each pipe having one of three initial recommended actions:

- No action: although defects may have been found, no repair/renewal actions are recommended due to the absence of critical defects. Latent defects need to be managed by the CCC as part of maintenance operations, instead of by SCIRT, after earthquake repairs have been completed.

- Action--Repair: pipe will be repaired for less than its full length, and any pipe segment replaced will be less than 6 m in length.
- Action--Renewal: the pipe will be lined for the full length between manholes or replaced with new materials for 6 m or longer following new design and construction specifications.

Once a recovery action recommendation has been made for each individual sewer pipe, system-level concerns are considered. The overall sewer network has been divided into 67 PS catchment areas, covering 3232 meshblocks with an average length of 634 m and an average population of 105 persons per meshblock. The boundaries of the meshblocks generally correspond to sub-catchments of the gravity sewer network, often ending in pumping stations where sewage in a catchment is gathered and conveyed to the next catchment area until reaching the treatment plant in Christchurch.

A multi-criteria decision-making process is deployed to systematically consider pertinent factors at the catchment scale. The geographical proximity and dependency of other pipelines (water and stormwater pipelines), critical buildings (e.g. hospital and school), and external factors (i.e., social and environmental, funding) are key factors to be taken into account. This process has resulted in changes to the prioritization of sewer recovery work and the sequence in which those projects are carried out. For example, one 67.4 m gravity pipe with a diameter of 1250 mm was buried to a depth of 3.1 m in eastern of Christchurch. It sustained 4 faults and was classified as repair rather than renewal because the repair rate of this pipe is 5.3/90 m which is less than the critical rate of 6/90 m at this depth. However, after undertaking the multi-criteria decision making process, the initial decision was modified into renewal because it is a sewer trunk main and connected to a local primary school.

3.8 Chapter summary

In answer to the Objective 1 of the thesis (Section 1.2), this chapter investigated and documented the decision making process for restoring the CSS after the CES in 2010-2011. The chapter provides the overview of the decision making process of post-earthquake restoration of sewerage systems for readers to find relevant information.

CHAPTER 4

IDENTIFYING THE REQUIREMENTS FOR DECISION MAKING ON POST-EARTHQUAKE INFRASTRUCTURE RECOVERY

4.1 Introduction

This chapter synthesises organisational, technical, and information requirements for decision making on infrastructure recovery after earthquakes by identifying critical success factors (CSFs) in the Canterbury earthquake recovery. A combination of research approaches, including archival study, observations, and semi-structured interviews were conducted to collect data and evidence by engaging with participants involved at various tiers in the post-earthquake recovery and reconstruction, specifically of the Canterbury recovery.

The chapter commences with the definition and existing applications of the CSFs (Section 4.2). The research methodology adopted to identify the CSFs is presented in Section 4.3. Six salient CSFs aimed at promoting an efficient recovery of infrastructure post-earthquake are identified and explicated in Section 4.4. Section 4.5 provides lessons learnt for recovery authorities in relation to decision making on infrastructure rebuilding and determines relevant requirements for underpinning the decision making.

This chapter is based on the following journal paper:

> Liu, M. Scheepbouwer, E. and Giovinazzi, S. (2016) Critical success factors for post-disaster infrastructure recovery: learning from the Canterbury (NZ) earthquake recovery", Disaster Prevention and Management: An International Journal, Vol. 25 Iss: 5 (published online).

4.2 What are critical success factors?

CSFs are the requisite elements that are crucially needed for an organisation or a project to pursue its goals (Daniel, 1961; Rockart, 1978). They are factors that management professionals should pay considerable attention in order to achieve the success of the organisation or project of interest.

Although the concept of the CSFs was originally developed to serve in the field of business management and project management, an increasing number of researchers have adopted the CSFs to identify significant factors and enhance pertinent performance of post-disaster recovery (Rockart, 1986; Pathirage et al. 2012). Moe and Pathranarakul (2006), studying the Thailand tsunami in 2004 as a case study, specify ten CSFs that should be accounted for through project life cycle phases when managing public projects after disasters. Seneviratne et al. (2010) identify eight main categories of key factors for ensuring successful disaster management, namely: technological, social, legal, environmental, economic, functional, institutional and political factors, through extensive questionnaires and interviews. Brown et al. (2011) examine the decisions made in relation to solid waste management after the Black Saturday bushfires in Australia, finding five key factors, the clean-up process, covering organisation, funding, communication and technical issues (e.g., waste classification and landfill site construction). After the Canterbury earthquakes, Taylor et al. (2012) synthesise three key decisions: 1) establishing CERA; 2) residential zoning; 3) maintaining the cordon around the Central Business District for post-earthquake building environment. Additionally, they present seven critical factors during the post-earthquake recovery mostly regarding building reconstruction. These critical factors focus on the post-quake accessibility and evaluation of buildings (residential, commercial, and heritage buildings) as well as pertinent policies and bylaws aiming to ease the settlement of community from earthquake shocks, for example, the provision of earthquake support subsidy. Ophiyandri et al. (2013) summarise 12 CSFs contributing to the success of post-disaster housing reconstruction projects with specific emphasis on local community. The identified CSFs include: transparency and accountability; appropriate reconstruction policy/strategy; understanding the community-based method; gathering trust from the community; facilitator capacity; good coordination and communication; sufficient funding availability; implementer capacity; significant level of community participation/control; involvement of all community members; successful beneficiary identification; and government support.

Existing research on the CSFs of post-disaster recovery mainly focuses and addresses a single entity, such as solid waste management and building reconstruction. However, few works have been conducted in identifying the CSFs in the context of post-earthquake infrastructure recovery which involves multiple systems and thereby needs to consider the inter-relationship between each type of infrastructure systems as a system of systems.

4.3 Research method

Research questions, one of the key components for case study design (Yin, 2013), are the statements that identify the theory and phenomenon to be studied (Eisenhardt and

Graebner, 2007). They frame the research, determine the methods, and drive all activities and strategies related to the research. In particular, they guide the data collection process, which often combines archive study, interviews, observations, and questionnaires (Yin, 1994). The combined method could better substantiate concepts and hypotheses (Meyer, 2001). Conducting interviews is useful to capture views from multiple interviewees for providing a pluralist view regarding the research questions (Glick et al., 1990). Any replicated or contrasting information provided is of value in that they could enhance findings or disclose research breakthroughs (Hartley, 1994). In the preparation for decision-related interview questions, Schramm (1971) suggests delineating each factor/decision by answering why it was taken, how it was implemented and with what results. Examples of applying the abovementioned combined case study method to draw CSFs for ensuing the success of the disaster-related projects can be found in Brown et al. (2011), Lin Moe and Pathranarakul (2006), Ophiyandri et al. (2013), Pathirage et al. (2012), Seneviratne et al. (2010), and Taylor et al. (2012).

In this Section, the core research question is what is needed for post-earthquake infrastructure recovery. In other words, "which factors are considered critical in terms of the contributions to an efficient and informed decision making on infrastructure recovery after disasters?"

Towards that, archive study and observational work are firstly carried out. The archive study was conducted on national and international documentation referring to disaster recovery specifically for urban infrastructure recovery, for seeking relevant answers to the identified research question. In particular, the documents related to the Canterbury infrastructure recovery were scrutinised for identifying the lesson-learnt which might be of value to the question. Additionally, the author has participated in regional, national and international technical meetings/conferences in relation to the post-disaster rebuild and, in most cases, the Canterbury infrastructure recovery and thereby obtained first-hand observational experience.

Based on the nature of the research question, interview questions were formulated, in line with Schramm (1971), such that decision-making process, decision implementation and resultant consequences were examined.

In order to gather a pluralistic viewpoint of the infrastructure recovery following the CES, semi-structured interviews were conducted with a total of 17 interviewees selected from professionals working on the three phases of the infrastructure recovery in Christchurch, namely: decision making, decision implementation, and reconstruction delivery. The name list of the participants is provided in Appendix B of this thesis. At least four key personnel were chosen from each of the abovementioned phases for ensuring the representativeness and information richness. Since interviewees' expertise covers the whole process of the Canterbury infrastructure recovery, it is believed that the collected information by means of interviews is sufficient and reliable.

The interviews were carried out in 2013, approximately three years after the first earthquake in 2010. This allowed for the evaluation of the recovery decisions from a retrospective viewpoint, thereby effectively synthesising CSFs of the Canterbury infrastructure recovery. In particular, how each CSF has evolved along with the dynamic process of the post-earthquake recovery is scrutinised. Furthermore, the effectiveness and usefulness of the identified CSFs are evaluated and re-considered during the case study research.

Six CSFs have been identified as outcomes of the interviews. These 6 CSFs are itemised and summarised below. The next Section describes each CSF in detail relative to the CES.

- CSF 1: Establishment of a recovery vehicle

After a disaster event, it is useful to establish a recovery vehicle for holistically organising and managing the post-disaster reinstatement operations. Unlike recovery authorities that predominantly handle the institutional matters (e.g., Victorian Bushfire Recovery and Reconstruction Authority after the Australia Victorian Bushfire in 2009, Centre of Direction for Command and Control after the L'Aquila Earthquake (Italy) in 2009 and CERA in Christchurch), recovery vehicles mainly focus on the implementation of the decisions released by recovery authorities, design and engineering of the recovery works in field and on delivery of the post-event reconstruction to community.

- CSF 2: Formulation of a flexible funding plan

Funding is considered vital in the infrastructure rebuild post-disaster because it guarantees the effective implementation of infrastructure reinstatement. The sufficiency of recovery funding and the availability of funding plan could further reinforce the confidence and certainty of decision makers, residents, investors in post-disaster rebuilding.

- CSF 3: Selection of a rebuild driver

How to cope with massive scope of the damaged infrastructure networks becomes a big concern for decision makers after disasters. To aid in post disaster rebuild, it is useful to select one infrastructure asset as a rebuild driver around which other infrastructure systems can be accordingly planned. In other words, this infrastructure is considered as a baseline to be planned first, followed by the design and engineering for other infrastructures. For example, in a recovery area, water supply system is chosen as a baseline and decision makers formulate rebuild plans based on the rebuilding sequences of the water supply network. According to this sequence, the working schedule of other infrastructure systems can be determined such that pipes in the same geographical location as high priority water pipes are also prioritised. This could centralise logistics and labour at the time of high demands of these resources and avoid difficulties associated with simultaneously adjusting the working schedule of all infrastructure systems. Furthermore, it effectively avoids duplicating construction of the same location for different underground networks which exacerbates the inconvenience for road users and residents by, for instance, blocking/limiting the traffic.

- CSF 4: Determination of rebuild project prioritisation methodology

The post-disaster recovery process involves a wide range of shareholders, groups, individuals, who have different interests and intentions on the rebuilding projects. Because of that, a transparent and robust methodology to prioritise numerous repair/reconstruction tasks is of importance. In particular, the methodology needs to pay special attention to critical facilities (e.g. hospitals, schools).

- CSF 5: Standardisation of data management mechanism

A holistic understanding and interpretation of the damage (physical and functional) to infrastructure components could assist in the formulation of recovery plans, implementation of the informed plans and ultimately expedite post-disaster infrastructure recovery. Therefore, it is valuable to systematically document pertinent data and information regarding the impaired infrastructure networks in both digital and non-digital format. The recorded document is intended to facilitate the recovery work and for future reference.

Recent research shows that data collection and data sharing are important to both the post-event recovery and pre-event disruption reduction (Lin Moe and Pathranarakul, 2006;

Younis, 2010). However, previous international cases show that a large amount of data and information were not properly recorded or documented (Hsu, et al., 2005; Da Silva, et al., 2010). In some cases where relative information was logged, however, due to insufficient data management mechanisms, the availability and timeliness of the documented data limit the usage of the data by recovery organisations.

- CSF 6: Community engagement

The core role of post-disaster infrastructure recovery is to regain the service and serve community better. Therefore, the satisfaction of local community is one of the key criteria of recovery operations and consequently determines whether the whole recovery programme is successful (NIU, 2012). Effective communication with local community will create a pleasant working environment and, to a certain extent, speed up the recovery process. Due to this, it is useful to inform and notify locals of the upcoming inconvenience that the rebuild work on city roads might cause. This might earn more understanding and satisfaction of locals.

4.4 Identification of CSFs for post-earthquake infrastructure recovery

The six CSFs cover the organisation, finance, technical, and communication aspects of the Canterbury infrastructure recovery. CSF 1 and 2 entail managerial and organisational contexts of the post-earthquake infrastructure recovery from CERA’s viewpoint, whereas the rest looks into the restoration of the Christchurch infrastructure systems from a technical perspective. All the CSFs significantly contribute to the success of the infrastructure recovery in Christchurch. Without any of these, the recovery process would not have progressed well.

The focus of this analysis is on the operational involvement of each CSF in the decision making and decision implementation process, the discrepancy between resulting consequences and expected effects and on future challenges.

CSF 1: Establishment of a recovery vehicle

The 4 September 2010 Earthquake (M_w=7.1) caused "moderate" damage to infrastructure systems in Christchurch city. In the aftermath of the quake, CCC in collaboration with central government, NZTA, and the Earthquake Commission (EQC), played leading roles in the infrastructure recovery post-earthquake. CCC established an Infrastructure Rebuild Management Office (IRMO) to rebuild its damaged infrastructure assets as a result of this earthquake. IRMO comprised of 20-30 CCC staff responsible for design, construction management, finance, communication, programming, procurement, and project administration (CAG, 2013). IRMO entered into four design-build contract arrangements with four construction companies to reinstate the impaired infrastructure categorised by geographic locations. Six weeks after this seismic event, 280 and 200 repairs had been made to water supply and wastewater pipelines, respectively, under the guidance and supervision of IRMO, mainly in liquefaction areas.

After the 22 February 2011 earthquake with a magnitude of 6.2 it became clear that the infrastructure rebuild tasks would require significant support from central government, beyond funding alone. Hence, CERA was established by central government to lead, direct and coordinate the massive recovery activities to be undertaken following the Canterbury earthquake sequence. Upon CERA's establishment and the formation of an initial infrastructure group within CERA, the government, CCC and NZTA examined various contracting models through which a large-scale infrastructure rebuild could be undertaken.

There were reservations about a traditional contracting model being able to cope with the need for an end-to-end investigation, design and construction process, especially as the procurement and contract management of hundreds of projects would be logistically challenging and expensive. The volume of rebuilding projects was expected, in the short term, to be tenfold the annual maintenance programme conducted by the CCC (Liu et al., 2013).

Other models were considered and the three partners (i.e., CCC, CERA and NZTA) selected an alliance-contracting model to establish SCIRT which has three funding partners and five contracting companies. SCIRT is the delivery team rebuilding around 85% of the earthquake damaged horizontal infrastructure networks in Christchurch, including roads, fresh water, wastewater and stormwater networks. CCC, CERA and NZTA are infrastructure rebuilding clients, collaborating through a Client Governance Group to audit and supervise the rebuilding delivery (Figure 1). SCIRT was established in June 2011 (nine months after the September Earthquake in 2010) and through three months of pre-operation period, it officially took over the overall responsibility of IRMO one year after the first seismic event. At that time, SCIRT took over 148 projects that were in the design, construction, and handover phases from IRMO and 125 projects in the damage inspection stages. Using wastewater catchments as spatial units, SCIRT has been reinstating the aforementioned systems according to Infrastructure Recovery Technical Standards and Guidelines (IRTSG; CCC, 2012a), in conjunction with CCC Infrastructure Design Standard (CCC, 2013a) and CCC Construction Standards Specification (CCC, 2012b). Until November of 2015, 80 % of reconstruction tasks had been completed with a total value of NZ$1,379.9 million (SCIRT, 2015).

The establishment of a recovery vehicle is of technical benefit in interpreting recovery decisions, developing innovative techniques and achieving rapid post-disaster recovery.

However, whether to form a recovery-oriented vehicle depends on, among others: the magnitude of the disaster, the severity of the disaster-induced damage, the flexibility of the government, and the resilience of society and community. SCIRT was established after the occurrence of a series of intervening earthquakes, which led to a realisation of local government that IRMO is not managerially and organisationally capable of coping with this large-scale post-earthquake recovery. Subsequently, the establishment of SCIRT as a recovery vehicle is a well-recognised success in that it has promoted the post-earthquake infrastructure rebuilding in Christchurch under the guidance and supervision of the three funding agencies within time and budget constraints. However, the responsibility shift from IRMO to SCIRT and the long deliberation period of this shift might have resulted in a delay of overall rebuilding process and inconsistency of recovery guidelines. Potential risks lie in the managerial and technical adjustments of all recovery projects back to CCC as part of daily maintenance practice after SCIRT will be disbanded in 2016.

CSF 2: Formulation of a flexible funding plan

Following a number of intervening seismic events in 2010 and 2011, the severity and quantity of the impaired infrastructure assets highlighted that extensive support from central government and pertinent organisations were needed in terms of funding. Central government is expected to play a major role in financially assisting in reinstatement of the horizontal infrastructure systems, considering the widespread physical damage induced by such a large scale of natural disaster. The central government of New Zealand through CERA pays 60 % of the costs for three waters infrastructure (CCC, 2013b).

Multiple interviewees stated that since the September earthquake, cost sharing between CCC and central government has been a hot topic. In 2011, a Canterbury Earthquake

Recovery Fund of NZ $5.5 billion was set up for the purpose of supporting and subsidising the infrastructure rebuilding in Canterbury region. The funding was formed in the combination of re-allocation of existing budgets for public utility and a new source of government funding. Of the overall funding, NZ $1.65 billion is allocated for the Christchurch infrastructure systems rebuilding. In 2013, a NZ $4.8 billion agreement was formulated between CCC and central government on the cost sharing of NZ$1.9 billion and NZ$2.9 billion to the rebuild, respectively (CCC, 2013b).

The interviewees realised that there was a lack of a funding division plan available in place prior to the Canterbury recovery. The recovery would have benefited more if there were pre-defined funding plans. For instance, a funding division plan formulated prior to disasters may shorten the time taken for applying for financial support from central government, expedite infrastructure recovery post-disaster and thus facilitate functional recovery of society and community. However, it is important to envisage that there will be underlying risks in exclusively setting up post-disaster funding plans, especially when the severity of a disaster is unknown. Therefore, a flexible funding plan might be an ideal solution.

CSF 3: Selection of a rebuild driver

The rebuild programme SCIRT has been executing involves all system assets of the water supply, wastewater, stormwater, roading systems in Christchurch city. Interviewees believed it is more efficient to systematically restore the underground facilities according to geographic proximity. SCIRT chose the sewerage system as a rebuild driver when planning and implementing the infrastructure rebuilding programme. SCIRT planners firstly determine recovery plans depending on the priority and severity of the impaired sewerage assets. Then the necessity of repairing other underground infrastructure in the same location is identified.

By this means, the recovery operations for distinct infrastructure in the same geological locations are carried out coordinately and the unnecessary duplication digging and traffic blocking can be avoided.

There are three reasons for the selection of the wastewater system. Firstly, the CSS suffered the most extensive physical damage as a result of the earthquakes. Secondly, it is the infrastructure that is buried deepest since the sewerage system is primarily a gravity-fed system. Lastly, the Christchurch rebuilding projects are zoned using waste-water catchments as common spatial units.

The selection of the Christchurch wastewater system as a rebuild driver enables recovery planners to systematically and efficiently restore the damaged horizontal infrastructure networks in Christchurch. The implementation of the rebuild driver in Christchurch has helped in expediting recovery, maximising the efficiency of resource and reducing extra expense.

It should be noted that the selection of the rebuild driver may vary along with the post-disaster recovery process. The main focus of the emergency response phase is on the provision of rescue service and basic living needs for community. The functionality of infrastructure systems is crucial to guarantee the accomplishment of these goals. In the emergency response period, the elemental human needs which include clean water and stable electricity are the first priorities. Therefore, water supply and electricity power systems can be designated as rebuild drivers in this phase. As for long term recovery plans, the choice of a rebuild driver is not that straightforward in that it yields many other factors, for example, damage level of infrastructure facilities, community expectation as well as service standards.

CSF 4: Determination of rebuild project prioritisation methodology

SCIRT developed a spatial prioritisation methodology shown in Figure 4.1 to underpin the decision-making process of post-earthquake reinstatement for horizontal infrastructure systems. The prioritisation methodology aims to prioritise rebuilding projects of infrastructure facilities and the sequence in which those projects are carried out. It is run in a platform Feature Manipulation Engine, by where geographic information system (GIS) data and non-GIS data could be incorporated and integrated to rank infrastructure facilities of interest. The methodology allows for the global evaluation of asset condition, criticality, residual serviceability and maintenance cost of individual assets of all infrastructure network considered. Based on that, and accounting for geographical dependency and priorities of critical facilities, along with any resource constraints and external factors, rebuilding schedules are formulated. The results require further verification by use of common sense check. The project prioritisation analysis is run on a three monthly interval based on latest data upgraded. This method separately considers and analyses individual structures (such as bridges, PSs) as stand-alone projects.

The prioritisation methodology has been considered as a success by the majority of interviewees in that it has achieved an integrated combination of technical factors and societal influences of infrastructure rebuilding post-earthquake. It allows for a multi-criteria assessment of the damaged infrastructure at both component and system levels in a step-wise manner, with particular emphasis on critical structures. The regular operational check and information upgrade ensure the appropriateness and effectiveness of the identified priorities (Figure 4.2). Therefore, the rebuild project prioritisation methodology can provide policy-makers with solid information upon which to base recovery plans. Possible improvements could be made by adding more generic asset attributes (e.g. length, depth) and even by assigning weights to each comparable factor. These could probably increase the accuracy and reliability of the prioritisation outcomes. However, the trade-offs of doing so, such as added time and expense, would be a challenge for decision makers.

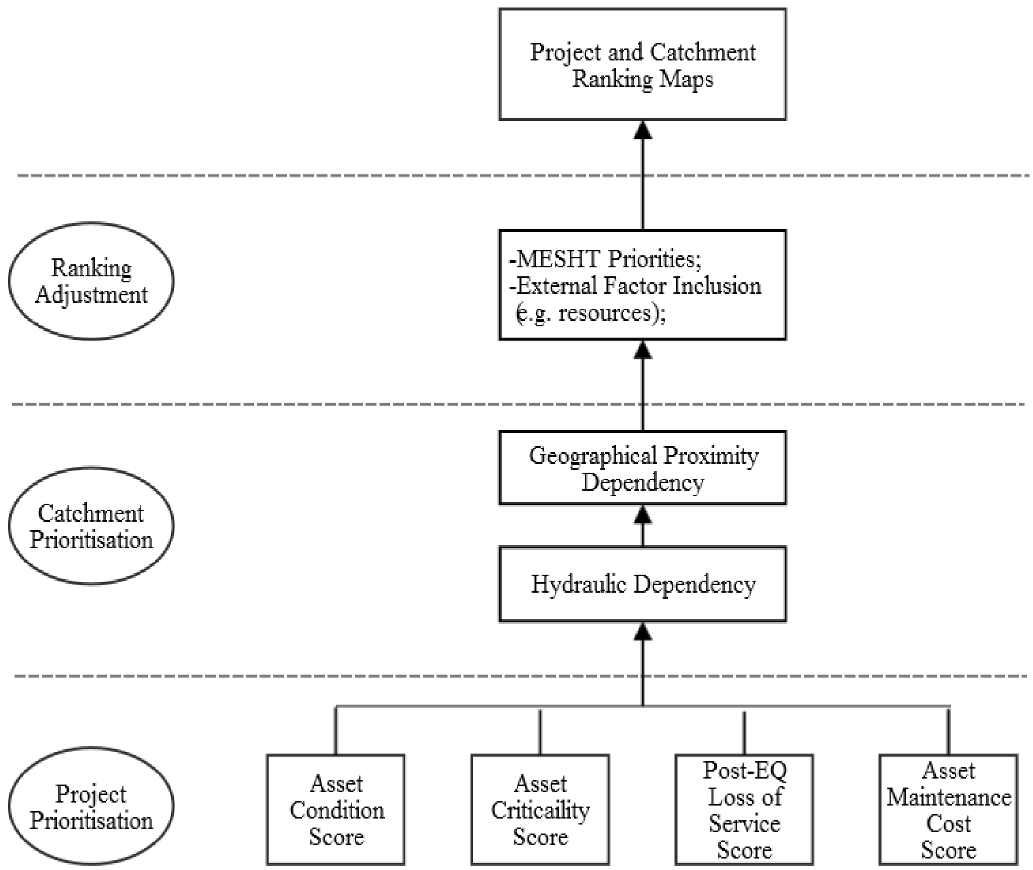


Figure 4.1 Flowchart of rebuild project prioritisation methodology

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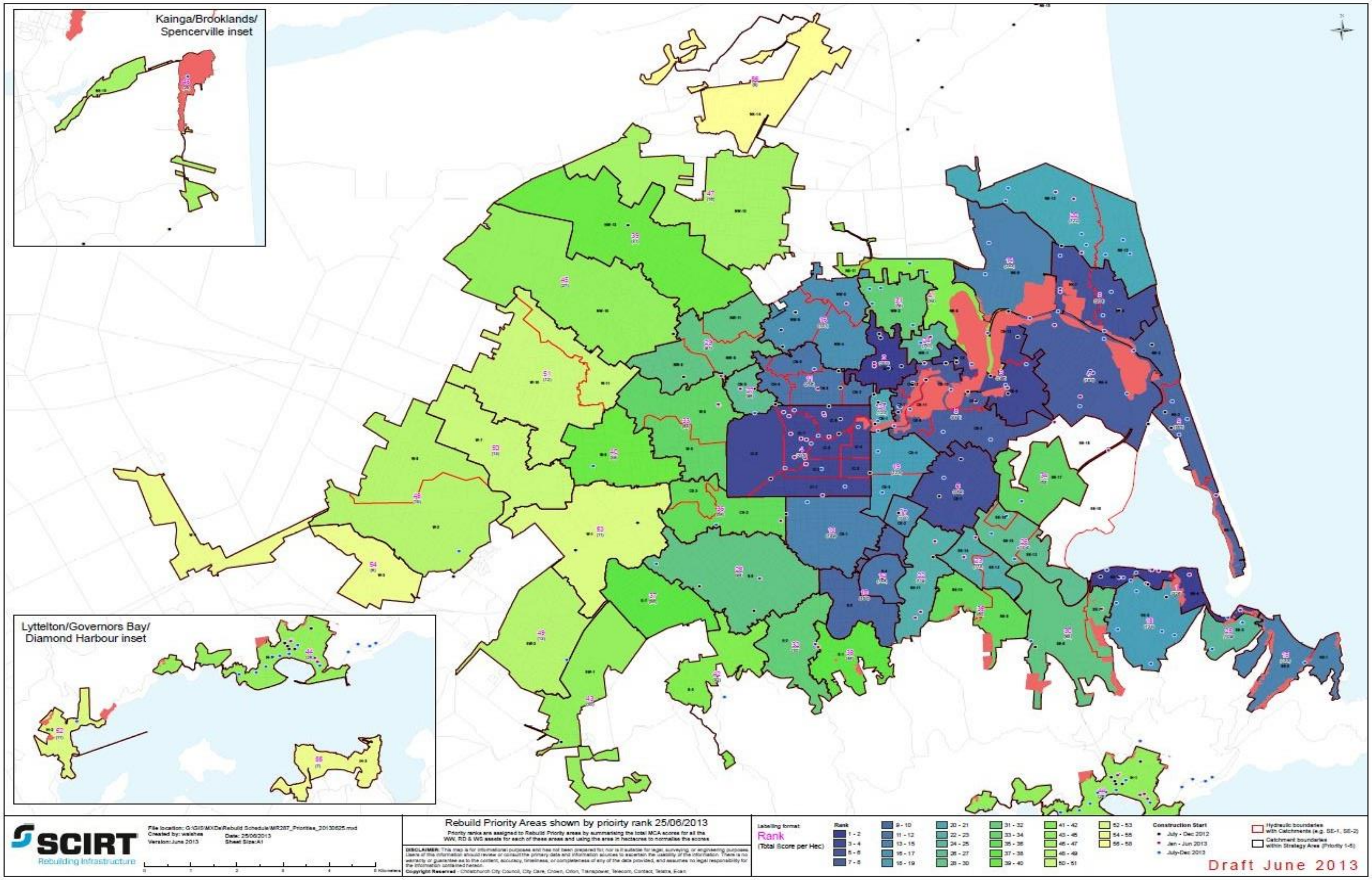


Figure 4.2 An example of a ranking map generated after the catchment prioritisation process (SCIRT, 2014; used with permission)

CSF 5: Standardisation of data management mechanism

After the Canterbury earthquakes, diverse assessment teams were summoned nationally and internationally and distributed to investigate the earthquake-induced physical and functional damage to local infrastructure systems. For example, three types of damage assessment teams were assigned to investigate the Christchurch wastewater reticulation system, namely: 1) Manhole level survey team; 2) Closed Circuit Television inspection team; 3) Pipe profilometer assessment team, for the purpose of gaining a comprehensive understanding of the level of the physical damage to the sewerage system pipelines in Christchurch.

The collected information was logged to the GIS database that is maintained and jointly owned by the CCC and SCIRT. A suite of geospatial databases created by the SCIRT GIS team include, among others, system inventory, physical damage, repair operations, renewal activities of all types of horizontal infrastructure systems (water supply, wastewater, storm water and road networks). Moreover, a web spatial platform was conceived and developed by SCIRT. The main role of this platform is to facilitate data sharing between planners, designers, operators and decision makers involved in the recovery process. It has basic data manipulation functions and a map interface for users to operate. The information contains descriptive spatial GIS layers, photos, evaluative statements, covering all projects conduced or being conducted in Christchurch. The GIS team within SCIRT updates the master database regularly by incorporating the latest data into the platform.

It is recognised by interviewees that data collection and data sharing have been effective amongst distinct stakeholders, authorities, agencies and operators. The databases and web platform developed by SCIRT enable effective data exchange and distinct usage of the information available. However, there are two issues that have ocurred during data collection and data transference process in Christchurch. The first is the lack of an integrated information documentation mechanism such that inconsistent format and incomplete data can be found in the databases. The second one is the incompatibility and inconsistency of different data sources due to a variation of data management systems deployed by different users. In particular, the misunderstanding and information discrepancy have arisen from data transference between different organisations. This severely limits the use of the recorded data/information for guiding and assisting in recovery operations.

CSF 6: Community engagement

The communication team in SCIRT intends to inform the community regarding the rebuilding operations that SCIRT is doing and clear up the uncertainties of locals, building up their confidence. They have done extensive work to promote community engagement in the Canterbury recovery. Until November of 2015, approximately 6,047 work notes have been specifically produced and delivered to 1,409,083 residents/businesses. 34,921 face-to-face meetings were organised with locals who were living/working in SCIRT rebuilding areas. In addition to this, 160 visits to local schools were acted to engage with students in relation with SCIRT's work (SCIRT, 2015). A SCIRT webpage is built as an interface with public for updating work progress, informing the upcoming tasks and answering people's inquiries. The communication team conduct surveys and interviews to collecting people's ideas and satisfaction levels with regard to SCIRT's rebuilding operations on a six-month interval. The results of a survey conducted in November 2013 by Opinions Market Research Ltd are presented in Table 4.1 (SCIRT, 2014). All of the surveyed subjects receive more than half of support level. The high support levels (90 % and 86 %) show the community feel informed and satisfied regarding the construction work.

Table 4.1 Sample of survey reports conducted in November 2013 (SCIRT, 2014; used with permission)

Subject area of survey questions	Support Level
Acknowledged impact on road travel (approximately)	90%
Satisfaction with communications	86%
Tolerance of traffic impacts in central city	79%
Tidiness of sites	77%
Very satisfied or satisfied with local works	75%
Clarity of information received	73%
Ease of navigation past works	66%
Residents with works in their neighbourhood	66%
Acceptable standards and time frames (approximate sum)	66%
Priorities believed appropriate	64%
Awareness of SCIRT	59%

SCIRT, as a rebuild delivery team, has been effectively kept local community engaged in the Canterbury recovery by means of, among others, face-to-face meetings, work notes, and surveys. The high satisfaction levels represented from the conducted surveys reflect the well-recognised performance of SCIRT and in turn facilitate the implementation of the infrastructure rebuilding. However, the implementation of community communication could have been improved. The community communication efforts have been only concentrated on the rebuild practice executed by SCIRT. The information has only been related to upcoming and on-going projects without including the overall viewpoint of the recovery scheme.

4.5 Lessons learnt from the Canterbury post-disaster infrastructure recovery

The infrastructure recovery in Christchurch provides an example for others potentially facing similar situations. The CSFs identified in Section 4.4 disclose the opportunities for improvements in the field of post-disaster recovery management specifically for infrastructure systems.

For the purpose of better preparing for future events, the following lessons are summarised:

- A recovery vehicle/organisation in charge of infrastructure rebuilding should be established. The scale of the structural vehicle is contingent on the severity and quantity of the damage (physical and functional) induced by disasters. It is imperative to shorten the deliberation period of setting up the recovery vehicle because this could save time and expense and also expedite post-disaster recovery. Roles and responsibilities of distinct parties involved should be clearly defined.
- A pre-established funding plan for post-disaster infrastructure recovery is necessary. In particular, rational regulations regarding funding division among relative parties (e.g., central government and local authority) should be well defined, taking into account likelihood of seismic events.
- A type of infrastructure system should be selected as a rebuild driver for facilitating the formulation of post-event infrastructure recovery where all infrastructure components can be systematically and efficiently restored. It should be noted that the selection of the rebuild driver may vary along with the post-disaster recovery process as the recovery objectives and focus may morph at different recovery stages. It is necessary to understand in advance of the selection that the severity of the

earthquake-induced damage to the system physically and functionally so that a well-informed decision could be drawn.

- A prioritisation methodology accounting for relevant factors involved in post-event infrastructure reconstruction is of value. Increasing the number of factors pertinent to infrastructure can improve the accuracy and efficiency of the prioritisation outcomes. However, the associated added resources (e.g., expense and time) would be a challenge.
- A standardised data collection and management mechanism is needed. In particular, asset taxonomy, data format, damage classification should be standardised and identified in advance of information documentation process. Data documentation mechanism and management procedures should be defined and clarified for avoiding inconsistent logging and incomplete data to the largest extent. It is desirable to carry out staff training with regard to the proposed data management mechanism.
- Further to the current community engagement plan, it is of importance for community to be informed of the best estimated restoration time of the lost services (e.g., sanitation service). In this way, community could be better prepared for the service outage and thus minimise the disruption it may cause. Furthermore, the information regarding the restoration time enables decision makers to strategize reconstruction resource allocation and coordinate multiple tier operations.

Based on the identified CSFs and lessons learnt, the pertinent requirements for underpinning decision making on infrastructure recovery after earthquakes are determined, but not limited to:

- Organisational requirements:
  - Establishment of recovery vehicle;
  - A flexible funding plan;
- Information requirements:
  - Physical and functional impacts on infrastructure systems and wider community;
  - Estimated post-earthquake restoration duration;
- Technical requirements:
  - Selection of a recovery driver;
  - A prioritisation methodology;
  - A standardised data collection and management mechanism.

It is noted that the requirements are elicited in the identification of the CSFs and they may not be exhaustive. The author is aware of other existing practical requirements that might be requisite for post-earthquake decision making.

4.6 Chapter summary

In answer to the Objective 2 of the thesis (Section 1.2), this chapter identified organisational, technical, and information requirements for decision making on post-earthquake infrastructure recovery by determining six CSFs that play crucial roles in the post-earthquake infrastructure recovery after the CES. Through a method combination of archival study, observations, semi-structured interviews, and technical meetings, the CSFs were evaluated and analysed by tracking the decision making process, examining resultant consequences and foreseeing onward challenges. The CSFs provide a reference and guidance for recovery authorities facing decision making on infrastructure recovery in future earthquakes. The governmental and technical requirements for post-earthquake infrastructure recovery are beyond the scope of the thesis. The identified information requirements strengthening decision making on infrastructure recovery management will be delineated in the following chapters.

CHAPTER 5

PROPOSAL FOR DECISION SUPPORT FRAMEWORK FOR POST-EARTHQUAKE RESTORATION OF SEWERAGE PIPELINES AND SYSTEMS

5.1 Introduction

Based upon the critical success factors and information requirements identified in the previous chapter, a framework is proposed for assiting decision makers in the post-earthquake recovery of sewerage systems. The decision support framework is intended to enable the assessment of physical damage, the evaluation of functional impacts, and the prediction of restoration time through three modules inbuilt in this framework. This chapter summarises the roles and relationships of these modules to the overall framework.

Section 5.2 lists the informational needs for decisions in relation to post-earthquake sewerage system restoration. A decision support framework for restoration of sewerage systems post-earthquake is proposed and demonstrated in Section 5.3. The databases and seismic hazard parameters implemented in the development of the proposed decision support framework are depicted in Section 5.4.

This chapter is based on the following conference paper:

> Liu, M., Giovinazzi, S. and Beukman P. (2015). Towards a decision support framework for post-earthquake restoration of wastewater systems. *IFME World Congress on Municipal Engineering and IPWEA International Public Works Conference*, Institute of Public Works Engineering of Australasia, 7-11 June 2015, Rotorua, New Zealand.

5.2 Information requirements for decisions in relation to post-earthquake restoration of sewerage pipelines and systems

The post-earthquake restoration of a sewerage system poses challenges to decision makers. An effective and timely restoration is contingent on the strategic allocation of scare resources through good decision making. The problems lie in: 1) what information/evidence is needed for making rational and informed decisions on sewerage system recovery; and 2) how to use the information and resources available and/or the integration of them as required to underpin the decision making.

In the previous chapter, the information requirements for decision making on infrastructure recovery are identified, including: 1) Physical and functional impacts on infrastructure systems and wider community; and 2) Estimated post-earthquake restoration duration. In accordance with this, the decision making process of sewerage system recovery post-earthquake is in need of:

- Knowledge of earthquake-induced physical damage to sewerage system components;

- Knowledge of functional impacts on hydraulic, structural, environmental, social, and economic contexts that have arisen from the malfunction of the system as a whole; and

- Estimates of restoration duration of the sewerage system after earthquakes.

In terms of the usage of the identified information and data, decision support frameworks can serve to inform and assist wastewater system managers by providing a platform for collating, organising, processing the data and information available and by composing a range of possible alternative solutions on which recovery strategies and plans can be developed (Alçada-Almeida et al., 2013; Sousa et al., 2009). A framework specifically defined for the restoration of wastewater systems post-disaster can support recovery authorities in making strategic decisions by providing approaches and tools to:

- Gain a comprehensive overview of the earthquake-induced physical damage and functional impact sustained by the impaired wastewater systems;

- Efficiently manage resource allocation for reconstruction operations;

- Coordinate resource procurement and transportation;

- Assess the cost-effectiveness of alternative strategies to support their selection.

Furthermore, the decision support framework should underpin the provision of information (e.g., timeline for partial and total restoration of sanitary service) to the affected communities and end-users.

5.3 Overview of the decision support framework for post-earthquake restoration of sewerage pipelines and systems

In this Section, a framework is proposed for supporting the decisions in relation to wastewater system recovery after earthquakes. Figure 5.1 demonstrates the proposed decision support framework, the relationships between the three modules, and the information required to use them. This framework first assesses and estimates the earthquake-induced physical damage to the wastewater systems. Given a certain level of seismic hazards, the framework could assess and/or predict the number of faults or repairs sustained by the sewerage system components, categorised by component attributes (e.g. material). Secondly, the assessed or predicted physical failures are utilised to evaluate the functional impacts on the impaired wastewater systems and to estimate the expected consequences on the community, environment and economy, by means of a set of PIs established in advance. Finally accounting for the pre-earthquake asset conditions of the different components and post-earthquake time and financial constraints, the decision support framework can predict the restoration time for sewerage systems. In sum, the decision support framework aims to promote an effective and informed restoration of sewerage systems after earthquakes. Further details on the decision support framework are provided in relation to its three modules: 1) Physical Damage Module (PDM); 2) Functional Impact Module (FIM); 3) Pipeline Restoration Module (PRM).

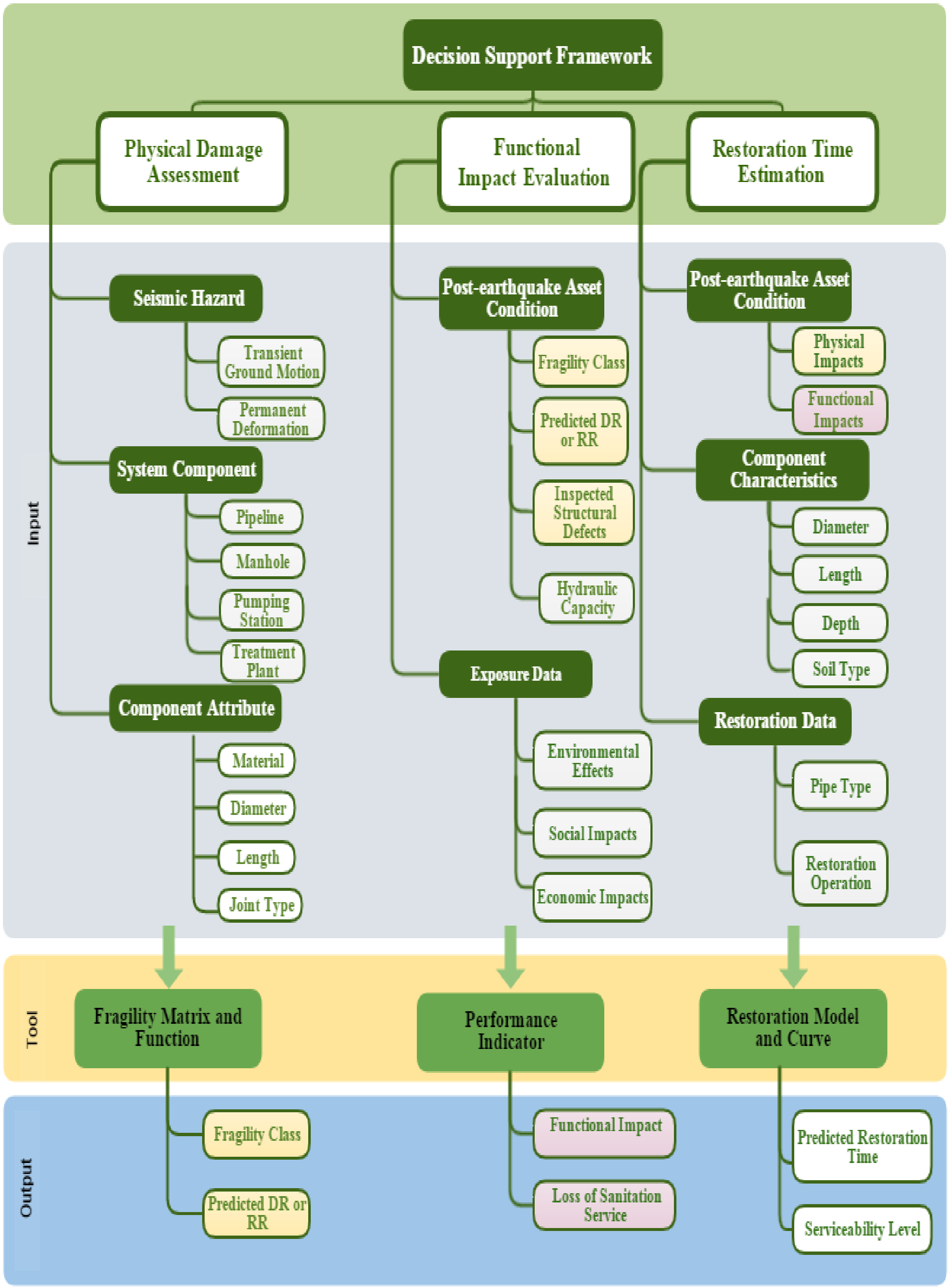


Figure 5.1 Inputs, tools and outputs of the decision support framework for post-earthquake restoration of sewerage systems

5.3.1 Physical damage module

One of the necessary conditions for making rational decisions in relation to recovery operations is the knowledge of the post-event conditions of the sewerage systems from both physical and functional viewpoints. The assessment of the damage via CCTV or other advanced techniques might be highly expensive and time consuming. Thus, fragility matrices and curves might be employed to gain a rapid, although imprecise, estimation of the possible earthquake-induced physical damage to wastewater system components. In the PDM of the decision support framework, fragility functions for gravity pipes, pressure pipes and council-owned laterals are developed as a function of peak ground velocity, for different pipes materials based on the seismic performance observed following the CES in 2010-2011 (Liu et al., 2015). Details of the development of these matrices and functions are presented in Chapter 6 of the thesis.

5.3.2 Functional impact module

In addition to the earthquake-induced physical damage to each component of the system, it is necessary to gain an understanding of the performance, functionality and serviceability of the impaired system (Davis, 2014). The FIM proposed evaluates the loss of the wastewater service and the associated serviceability through a set of PIs for the three post-earthquake recovery phases: 1) emergency response, 2) short-term recovery, and 3) long-term restoration. The PIs are formulated in structural, hydraulic, environmental, economic, and social domains. The inter-relationship and inter-action amongst the five domains are not considered or evaluated in the thesis. Details relating to the post-earthquake PIs for sewerage systems will be presented in Chapter 7 of the thesis.

5.3.3 Pipeline restoration module

The knowledge of the physical and functional status of the system post-quake should support the understanding of the reduced capability and loss of serviceability of wastewater systems. Based on this understanding, and accounting for the identified restoration priorities, along with any existing financial and time constraints, restoration plans can be made. The PRM included in the proposed decision support framework, aims to predict the post-earthquake restoration duration of sewerage systems. The module provides post-earthquake restoration models, graphically represented in terms of restoration curves. The restoration curves illustrate sewer restoration rates as a function of restoration time for selected reinstatement strategies, given the availability of recourses (e.g. crew, equipment, material and budget). Furthermore, the restoration models have the potential to aid in the determination of recovery strategies (i.e., repair or renewal). Details will be presented in Chapter 8 of the thesis.

5.4 Databases and seismic hazard parameters implemented in the development of the decision support framework

5.4.1 Database description

Table 5.1 shows the four databases analysed in this thesis. The Christchurch sewerage network (CSN) inventory records the Christchurch sewer pipelines before the February earthquake. The CCTV inspection database, the combined completed repair database and the completed renewal database are all dated 21 January 2015 and linked via a sewer pipe ID. The data, jointly owned by the CCC and SCIRT, were provided by SCIRT. The details in relation to how the databases are established and the decision making pertaining to the sewer recovery in Christchurch can be found in Section 3.7.

Table 5.1 Databases used in this thesis

	CSN inventory	**CCTV inspection database**	**Combined completed repair database**	**Completed renewal database**
Pipe number	✓	✓	✓	✓
Pipe type	✓	–	✓	✓
Pipe material	✓	✓	✓	✓
Diameter	✓	✓	✓	✓
Year laid	✓	✓	✓	✓
Burial depth	✓	–	–	✓
Pipe length	✓	✓	✓	✓
Grade	✓	–	–	✓
Service status	✓	–	–	✓
Pipe shape	✓	–	–	✓
Upstream pipe	✓	–	–	✓
Downstream pipe	✓	–	–	✓
Number of faults	–	✓	–	–
Assessment results	–	✓	–	–
Surveyed length	–	✓	–	–
Surveyed date	–	✓	–	–
Task status	–	✓	–	–
Number of repairs	–	–	✓	–
Records	34,158	20,834	9,693	3,177
Database maintainer	CCC	SCIRT	SCIRT, CCC	SCIRT

The CCTV inspection database summarizes the physical damage to the Christchurch sewerage pipes. These data were collected by a damage assessment team assigned by SCIRT, equipped with a suite of cleaning jets, suction trucks, and CCTV systems. By January 2015, CCTV crews had completed inspections of 20,834 gravity sewer pipes. The database did not include all the earthquake-damaged pipes, but a much higher proportion of these pipes were damaged than one would expect to find in the non-assessed pipes. As the damage assessment has proceeded, more pipes have been inspected and logged into the damage database. Of the 20,834 pipes assessed, 13,784 pipes were labelled as 'damaged' because they had at least one fault, with the remainder (7,050) being assessed as 'undamaged'. Most of the inspections of pipes with damage were able to run CCTV the whole length of the pipe, counting the total faults. Of all CCTV investigations, 725 (included in the 13,784 pipes) were abandoned in the middle of the survey because of either high wastewater flow or inaccessibility associated with crushed pipe walls. In severely damaged areas, up to 10% of pipes had only a partial survey because the CCTV survey had to be abandoned. For these 725 partial surveys, the number of faults per meter of pipe surveyed has been calculated for this work, and this factor was applied over the whole length of the pipe to give an estimate of the total number of faults for that pipe. The number of faults for the 13,784 damaged pipes varied from 1 to 128, with a mean of 11.3 faults per damaged pipe.

The combined completed repair database combines 9,693 records in relation to the sewer repairs conducted by SCIRT rebuild contractors and the pipes repaired by CCC sewer maintenance teams as part of business-as-usual rehabilitation program. Because many pipes did not have CCTV inspection, this thesis cannot address the issue of exactly how many sewer pipe defects resulted from the earthquake. Therefore, it is difficult to determine whether the conducted repairs in Christchurch are earthquake-triggered. In this thesis, all repairs carried out after the February event are assumed as post-earthquake restoration and are analysed. In the Canterbury recovery, a repair operation is defined as a repair of a pipe for less than its full length and any pipe segment replaced with be less than 6 m in length. This database comprises pipe attributes such as diameter and material and the number of repairs that had taken place on each pipe. Aligning with the IRTSG (CCC, 2012), most of the recorded pipes in this database sustained fewer than six repairs per 90 m of pipe length.

The completed renewal database documents the 3177 new pipes that are installed after the February earthquake to replace the damaged sewer pipelines. A renewal operation in the Canterbury recovery refers to the relining of a pipe for the full length between manholes or replacement with new materials for 6 m or longer, following new design and construction specifications. The renewal operations have been conducted using new PVC (150 to 375mm diameter) or RCRR (450 to 600mm diameter) pipe. The term ‘renewal’ is used instead of ‘replacement’ to clarify that any new pipe will not be a simple exchange and instead will be selected and installed based on revised design and construction rules.

The four databases will be further processed and analysed for evaluating the appropriateness and effectiveness of observational data as physical damage measurements, developing fragility functions for sewer pipelines (Chapter 6), and for presenting a statistical restoration method for estimating sewer restoration duration after earthquakes (Chapter 8).

5.4.2 Seismic hazard parameters used in the research

Among all seismic events that occurred during the CES in 2010-2011, the February quake caused the most severe damage to buildings and infrastructure in Christchurch (Cubrinovski et al., 2011). Therefore, this quake is considered for developing decision support framework for post-earthquake restoration of sewerage systems. The PGV values were obtained from U.S. Geological Survey (USGS) website (Figure 5.2). These values were recorded from around 50 strong motion stations in the Christchurch and Lyttelton area (Cubrinovski et al., 2011a).

The Liquefaction Resistance Index map (LRI; Cubrinovski et al., 2011b) is utilized to partition the physical damage and repair operations in each liquefaction zone (Figure 5.3). The map was produced by use of extensive field mapping conducted by professional geotechnical engineers after the February Earthquake. The average lateral displacement and ground settlement estimates from the map were combined using vector addition to create PGD values for each region of the map. LRI zone 0 refers to areas suffering the most severe damage to the ground surface with estimated ground settlement greater than 500 mm and lateral spreading in excess of 400 mm. LRI zone 4 areas experienced the least ground deformation (less than 20 mm) after the CES. The no observed liquefaction zone is labelled as No Liquefaction Observation (NLO).

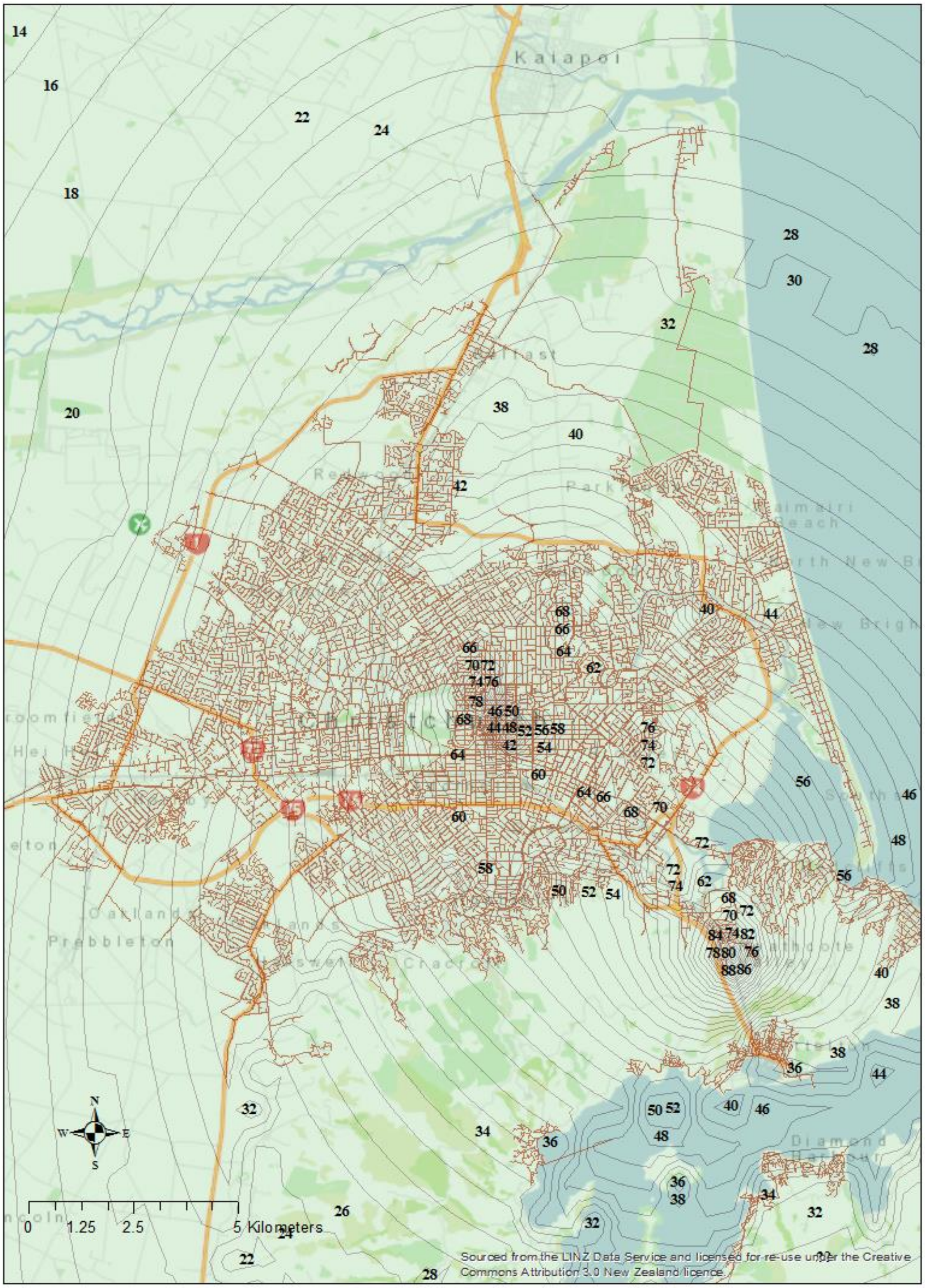
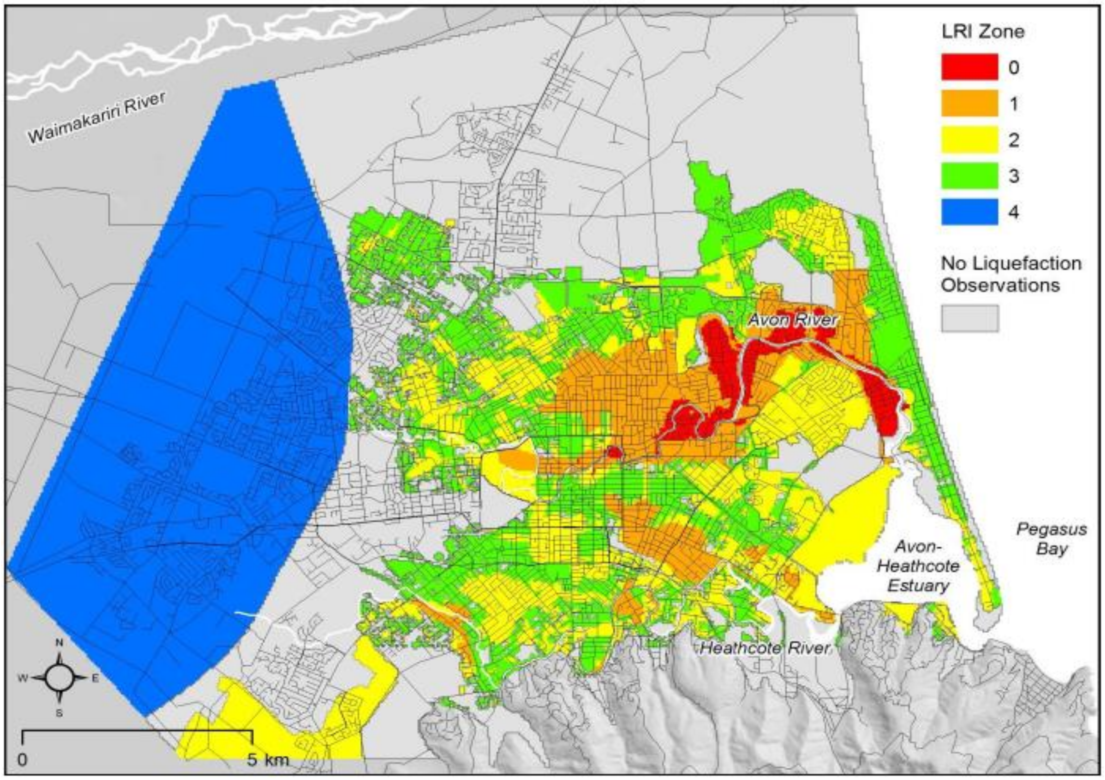


Figure 5.2 The CSN and the PGV values (cm/s) of the February earthquake, reproduced from data published by the USGS (2010)



(a)

	Zone	Equivalent CRR (at water table)	Representative LRI (at water table)	Estimated Ground Settlement (mm)	Estimated Lateral Displacement (relative; transient) (mm)	Equivalent ground strains & thickness of liquefied layer
	0	< 0.065	-	> 500	> 400	$\varepsilon_v > 5\%$, $\gamma > 4\%$, $H_L = 5-10$ m
	1	0.065 - 0.11	0.065	250 - 500	200 - 400	$\varepsilon_v = 5\%$, $\gamma = 4\%$, $H_L = 5-10$ m
	2	0.11 - 0.16	0.13	50 - 250	40 - 200	$\varepsilon_v = 3\%$, $\gamma = 2\%$, $H_L = 4-8$ m
	3	0.16 - 0.23	0.195	20 - 50	20 - 40	$\varepsilon_v = 1\%$, $\gamma = 1\%$, $H_L = 2-4$ m
	4	> 0.23	0.26	< 20	< 20	$\gamma < 0.5\%$, $H_L = 0$ m
	No Liquefaction Observations					

(b)

Figure 5.3 Liquefaction Resistance Index (LRI Zoning) for Christchurch City: a) observed LRI zones; b) LRI Zones and associated ground deformation (settlements, lateral displacements, and ground strains) (Cubrinovski et al., 2011)

5.5 Chapter summary

In answer to the Objective 4 of the thesis (Section 1.2), this chapter detailed the information requirements for making decisions on sewerage system recovery post-earthquake and proposed a framework for supporting the decision making process in the move towards an effective and informed reinstatement of sewerage systems after earthquakes. In particular, this chapter demonstrated the roles and relationships of the three models (PDM, FIM, and PRM) that form the framework. The three modules of the decision support framework were briefly introduced herein and will be further described in the Chapters 6, 7, and 8, respectively.

CHAPTER 6

PHYSICAL DAMAGE MODULE: FRAGILITY MATRICES AND FUNCTIONS OF SEWERAGE PIPELINES

6.1 Introduction

This chapter presents the physical damage module embedded in the decision support framework for restoring sewerage systems post-earthquake. The module aims to predict earthquake-induced physical damage to sewer pipelines by use of simplified (i.e., fragility matrices) and advanced assessment methods (i.e., fragility functions) developed for sewer pipelines.

In Section 6.2 the four databases regarding the CSS are analysed. Section 6.3 presents a fragility matrix developed based on the field observations on the performance of the CSS. The fragility functions of sewer gravity and pressure pipelines with respect to six pipe materials in five liquefaction zones are proposed for advanced fragility assessment in Section 6.4. The developed fragility curves for sewer pressure pipes are compared with the ones designed for water supply pipelines available from the literature in Section 6.5.

This chapter is based on the following journal and peer-reviewed conference papers:

Liu, M., Milke, M., Heiler, D. and Giovinazzi, S. Post-earthquake decision-making on sewer recovery and the roles of damage and repair data. *Journal of Infrastructure Systems* (in review).

Liu, M., Giovinazzi, S. and Lee, P. (2015). Seismic fragility functions for sewerage pipelines. America Society of Civil Engineering: Pipelines Conference 2015, 23-26 August, Baltimore (MD), USA.

Giovinazzi, S., Black, J. R., Milke, M. … and Liu, M. (2015). Identifying Seismic Vulnerability Factors for Wastewater Pipelines after the Canterbury (NZ) Earthquake Sequence 2010-2011. Pipelines Conference 2015, 23-26 August, Baltimore (MD), USA.

6.2 Comparative study of the databases on the CSS

6.2.1 Analysis of the CCTV inspection database

The CCTV inspection database contains the information relating to the damaged sewer pipes inspected by use of CCTV cameras. In this thesis, a pipe refers to a single pipe section or multiple pipe sections jointed together in a straight line. Each pipe in the database had all segments of the same pipe material and had been installed at the same time. In view of the wide range of pipe lengths, a fault ratio of each pipe was calculated by dividing the number of faults by the pipe length. In line with the CCC repair specification, the fault ratio is multiplied by 90 to give the average faults per 90 m. For pipes in each pipe length category (20 m interval), average faults per 90m were computed and plotted in Figure 6.1, compared with the total length of pipes in this category in the CSN inventory database.

The average faults per 90 m increases along with the length of pipe, reaching a peak at 21 faults/90 m at pipe length between 101-120 m. Pipes between 101-120 m long have the highest average faults but a fairly low total length. A general decrease in faults per meter was found when pipes are longer than 120 m. The number of sewer pipes drops dramatically in the long pipe range.

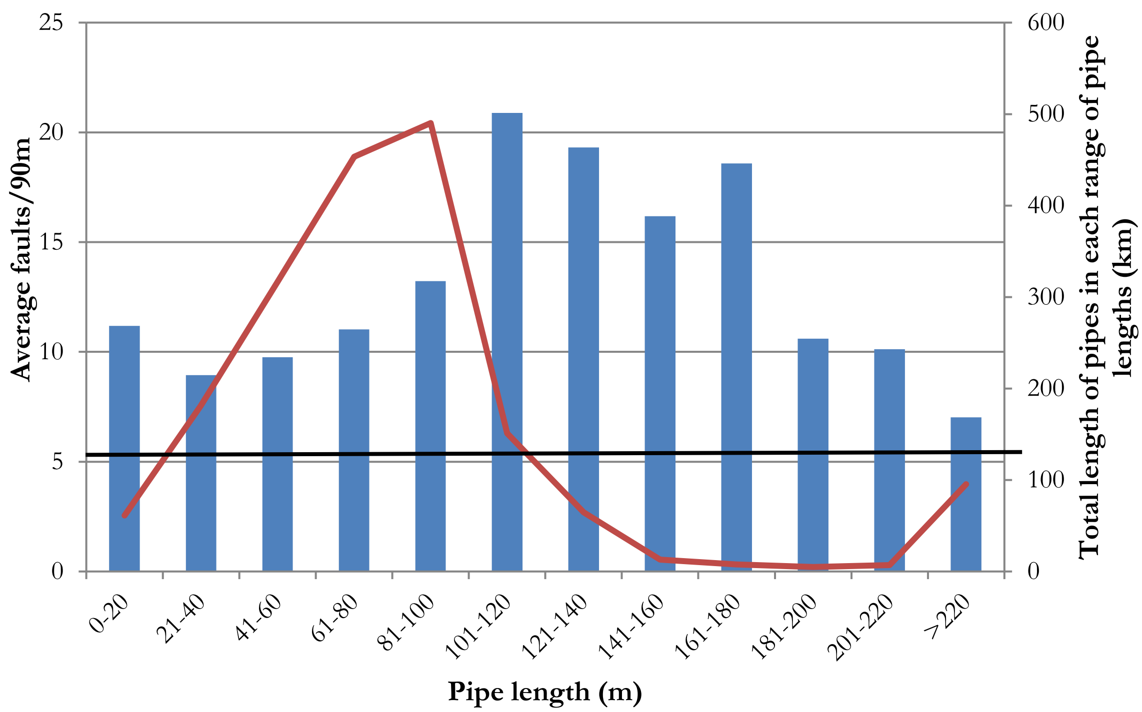


Figure 6.1 Average faults on the damaged pipes (bars) and total length of pipes in that range of lengths in the network (line) according to pipe length. Black horizontal line in the figure is the CCC maximum repair guideline of six faults/90 m.

The results highlight a few key points that could be of value to others facing decisions related to sewer recovery after earthquakes. First, a large number of pipes had far more faults than the critical rate of six faults/90 m used as a decision discriminator between repair and renewal operation recommendations. This indicates that, even for longer pipes, it has proved more economical in many cases in Christchurch to renew a pipe rather than repair it. The number of faults per 90 m of pipe drops off only when the pipe length exceeds 180 m, but even here the average rate is still higher than the critical rate.

Second, the numbers of faults per pipe were very high after thorough assessment by CCTV. For pipes of 161-180 m in length, there was an average of 31.5 faults/pipe, when for that length of pipe it was uneconomical to repair instead of renew once there were over 11 or 12 faults found. In view of the high cost of CCTV assessment (e.g., assessor training, data review and entry), a specification has been applied in later parts of the Christchurch rebuild that instructs operators to ignore small and medium defects (see Table 1) when ten or more large defects have been identified (CCC, 2014). This indicates that, in future, organizations may wish to consider methods to reduce the cost of CCTV inspections needed to reach a decision to repair or renew. For example, CCTV guidance could be devised to determine a maximum number of faults that would need to be found prior to abandoning a CCTV survey and allow a peremptory decision of renewal rather than repair.

Third, the data show that the average number of faults per pipe does not decrease in inverse proportion to pipe length. Because of this, it is clear that a decision criterion related to repair/renewal should not be based solely on the number of faults with no consideration for pipe length.

It is important to note that this analysis has not considered the important effects that pipe material, diameter, ground conditions, or method of installation might have. Because many pipes did not have a CCTV inspection, this thesis cannot address the issue of exactly how many sewer pipe defects resulted from the earthquake.

6.2.2 Analysis of the combined completed repair and renewal databases

The completed repair database combines the repair projects conducted by SCIRT's contractors and CCC maintenance teams and excludes the records of renewed pipes. It comprises such pipe attributes as diameter and material, and, particularly, the number of repairs that had taken place on each pipe. Aligning with the IRTSG (CCC, 2012), most of the recorded pipes in this database sustained fewer than six repairs per 90 m of pipe length.

Average repairs/90 m of repaired pipes are plotted according to the length of pipes in Figure 6.2. Pipes with a length of 21-40 m have the highest average repairs per 90 meters, with a steady decrease along with an increase of pipe length. Most of the pipe length categories are under the critical rate of six repairs/90 m, except for pipes with length between 21 -80 m. This is due to the fact that short pipes have more joints per meter of pipe length, and because joint failures (e.g. joint separation and joint crushing) are one of the most common defects in the damaged wastewater pipelines observed in Christchurch as a result of the Canterbury earthquakes (Zare et al., 2011). It is not practical to renew a whole pipe just because of joint failures. Therefore, short pipes (i.e. pipes shorter than 90 m) have had high average repairs per 90 m.

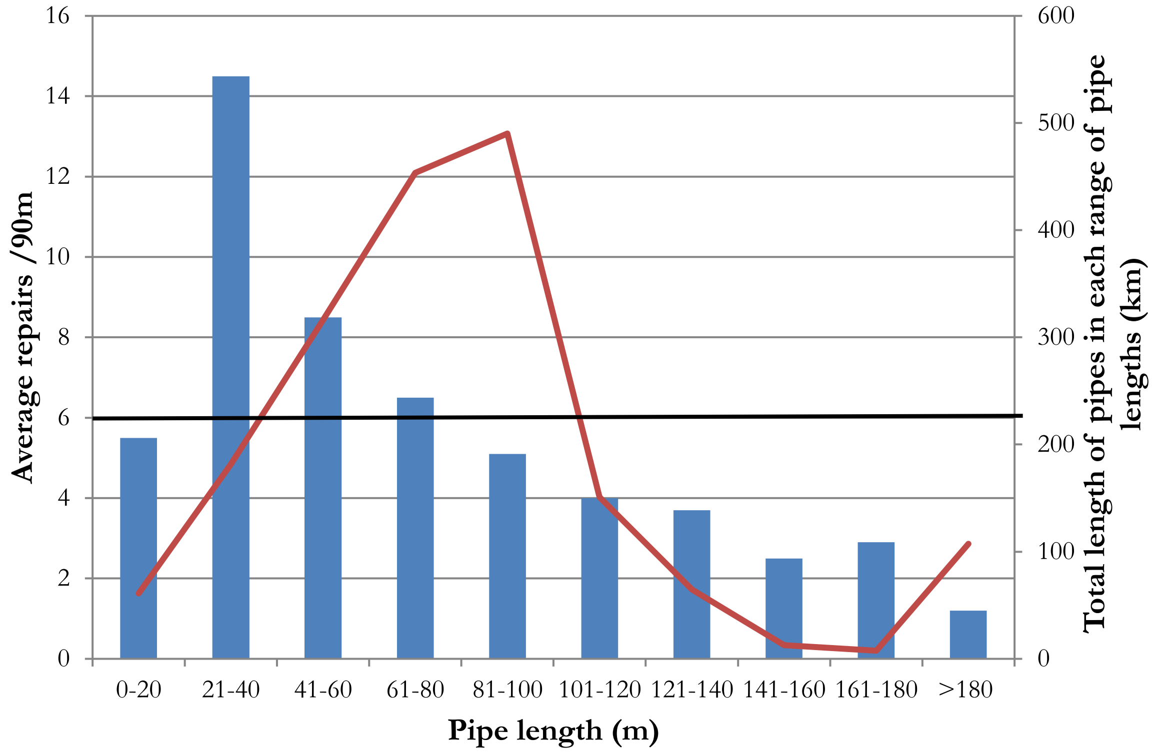


Figure 6.2 Average repairs on the repaired pipes (bars) and total length of pipes in that range of lengths in the network (line) according to pipe length. The critical rate of six repairs per 90m is shown in black.

The relationship between average repairs per 90 m and pipe diameters is plotted in Figure 6.3. The analysis shows that small diameter pipes (<450 mm) have high repair rates; however, large diameter pipes transferring high volume of wastewater have low repair rates. In general, large diameter pipes are relatively more important in the network as they are serving more people. Pipe diameter, as a surrogate for pipe criticality, has been accounted for when a pipe recovery recommendation has been made (SCIRT, 2013). As a result, a number of large diameter pipes with fewer faults than the critical rate have been classified as renewal because of criticality.

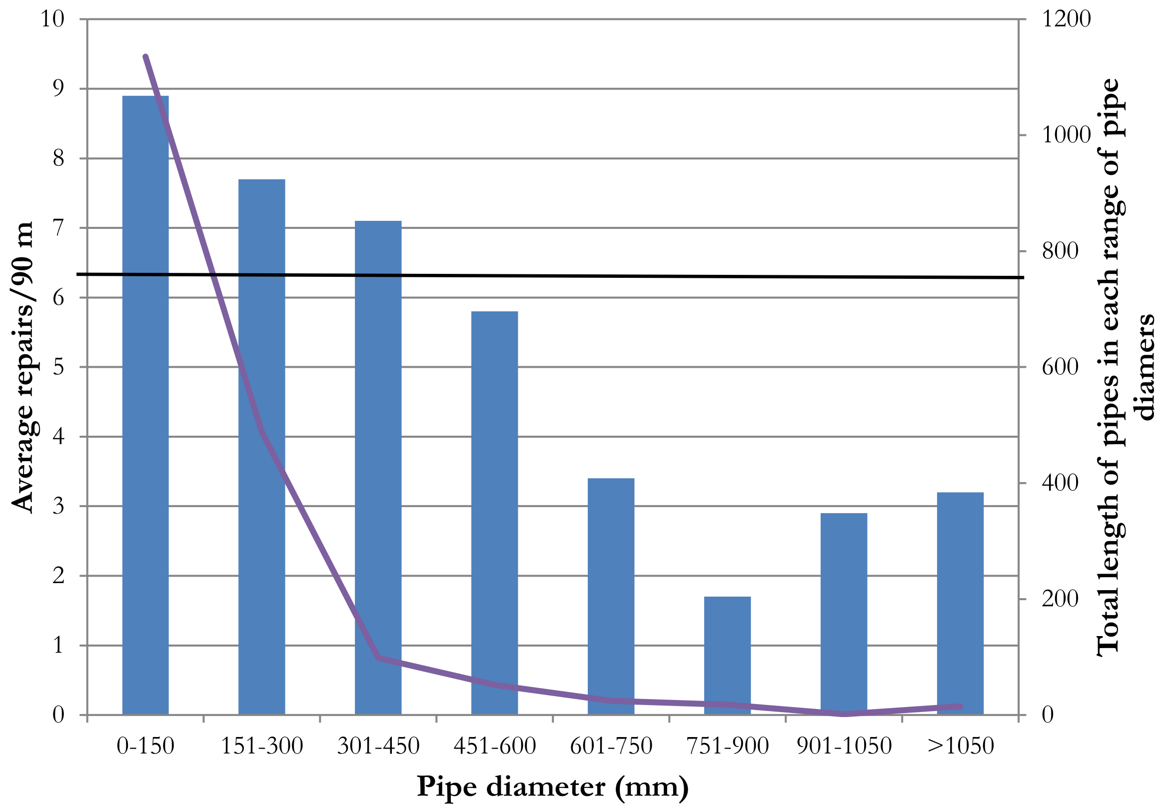


Figure 6.3 Average repairs on the repaired pipes (bars) and total length of pipes in that range of diameter in the network (line) according to pipe diameter.

The renewal database was formed with records of the sewer assets that were renewed after the February earthquake in 2011 up until 21 January 2015. It contains pertinent attributes of 3177 newly-installed assets in accordance with the attribute categories of the CSN inventory database.

Table 6.1 represents the overlap between the repair, renewal and CCTV inspection databases. Discrepancies between the recommended action results and actual repairs as well as actual renewals were found. For instance, 257 pipes were advised no recovery action but have been repaired. 62 pipes that were initially suggested as "no action" were renewed.

Table 6.1 Breakdown of the overlap of pipes between repair, renewal and CCTV inspection databases

Category		Combined completed repair database	Combined completed renewal database	Others*	Total
CCTV inspection database	Action	1540	38	11760	13338
	No action	257	62	6452	6771
	Abandoned survey	209	2	514	725
Pipe profilometer		756	2	1706	2464
Manhole level survey		6931	3073	10	10014
Total		9693	3177	20442	33312

*Others include: 1) no action; 2) field work not complete; and 3) work completed but not yet entered into database.

The interpretation of the datasets is challenging because of the wide variety of pipe types, construction details, and ground conditions in Christchurch. Although a fuller analysis will be possible when repairs and renewals are complete, it will be valuable to at least indicate now the common decision outcomes.

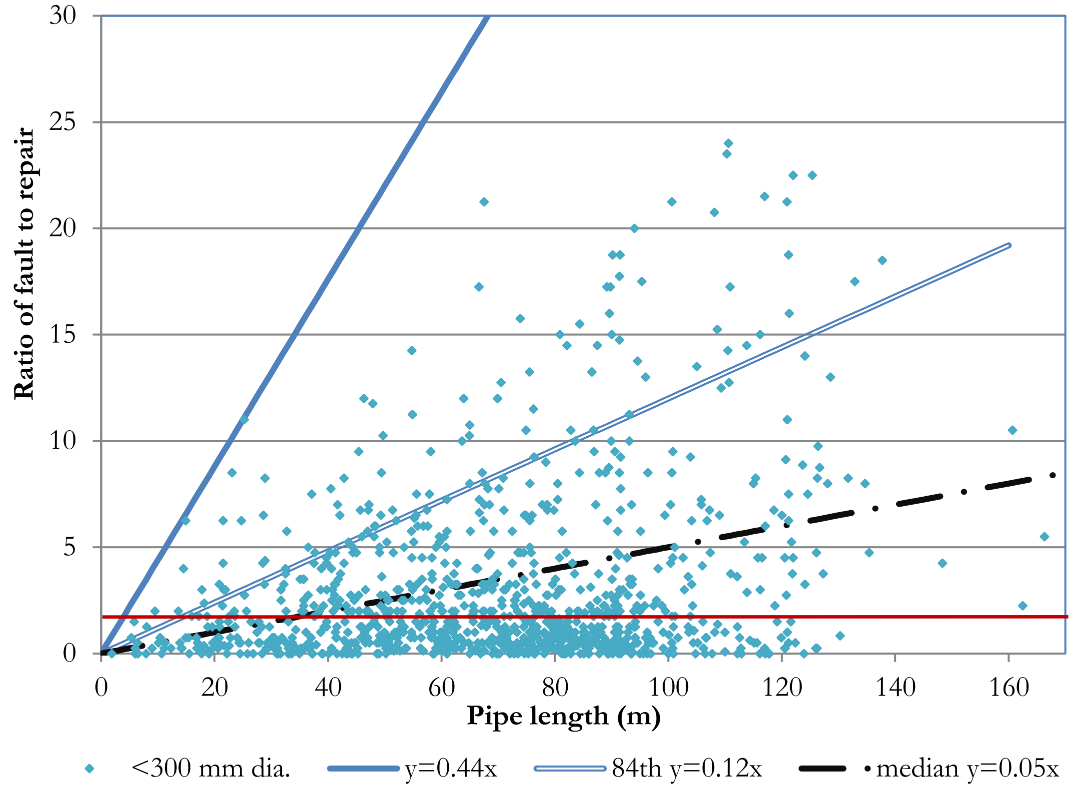
Decisions on repair or renewal activities were not made solely depending on the actual physical damage to sewer pipelines. Pipeline attributes such as buried depth and ground condition as well as pipe criticality (represented roughly as diameter) have been taken into account in recovery decision-making, normally together with their function mechanisms (gravity/pressure). Furthermore, pipe location and the associated future seismic intensity play an indispensable role in the consideration of reinstatement of sewer pipes, especially for those that are situated in liquefaction-prone areas.

An example can be found on one gravity trunk sewer with a diameter of 600 mm near the Avon River. This pipe suffered four minor to moderate faults but was replaced by a more earthquake-resistant PVC pipe and not repaired. This is because it plays an important role in transferring a large volume of sewage and lies in liquefiable soil. This shows that the catchment-wide decisions on rebuild operations involve not only physical damage to pipes but such pipe attributes as significance and location. In conclusion, when making decisions on recovery actions, apart from the damage itself, pipe length, ground condition, buried depth and pipe criticality play influential roles. Hence, the use of repair or renewal data to estimate damage in future earthquakes, or even to estimate repair/renewal, will have severe limitations.

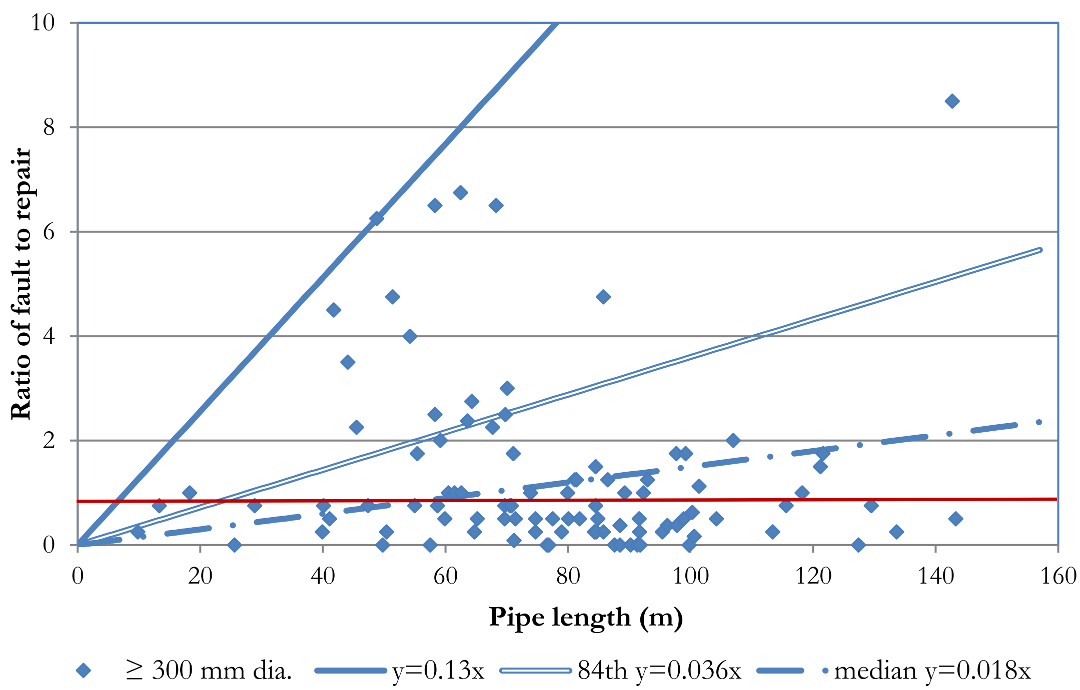
6.2.3 Analysis of the overlap of pipes in the CCTV inspection and completed repair databases

There are 1540 pipes that are in both the CCTV inspection database and the combined completed repair database. They have been inspected by means of CCTV, repaired by construction contractors and then uploaded into the repair database.

The ratios of recorded faults and repairs undertaken on each pipe were computed and are plotted in Figure 6.4a for pipes with a diameter of < 300 mm (1405 pipes) and in Figure 6.4b for diameter ≥ 300 mm pipes (135 pipes), respectively. The median and 84 percentile of the two sub-datasets of pipes are also illustrated in both figures. The faults are recorded in the CCTV inspection database and it is very common to find multiple faults on one pipe.



a)



b)

Figure 6.4 Ratios of fault to repair of pipes: (a) diameters less than 300 mm; (b) diameters of 300 mm and greater vs. pipe length and the ratio of one (horizontal line).

Recall that some earthquake-induced defects are not included as faults, and not all faults are repaired. As a result, the number of repairs is often fewer than the recorded faults on individual pipes, which makes the fault-repair ratios greater than one. The minimum repair on each pipe is one. However, exceptional cases where the number of repairs is greater than the recorded faults exist. Any new faults that are caused by following aftershocks after the last CCTV inspection will not be recorded but could be repaired. This led to a few cases where the number of completed repairs for pipes is more than faults noted in the database.

In Figure 6.4, there seems to be a general tendency for the ratio to increase with pipe length. To help see how this trend varies, the median, and 84th percentile values for the rate are shown. These trends vary with pipe diameter and so separate plots and separate rates of changes are displayed. The red line illustrates where the number of faults detected equals the number of repairs undertaken. Take small diameter pipes (dia. < 300 mm) with a length of 90 m as an example. In accordance with the relationship shown in Figure 7, 50 % of pipes with a length of 90 m can be found with a fault-repair ratio below 4.5 and 84 % of them have fault-repair ratios below 10.8. The maximum ratio of fault over repair is 39.6. If 30 faults were detected on a 90 m pipe, the probability that it requires approximately seven repairs is 50 %, and 84 % probability that at least three repairs are needed. The least estimated repair is one for this pipe.

In contrast to the seismic response of small diameter pipes, sewer trunk pipelines (diameter ≥ 300 mm) have relatively low fault-repair ratios. It is also noted that there are some 40 m to 70 m long pipes where the fault-repair ratios are as high as around 6. The analysis shows that sewer trunk pipelines (dia. ≥ 300 mm) have lower fault-repair ratios than small diameter pipes. The underlying reason could be the earthquake resistance of larger diameter pipes and/or pipe attributes (e.g. material and age). However, a justification is not provided in this thesis but needs further investigation.

O'Rourke et al. (1998) and Toprak (1998) conclude that peak ground velocity (PGV) correlates well with the seismic response of underground pipelines. Layers of the Christchurch sewer pipeline inventory, the CCTV inspection data and repaired pipe data were jointly superimposed in a Geographical Information System in order to assign PGV values of the February earthquake for individual pipes. The correlation of fault-repair ratios and PGV values for the 1540 pipes that have been both repaired and had faults found through CCTV are plotted in Figure 6.5.

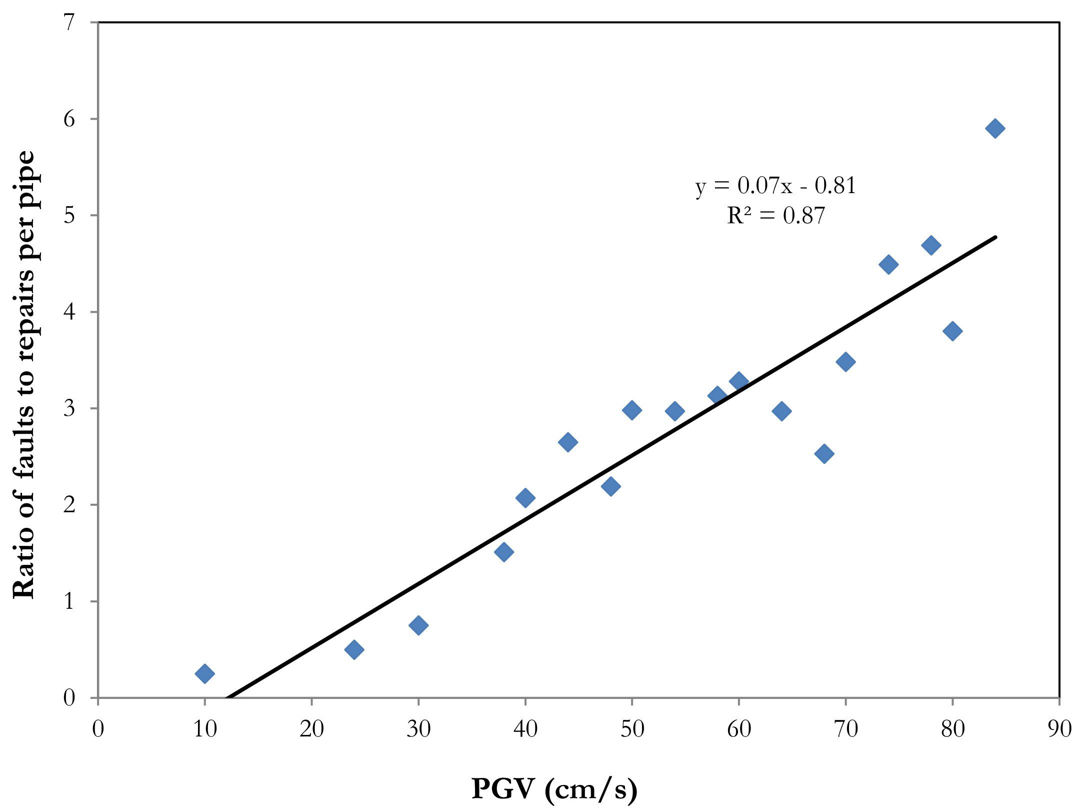


Figure 6.5 Correlation of average fault/repair ratios at each PGV value for the 1540 pipes that have been both repaired and had faults found through CCTV.

The fault-repair ratios increase linearly along with the PGV values. This is because stronger ground motions trigger more physical faults on pipes but the number of repairs does not necessarily increase. This leads to a continuous increase in the ratios.

This fault-repair equation as a function of PGV can be used to estimate either the number of repairs to be expected once gaining the number of detected faults from damage inspection (i.e., CCTV inspection), or number of physical faults if the number of repair operations is obtained when fault information is unknown, provided a certain level of ground motions. For instance, a gravity pipe situated in PGV of 60 cm/s zone was detected with 10 faults. Based on the function, the fault/repair ratio is 3.4 and the anticipated repairs are approximately 3. In many cases, damage inspection has not been conducted or not applicable; in these situations, this equation could help estimate the number of earthquake-induced faults.

6.3 A fragility matrix of sewerage pipelines

Fragility assessment serves as a pivotal approach for predicting potential damage to infrastructure. Simplified fragility assessment could be deployed for preliminary seismic vulnerability evaluation (e.g., screening and ranking) by use of fragility factors or matrices. In this Section, a seismic fragility matrix is developed through field investigations, in an effort to identify seismic fragility of sewerage pipelines based on pipe materials when accurate information regarding seismic hazards and pipe constructive characteristics is limited.

6.3.1 Observed seismic vulnerability from field investigation

The seismic behaviour of the different pipe materials together with the joint types during the CES were investigated and collected in hopes of eliciting underlying causes of pipe physical damage. Due to the extensive liquefaction and associated lateral spreading incurred in Christchurch, the focus was mainly on the buried pipelines in liquefaction areas, characterised by the LRI map (Cubrinovski et al., 2011).

Three contributors are identified to poor performance of sewer pipes in liquefaction areas in Christchurch, including:

- Pipe characteristics;
- Manufacturing quality; and
- Deterioration issues.

The pipe characteristics that affect the seismic vulnerability of sewer pipes are, among others, pipe material, joint type, and diameter. Brittle pipes with rigid joints are found highly vulnerable with the greatest number of earthquake-induced failures (Black, 2012). Common brittle pipe materials, such as earthenware, AC, and CI pipes, are less flexible and more susceptible than ductile material (e.g., PVC and steel) when facing strong ground shaking and/or differential ground settlement. During the Canterbury earthquakes, brittle pipes suffered a range of defects, for example, circumferential cracking and longitudinal splits (Figure 6.6a). Rigid joints are stiff and designed to resist connection movement. Pipes with rigid joints are particularly vulnerable to compression and tension forces as well as joint rotation resulting in joint pull-out and re-insertion (Figure 6.6b). In general, pipes with larger diameters (even of brittle materials) are less susceptible to earthquake damage because they have relatively greater beam strength or ability to resist deflection (Black, 2012). In sum, pipe characteristics, in particular, material, diameter, have a direct and significant influence on the seismic vulnerability of sewer pipelines. Therefore, it is of value to conduct a fragility assessment using pipe attributes for categorisation in differentiating the seismic behaviour of sewer pipes. Table 6.2 summarizes the observed seismic vulnerability, for different pipe materials, joint types, and diameters (when such information is available) according to three qualitative vulnerability classes, namely: "high", "medium", and "low".

a)

b)

Figure 6.6 Physical defects on sewer pipes: a) longitudinal split on an AC pipe; b) pipe joint pull-out (Courtesy of Matthew Hughes)

Table 6.2 Observed seismic fragility for wastewater pipes by pipe material, joint type and pipe diameter (adapted from Black, 2012)

Pipe Material	Joint Type	Diameter	Observed fragility
Brick and stone barrels	Lime mortar jointing		High
Ceramic pipes	Mortar		High
Ceramic pipes	Rubber ring		High
Unreinforced concrete pipes	Rubber ring		High
Reinforced concrete pipes (old)	Rigid lead joints		High
Reinforced concrete pipes (old)	Rubber ring	Small	High
Reinforced concrete pipes	Rubber ring	Large	Medium
Cast iron (CI) pipes	Rigid, run-lead joints		High
Cast iron (CI) pipes	Rubber ring		High
Asbestos cement (AC) pipes		≤ 150 mm	High
Asbestos cement (AC) pipes	Rubber ring	> 200 mm	High
Steel	Screwed	≤ 50 mm	High
Steel	Lead joints		High
Steel pipes (concrete lined steel CLS)	Rubber ring joints		Medium
Steel pipes (concrete lined steel CLS)	Full strength welded joints		Low
Glass reinforced plastic (GRP)	Butt and strap joints		Medium
Glass reinforced plastic (GRP)	Rubber ring		Medium
Ductile Iron (DI)	Rubber ring		Medium
Ductile Iron (DI)	Locking rings		Low
Ductile Iron (DI)	Seismic joints		Low
PVC-U – Polyvinylchloride	Solvent Cement Joints		Medium
PVC spigot and socket pipes	Rubber ring joints		Medium
Polyethylene (PE) pipes with structured walls	Rubber ring joints		Medium
PE pipes (first generation-type 5 HDPE resins)	End-load bearing joints		Medium
PE 80B or PE 100 pipes	End-load bearing mechanical joints		Low
PE 80B or PE 100 pipes	Electro-fusion joints		Low

Manufacturing quality plays an important role in the seismic vulnerability of sewer pipes. Deficient manufacturing quality often refers to: 1) poor quality of pipe itself; 2) inappropriate workmanship during transportation, handling, and installation process; and 3) problematic design issues. Any of them or any combination of them could contribute to pipe failures during seismic events. In the Canterbury recovery, many sewer pipes, especially AC pipes, were actually damaged during digger operations undertaken with the aim of pipe renewal (Black, 2012). This led to a large number of broken AC pipes being abandoned and eventually removed.

The third factor that contributes to the seismic fragility of sewer pipelines is the deterioration issue (e.g., corrosion, aging). For conventional pipe materials, such as AC, CI, and steel, the pipes might suffer from a range of deterioration mechanisms that reduce their strength and make them progressively more vulnerable to failure as they deteriorate. Modern corrosion protection methods might delay the onset of corrosion but they must remain effective for the design life of the pipe, usually at least 100 years. The plastics pipes, like PVC and PE do not suffer from corrosion but other mechanisms might affect their vulnerability, including: i) chemical break-down of polymer structure; ii) break-down of stabilizers. In New Zealand, the stabiliser break-down is found in the HDPE and often leads to longitudinal splitting (Black, 2012).

6.3.2 Proposal for a fragility matrix of sewer pipelines

From observations in field and expert judgements, it is confirmed that brittle pipe materials with rigid joints proved to be the most vulnerable. Similarly, as far as the pipe diameter is concerned, the larger the pipes, the less susceptible they seemed to be to the earthquake damage. A performance-based fragility matrix is produced in Figure 6.3 out of the field observations, identifying the fragility of sewer pipes according to three qualitative classes (green=low fragile; yellow= medium fragile; red=high fragile).

Table 6.3 A fragility matrix for sewerage pipes according to liquefaction zones (green=low fragility; yellow= medium fragility; red= high fragility)

	Fragility		
Hazard	**Low**	**Medium**	**High**
LRI 4 and Non-liquefaction zones	UPVC HDPE MDPE AC PVC	CONC EW RCRR CI	
LRI 1, 2, and 3 zones	UPVC PVC	AC HDPE MDPE CI	EW CONC RCRR
LRI 0 zone	PVC	UPVC HDPE	AC CONC EW RCRR CI

The matrix gained from performance-based evidence could be of use in the definition of scorecard approaches and/or vulnerability indexes and/or rapid screening approaches (as the ones widely available for buildings e.g. FEMA 154) specific for buried pipelines.

6.4 Fragility functions for sewerage pipelines

6.4.1 Fragility function formulation

Fragility functions, or fragility curves when presented graphically, are a well-established tool used to assess the seismic risk to infrastructure, including sewerage systems. In this work, the February earthquake is considered and PGV values of this quake are correlated with DR/RR for developing fragility functions. Layers of the PGV map from the February quake, the LRI map and relevant databases regarding the CSN were jointly superimposed in Graphical Information System (GIS) in order to assign PGV values to individual pipes and then formulate fragility functions in five liquefaction zones and one non-liquefaction zone. Both DR (x) and RR (x) are represented as a function of seismic intensity which is PGV in this case. It is assumed that the fragility functions follow a log-normal cumulative distribution in a form of three-parameter functions as Equation 6.1. This Equation was first proposed by Maruyama et al. (2007) to predict the earthquake-induced physical damage to expressway embankments based on the actual damage data after the 2004 Mid-Niigata Earthquake. Subsequently, this equation has been applied to estimate the damage ratios for water distribution pipelines (Maruyama and Yamazaki, 2009) and sewerage system pipes (Nagata and Yamamoto, 2011; Nagata et al. 2011) in the aftermath of earthquakes.

$$R(PGV = x) = C\Phi\left(\frac{\ln x - \lambda}{\zeta}\right) \tag{6.1}$$

where R (x) can be either DR (x) or RR (x), expressing estimated DR/RR values of sewer pipelines given a ground motion of PGV = x, Φ () is the standard normal cumulative distribution function, C, λ and ζ are function parameters to be estimated with the method of maximum likelihood estimation. The usage of the maximum likelihood method instead of the least square method is because the latter can only be applied when the regression residuals have a normal distribution while the former can be adopted in all situations (Myung, 2003). In this analysis, the residuals are tested as not a normal distribution. In the maximum likelihood method, PGV values for each ground motion are assumed independent and the likelihood of the entire data set is the product of the individual likelihoods (Baker, 2014). The fragility function parameters are obtained by maximizing the likelihood equation as Equation 6.2 in the Microsoft Excel Solver.

$$Likelihood(x_i; C, \lambda, \zeta) = C^n \prod_{i=1}^{m} \phi\left(\frac{\ln x_i - \lambda}{\zeta}\right) \tag{6.2}$$

Where $\prod$ denotes a product over i values from 1 to m, n is the total number of ground motions.

6.4.2 Fragility functions of sewer gravity pipelines

The fragility functions in terms of PGV and liquefaction zones are developed by use of maximum likelihood estimation for six main pipe materials of gravity pipelines, namely: AC, CI, CONC, EW, RCRR and PVC & PE. PVC and PE pipelines were combined together as they are all ductile material and PE pipes performed relatively well during earthquakes with little physical damage. Table 6.4 to Table 6.9 show the calculated function parameters for sewer gravity pipes in six pipe materials.

Table 6.4 Parameters of fragility functions of AC sewer gravity pipes

Liquefaction Zone	λ	ζ	C	Constraint: ζ ≥
LRI-0	51.31	6.76	50.64	6.76
LRI-1	49.79	8.24	80.42	8.24
LRI-2	50.42	10.91	73.01	10.91
LRI-3	53.87	12.44	66.24	12.44
LRI-4	57.43	13.57	59.41	13.57
NLO	45.65	11.96	68.47	11.96

Table 6.5 Parameters of fragility functions of CI sewer gravity pipes

Liquefaction Zone	λ	ζ	C	Constraint: ζ ≥
LRI-0	58.6	4.2	41.3	4.2
LRI-1	52.3	9.1	85.6	9.1
LRI-2	45.3	5.9	60.1	5.9
LRI-3	50.1	8.9	55.6	8.9
NLO	43.7	8.4	65.8	8.4

Table 6.6 Parameters of fragility functions of CONC sewer gravity pipes

Liquefaction Zone	λ	ζ	C	Constraint: ζ ≥
LRI-0	41.5	7.12	117.9	7.12
LRI-1	46.78	8.4	167.02	8.4
LRI-2	33.9	8.8	152.4	8.8
LRI-3	36.4	7.1	138.4	7.1
LRI-4	36.45	5.2	103.1	5.2
NLO	32.9	7.8	183.1	7.8

Table 6.7 Parameters of fragility functions of EW sewer gravity pipes

Liquefaction Zone	λ	ζ	C	Constraint: ζ ≥
LRI-0	42.5	7.2	301.5	7.2
LRI-1	44.9	5.4	269.4	5.4
LRI-2	34.5	6.7	421.7	6.7
LRI-3	41.23	8.12	385.6	8.12
LRI-4	31.5	5.96	351.4	5.96
NLO	37.94	5.4	320.7	5.4

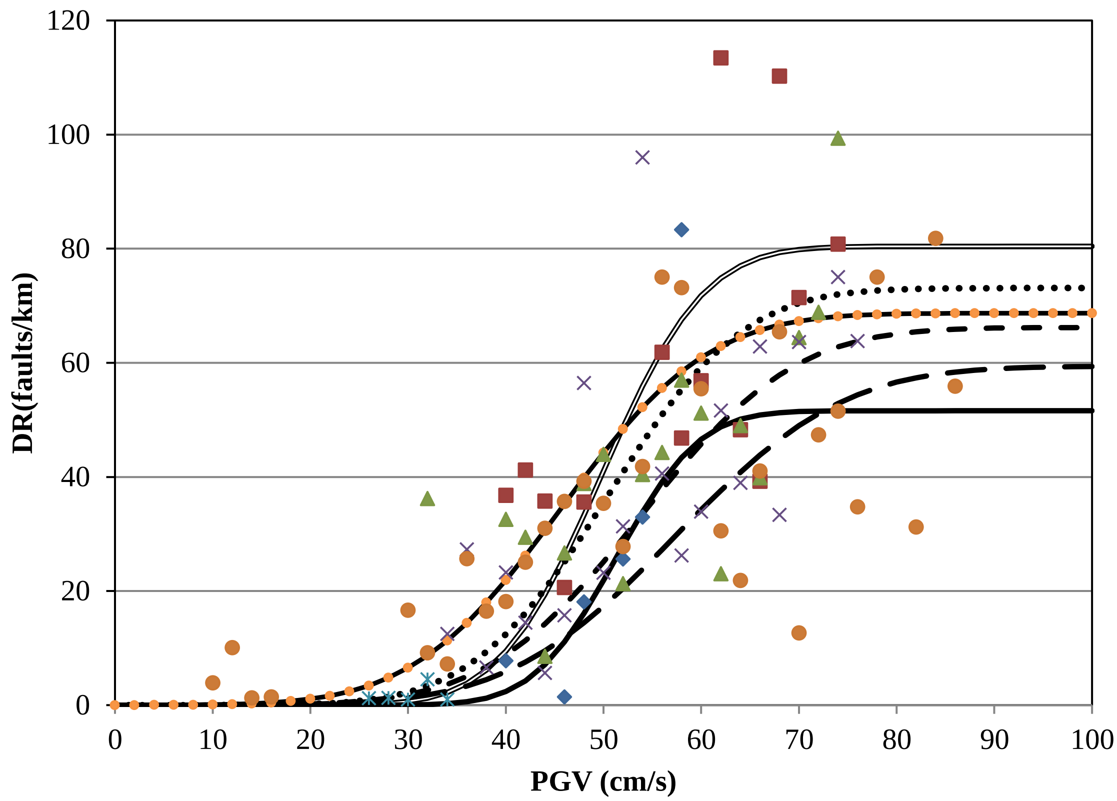
Table 6.8 Parameters of fragility functions of RCRR sewer gravity pipes

Liquefaction Zone	λ	ζ	C	Constraint: ζ ≥
LRI-0	53.9	7.1	67.5	7.1
LRI-1	45.69	12.9	59.4	12.9
LRI-2	34.21	6.2	52.6	6.2
LRI-3	36.25	6.9	45.96	6.9
LRI-4	35.13	8.3	22.7	8.3
NLO	36.42	8.96	78.9	8.96

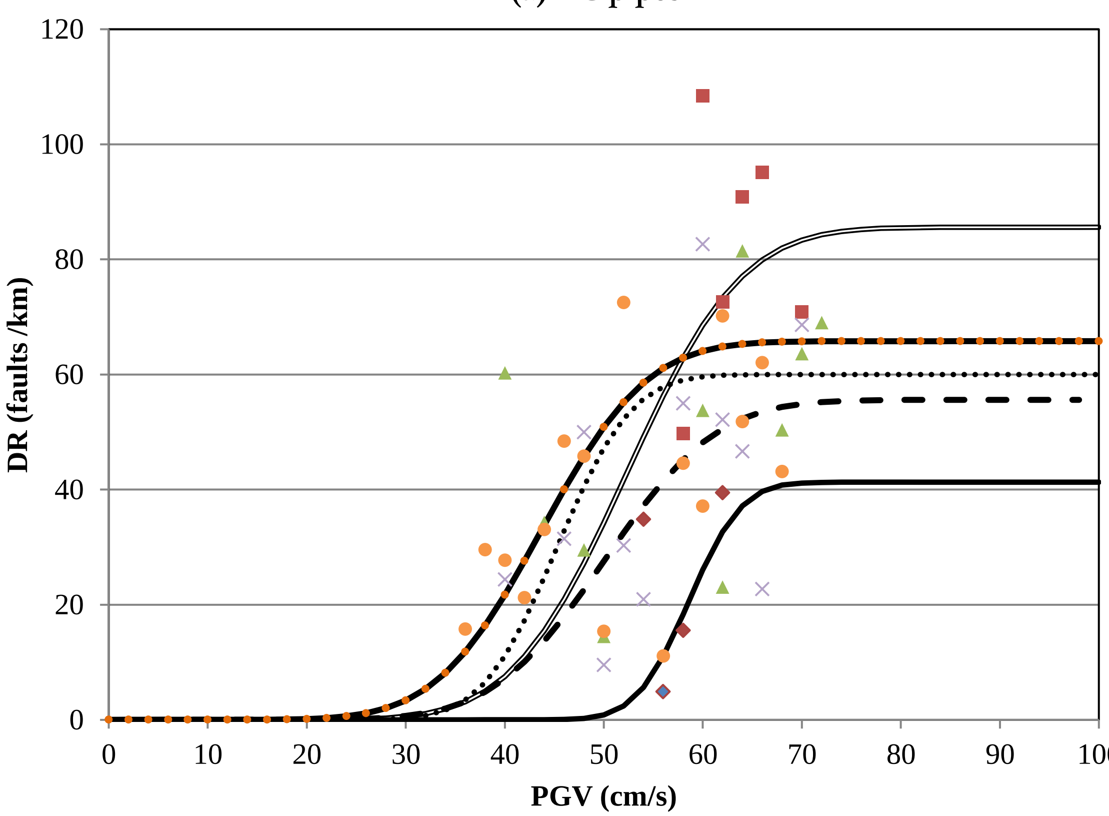
Table 6.9 Parameters of fragility functions of PVC & PE sewer gravity pipes

Liquefaction Zone	λ	ζ	C	Constraint: ζ ≥
LRI-0	51.23	6.2	28.6	6.2
LRI-1	53.02	5.6	50.5	5.6
LRI-2	44.2	5.1	23.6	5.1
LRI-3	46.7	4.8	13.5	4.8
LRI-4	50.83	6.4	9.2	6.4
NLO	12.4	4.3	14.2	4.3

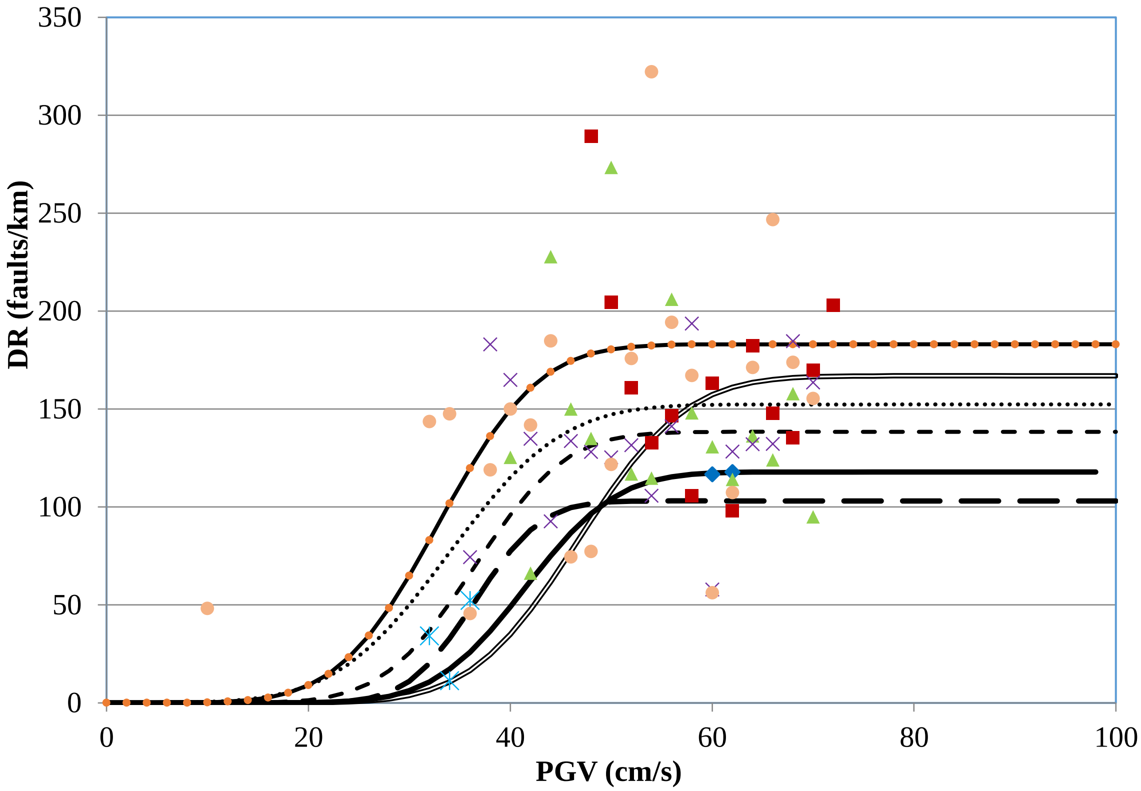
Fragility curves of and the observed damage to the six types of gravity pipelines, namely: AC, CI, CONC, EW, RCRR, and PVC & PE as a function of PGV in five liquefaction zones and one non-liquefaction zone are plotted in Figure 6.7 (a) – (f). The CCTV inspection has not been extensively conducted in LRI-0 zone and thus there are not many detected faults in this area. This is the reason that the pipes in LRI-0 zones do not possess the highest DR. This also explains why the proposed fragility curves of pipes in LRI-1 zone seem irregularly distributed. As for LRI-2 and LRI-3 zones, the fragility curves of all types of pipes show an agreement, as expected, that the severer the observed liquefaction is, the higher DR of pipes is found. No faults on CI pipelines were found in LRI-4 zone although ten CI pipes were functioning in the CSS with a total length of 0.063 km in the zone. In NLO zone where transient ground motion is considered as the only factor, a large amount of physical damage was still observed. CONC and RCRR pipes have the highest damage ratios in NLO zone. It is concluded that damage ratios of sewer pipes in non-liquefaction zones are not necessarily lower than those of liquefaction zones.



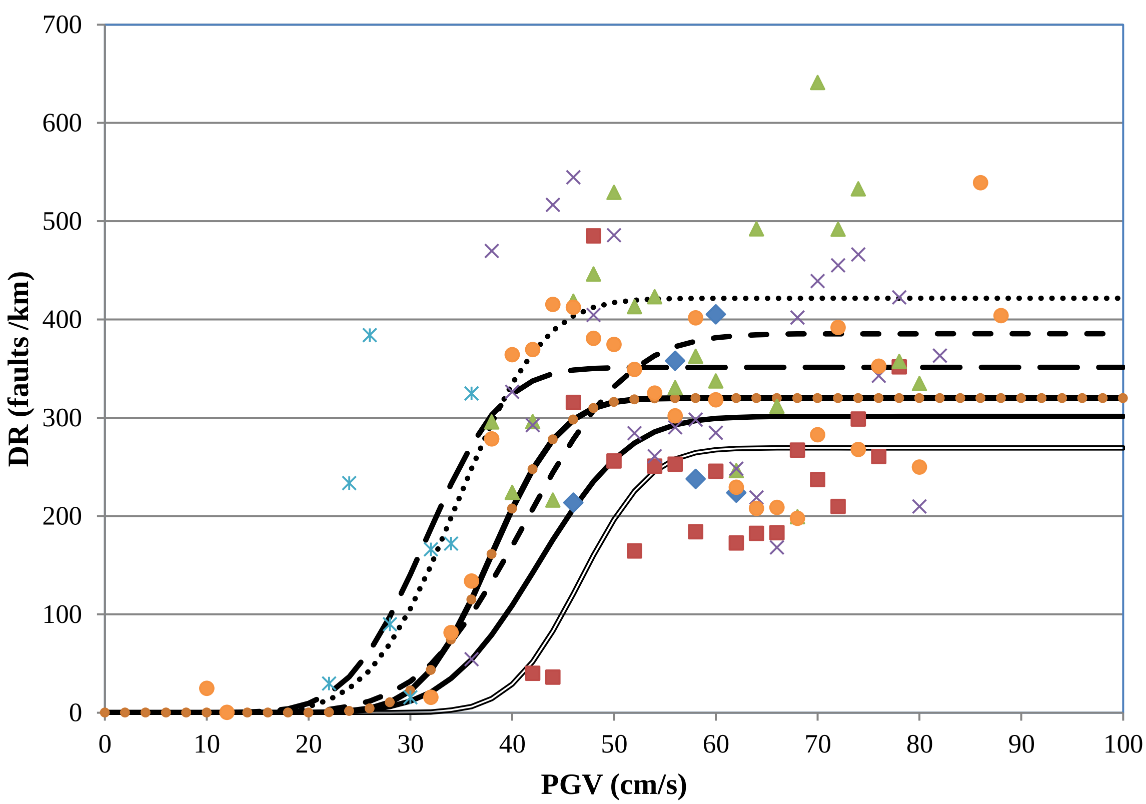
(a) AC pipes



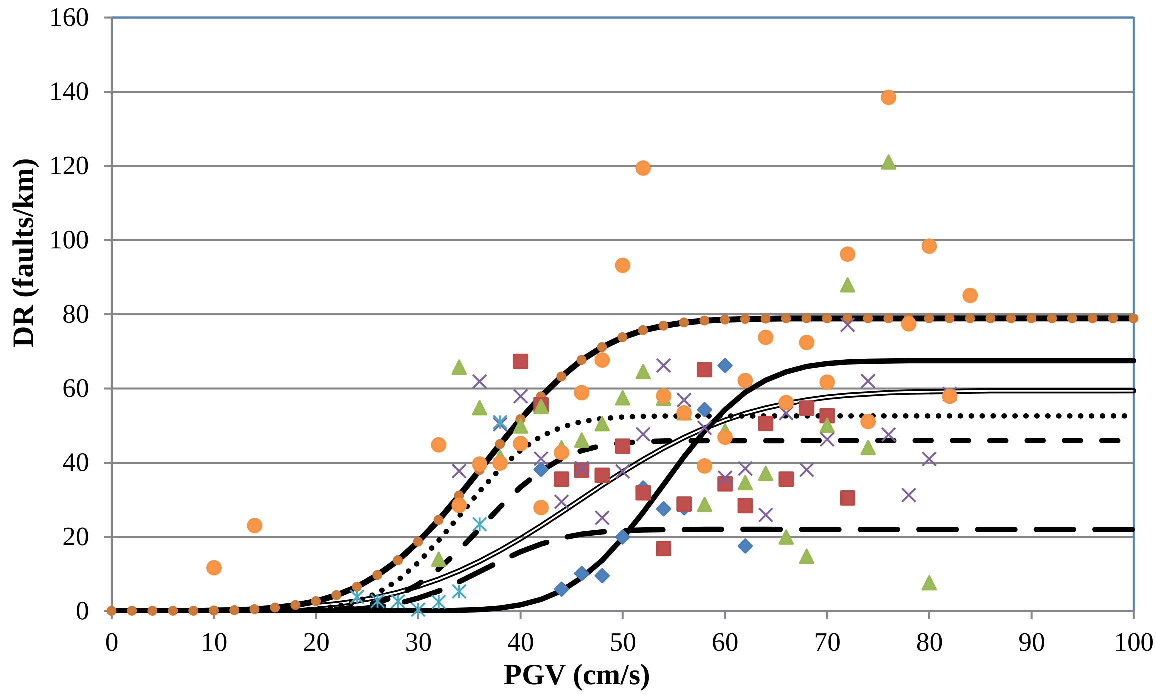
(b) CI pipes



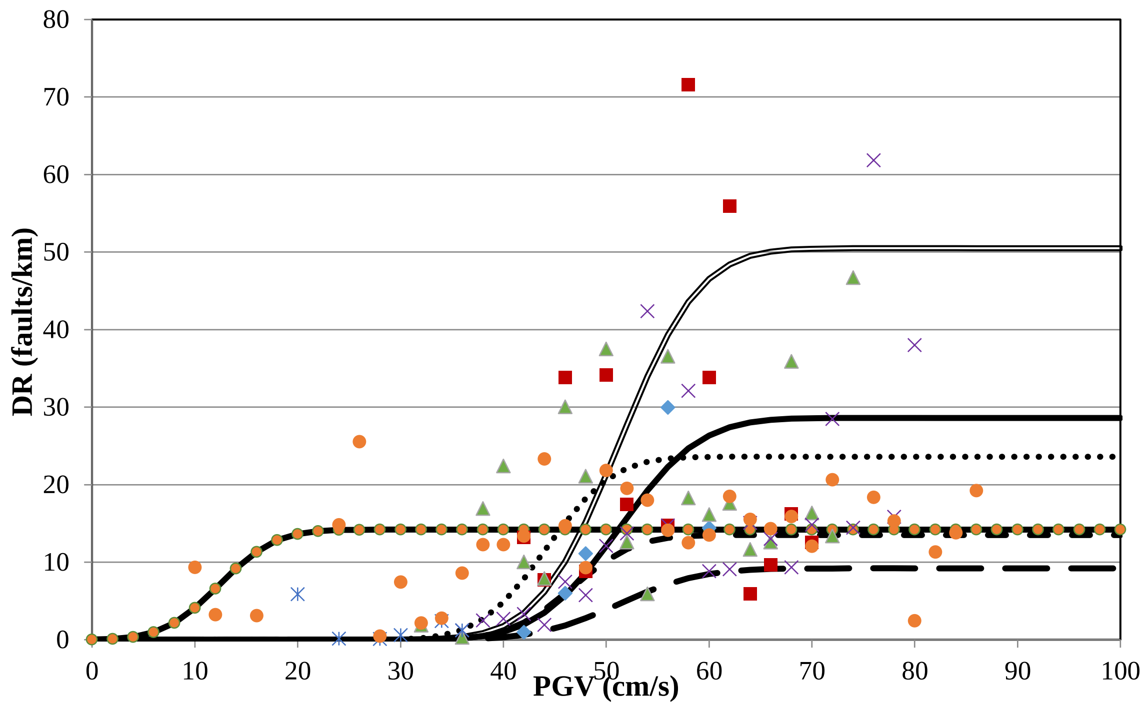
(c) CONC pipes



(d) EW pipes



(e) RCRR pipes



(f) PVC & PE pipes

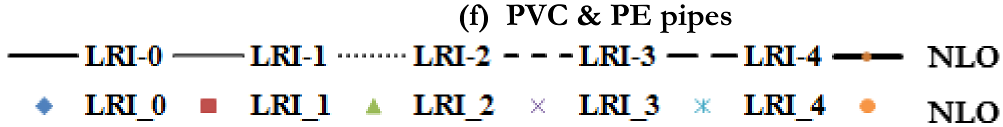


Figure 6.7 Fragility curves and observed damage data for six types of gravity pipes (namely: AC, CI, CONC, EW, RCRR, PVC & PE) as a function of PGV and liquefaction zones

AC pipes and CI pipes behaved similarly during this earthquake event. EW pipes suffered the most severe physical damage to their pipe bodies and the peak damage ratio was found over 400 faults per kilometre in LRI-2 zone. Following EW pipes, CONC pipelines sustained serious earthquake-induced damage, with the damage ratio ranging from 100 faults to 200 faults per km. Although extensive incidents occurred to RCRR pipes, due to the large distribution, their damage ratios are below 100 faults in every kilometre. PVC & PE pipes have the lowest damage ratios among all tested pipes but the greatest damage ratios at the lowest PGVs.

In Figure 6.7, fragility curves of six pipe materials derived for LRI-0 have medium damage ratios and, for AC and CI pipes, have the lowest ones. LRI-0 zone is mostly located in the CBD where a Cordon has been established in view of community safety. Therefore, limited damage inspection has been undertaken in this area.

It can be noted that there are a few points above the developed fragility curves, similar to the findings in the studies by Maruyama and Yamazaki (2009) and Nagata et al. (2011). However, it is fair to say that, for this specific application of this study that looks into rapid information support for decision making on sewer recovery, the focus falls more on pipe functionality. Due to the limited data in high PGV zones, the author assumes that the pipes have lost their functionality in these zones while physical damage may continue occurring. However, the additional damage is relatively minor (Maruyama et al., 2007). For example, the actual damage ratio of an EW pipe at the PGV value of 70 cm/s is 640 faults per km and higher than the estimated damage ratio of 420 faults/km. However, when an EW pipe sustained 420 faults/km that is equivalent to 1 fault on every 2.3 meters, this pipe has lost its functionality. It makes little difference in terms of 1 fault per 2.3 meters or 1.56 meters (640 faults/km). The inherent assumption of this equation is there is a limiting value of PGV at which the DR will not further increase. The author recognises there is a potential limitation within this assumption, that is, the developed fragility functions might be useful up to a certain PGV value. In sum, the fragility curves are developed empirically and asset managers need to take more care when applying the developed fragility curves to predict damage to sewer pipes in the high PGV areas.

6.4.3 Fragility functions of sewer pressure pipelines

As CCTV inspections have been only conducted on sewer gravity pipelines (SGP), there are no recorded faults on sewer pressurized pipelines (SPP). Additionally, the damage to the pressurized pipelines is not systematically investigated and documented by other methods. Therefore, the repair database which contains repair operations undertaken to the SPP is used to develop fragility functions. The fragility functions and associated parameters were generated by the method described above. There were no repair activities undertaken to pressure pipes in LRI-4 zone. Function parameters and fragility curves of the pressure pipes are listed in Table 6.10 and plotted in Figure 6.8.

Table 6.10 Parameters of fragility functions of SPP

Liquefaction zones	λ	ζ	C	Constraints: ζ ≥
LRI-0	50.91	8.73	90.53	8.73
LRI-1	53.29	10.12	81.23	10.12
LRI-2	57.59	7.82	18.61	7.82
LRI-3	48.92	10.92	14.27	10.92
NLO	45.56	10.06	21.93	10.06

The SPP appear to be quite robust in the low PGV range in Christchurch. They start to incur repair operations when PGV values increase up to 40 cm/s and repairs rise steeply afterwards. Unlike the gravity pipes, the SPP in LRI-0 and LRI-1 zones sustained a large number of repairs because their function as connections between PSs are necessary for the whole sewerage system to operate, especially in LRI-0 and LRI-1 zones. Severe ground settlement (> 250 mm) had significant effects on seismic performance of the SPP compared to median ground settlement (20 - 250 mm). The pressure pipes preformed relatively well when solely subject to transient ground motions, with a repair ratio of around 20 repairs per km. In conclusion, the SPP in Christchurch are less vulnerable to lower permanent ground deformation.

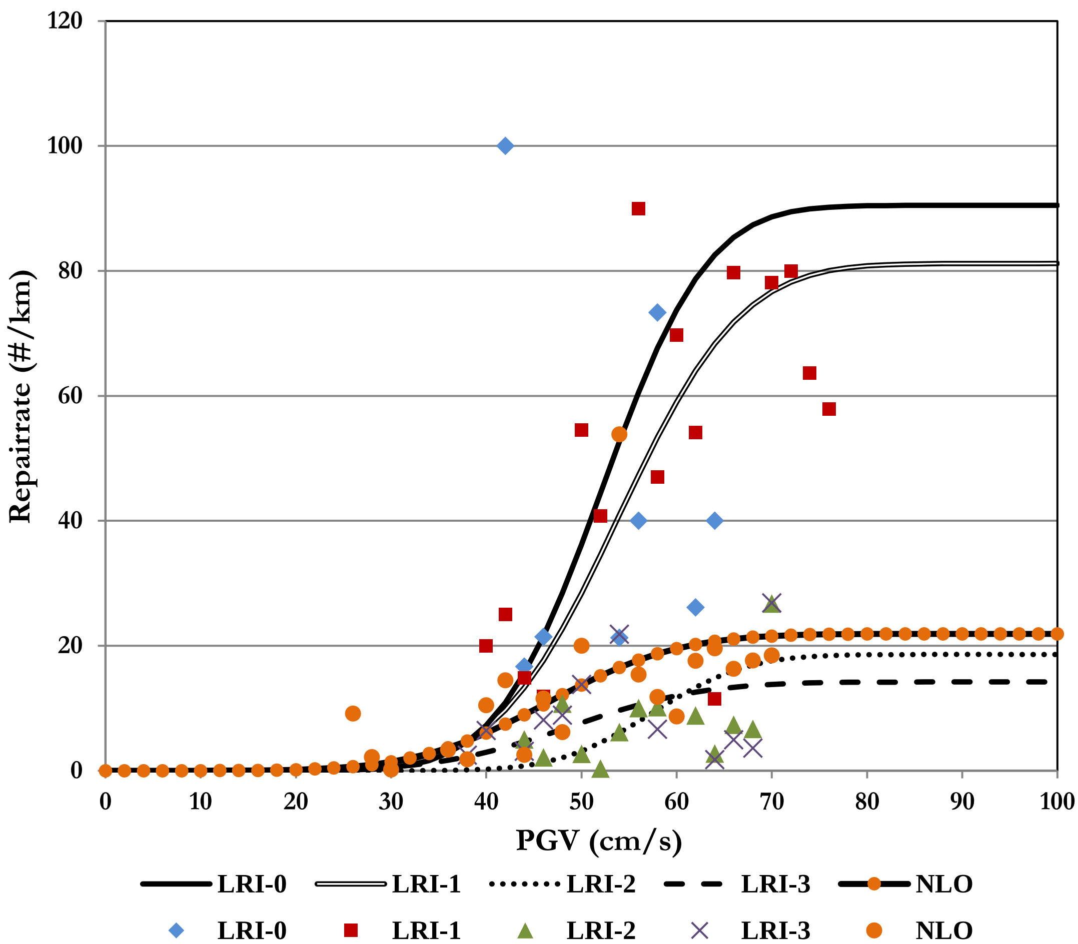


Figure 6.8 Fragility curves and repairs undertaken for the SPP in Christchurch as a function of PGV and of liquefaction zones

6.5 Comparing fragility functions of SPP and of water supply pipelines

In order to examine whether the fragility functions of water-supply pressure pipelines (WPP) can be applied to estimate seismic physical damage to SPP, the proposed fragility functions specifically developed in the last section are compared in Figure 6.9 with existing fragility curves of WPP in the literature. Sewer AC pressure pipes were selected for comparison purpose herein. The author chose k=1 as function coefficient to calculate fragility curve of ALA (2001). HAZUS (NIBS, 2003) and Syner-G (Alexoudi et al., 2010) recommend empirical fragility functions developed by O' Rourke and Ayala (1993) which was illustrated in Figure 6.9. The fragility function developed for AC water-supply pipelines derived from the observed damage data on the Christchurch water supply systems following the CES was utilized as well (O'Rourke et al., 2014).

It is shown that there is a certain level of agreement between the proposed fragility curve of the SPP and existing fragility algorithms designed for the WPP. The existing fragility algorithms of the WPP in the international literature slightly underestimated the repairs undertaken on the AC SPP in Christchurch. After the February earthquake, severe liquefaction and associated lateral spreading occurred near waterways where a number of SPP were installed. This leads to more repairs of the SPP happening to regain the sanitary service.

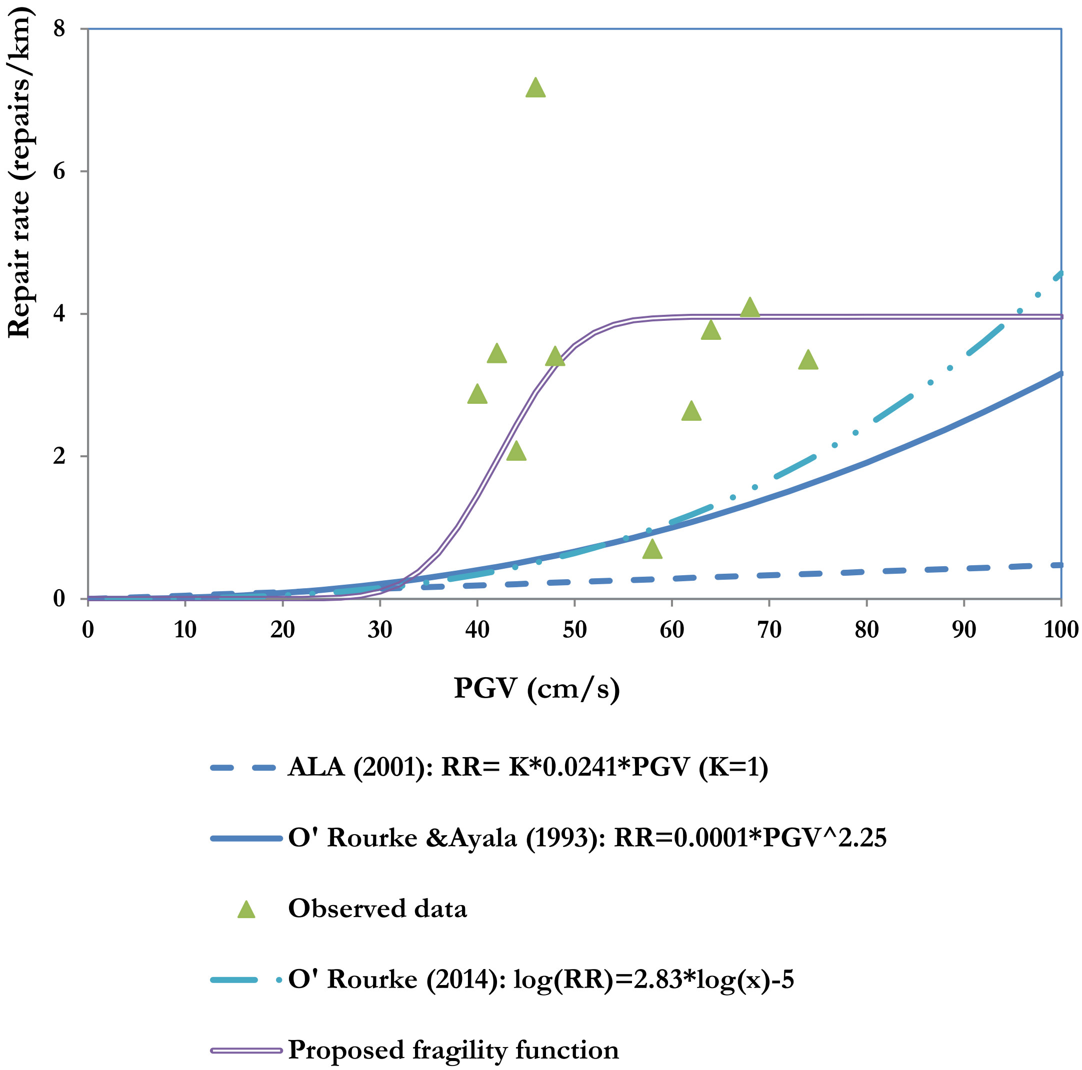


Figure 6.9 Comparison of the proposed fragility functions of sewerage AC pressure pipelines and existing fragility algorithms of AC water-supply pipelines

Furthermore, the uncertainties generated due to different sources of PGV values and various soil conditions surrounding sewer pipelines are of relative influence on the comparison results. Third, the fragility functions developed in this thesis consider the effects of PGD while other equations solely predict the physical damage from transient ground motion.

6.6 Chapter summary

In answer to the Objective 3a of the thesis (Section 1.2), this chapter compared and analysed four databases relating to the Christchurch sewerage pipelines, concluding that damage data over repair data could provide more reliable and accurate results in a seismic fragility assessment. Furthermore, it presented a fragility matrix as a simplified approach to assess the fragility of sewer pipes. The fragility matrix could allow for preliminary fragility screening for sewer pipes especially when detailed information on seismic characteristics (e.g., PGV) is unavailable and/or precise damage states (e.g., number of faults) are not required. Lastly, an advanced fragility assessment approach was proposed, namely: fragility functions for sewer pipelines, categorised by liquefaction zones. The developed fragility functions for gravity and pressured pipes can be directly applied in quantitatively estimating earthquake-induced physical damage to sewer pipes given a ground motion level for the preparation of rebuilding program. In addition, they can assist in seismic risk mitigation of sewerage pipelines before earthquakes.

CHAPTER 7

FUNCTIONAL IMPACT MODULE: POST-EARTHQUAKE PERFORMANCE INDICATORS OF SEWERAGE SYSTEMS

7.1 Introduction

Further to the earthquake-induced physical damage to sewerage system components, it is necessary to gain an understanding of the performance, functionality and serviceability of the impaired system as a whole. This chapter presents the functional impact module inbuilt in the decision support framework for post-earthquake restoration of sewerage systems. The module, through a set of PIs, assesses the loss of the wastewater service and the induced functional impacts in three different phases: emergency response, short-term recovery and long-term restoration phases.

Section 7.2 defines a three-phase post-earthquake recovery timeframe for providing a paradigm in terms of partitioning the post-earthquake recovery process. Built on the proposed recovery timeframe, the set of PIs for evaluating sewerage system performance after earthquake are demonstrated in Section 7.3, categorised in five domains, namely: structural, hydraulic, environmental, social and economic domains.

This chapter is based on the following journal paper:

Liu, M., Giovinazzi, S., and Beukman, P. (2015). Post-earthquake performance indicators for sewerage systems. In Proceedings of the Institution of Civil Engineers-Municipal Engineer (pp. 1-11). Thomas Telford Ltd. DOI: 10.1680/jmuen.15.00028.

7.2 The post-earthquake recovery phases

After a seismic event, the time required to recover infrastructure services to pre-earthquake level might be very long. The duration of the recovery process varies depending on, among others: the severity of the earthquake, the robustness of the infrastructure's components; the resilience of the infrastructure system; the identification and implementation of successful recovery strategies; and funding and resources available to implement the strategies. To clarify community's expectations and objectives of massive repair activities and to facilitate the establishment of recovery plans, it is useful to divide the total recovery period into various post-earthquake phases (Baptista & Alegre, 2003).

With reference to infrastructure, Kameda (1994) proposes phasing post-earthquake/disaster recovery processes according to the level of service of a specified infrastructure. However, a universal rule on how to phase the recovery process has not been provided in the international literature, considering that the specific peculiarities of each infrastructure type should be accounted for. In this thesis, a three-phase post-earthquake timeframe is proposed specifically for wastewater systems. The three proposed phases are: 1) emergency response, ER; 2) short term recovery, ST; 3) long term restoration, LT. Due to the change of the community's expectations and recovery's focuses along with the post-earthquake recovery process, the recovery strategies to be applied in each phase may vary.

Therefore, it is useful to clarify the expectations of local community and the recovery objectives in different post-earthquake recovery phases.

Table 7.1 shows the identified community's expectations and recovery objectives of each phase. It merits a highlight that the author is aware of and has deliberated over the independency and overlap amongst the three recovery phases. However, for simplicity's sake, the method of phasing the post-earthquake recovery process provided herein is expected to clarify and explicate the community expectations and recovery objectives in each phase with which the corresponding PIs can be developed accordingly.

Table 7.1 Community expectations and recovery objectives in the defined post-earthquake recovery phases, namely: emergency response (ER); short term recovery (ST); long term restoration (LT).

Phases	Community expectations	Recovery objectives
ER	Ensure community's health and safety	Remove immediate hazards caused by the damaged sewer system components to community
ST	Access to the sanitary waste disposal as fast and widely as possible	Reach up to 100 % of disposal accessibility by whatsoever means (e.g., temporary sanitary support)
LT	Permanently restore sewerage service, aiming for betterment	Restore pre-disaster serviceability and create a resilient sewerage system

When an earthquake happens, the first priority is the protection of life and property. Therefore, the removal of the immediate hazards threatening the community's safety is the main objective during the ER phase. Apart from the earthquake event itself, any cascading earthquake-induced hazards (e.g., unstable structures) are of primary concern during ER phase (FEMA, 2013). The collapse of sewer PS buildings may cause injury to the public. Uplifting of manholes and caving road surfaces incurred by broken sewer pipes could cause hazards to traffic.

The release of temporary recovery plans is marked as the threshold for entering the ST recovery phase. The target of this phase is to restore the provision of sanitation services, thereby meeting the public health needs of customers to the largest extent possible, while minimising the adverse effects on the environment and the ecosystem. Portable toilets, chemical toilets and emergency pumping are the main solutions adopted at this stage.

The release of permanent reinstatement plans is considered as the threshold for entering the LT restoration phase. The goal of this phase is to restore the service to pre-disaster level and, if possible, to accomplish a more robust and resilient wastewater system. The duration of this phase is often much longer than those aforementioned phases (Kameda, 2000).

7.3 Development of post-earthquake PIs for sewerage systems

The seismic-induced physical damage to sewerage systems and the resulting functional failures might have several consequences including impacts on the hydraulic, environmental, structural, economic and social contexts. These impacts should all be accounted for when, on one hand, assessing seismic performance to seek improvement opportunities and, on the other hand, when measuring the success of recovery practices according to community demands.

For simplicity and clarification purposes, the inter-relationship and inter-action amongst the abovementioned five domains are not considered or evaluated in the thesis.

7.3.1 Structural domain PIs of sewerage systems

Table 7.2 presents the structural domain PIs for sewerage systems. The structural domain of sewerage systems refers to buildings, structures of the system assets, such as PS buildings and sewer pipelines. The PIs for the structural domain look into the earthquake-induced structural failures of sewer components. Unlike fragility functions, that provide numerical estimates of expected failures/repairs on the systems, post-earthquake PIs for structural domain herein intend to evaluate the severity of physical damage and outage duration of the damaged components of interest. Moreover, the PIs aim to assess the structural betterment after the recovery operations. The quantitative evaluation of post-earthquake conditions of sewerage system components could be used to track system performance against pre-defined targets. It is noted that laterals herein only refer to those owned by the city council.

Table 7.2 Structural domain PIs of sewerage systems

Asset type	**Performance Indicators**	**Phases**	**Unit**
Pipeline	Number or length of pipes inspected via CCTV	ER and ST	number or km
	Percentage of pipes suffering minor/medium/severe damage	ER and ST	%
	Length of caving road surface (vertical settlement 300mm) caused by collapsed pipelines or joint seperations	ER	km
	Number or length of redundant pipelines installed	LT	number or km
	Length of pipelines replaced by robust pipe materials	LT	km

	Number or length of pipelines installed by new installation methods	LT	number or km
	Number or length of pipelines with revised pipe gradient	LT	number or km
	Number or length of advanced sewer installed (pressure or vacuum systems)	LT	number or km
	Length of pipelines repaired or renewed (CARE-S, 2006)	LT	km
Manhole	Number of manholes inspected via manhole level survey	ER and ST	number
	Number of uplifted manholes (> 300mm) (CCC, 2013b)	ER	number
	Number of uplifted manholes (< 300mm) (CCC, 2013b)	ER	number
	Percentage of manholes suffering minor/medium/severe damage	ER and ST	%
Pumping station	Number of PSs inspected	ER and ST	number
	Number of PSs suffering building instability or collapse	ER	number
	Number of dysfunction PSs caused by equipment failure (lack of power supply or pump failure) (Matos et al., 2003)	ER and ST	number
	Number of spare pumps installed in the PSs	LT	number
	Duration of PS outage (CARE-S, 2006)	ER, ST and LT	day
Lateral	Number or length of laterals inspected via CCTV	ER, ST and LT	number or km
	Percentage of laterals suffering minor/medium/severe damage	ER and ST	%
	Percentage of laterals disconnected to private households (CARE-S, 2006)	ER and ST	%

The post-earthquake PIs for sewerage systems in the structural domain focus on performance metrics for each type of sewer asset on a system scale except for the one examining the duration of PS outage which is aimed at individual PSs. Three main aspects of sewerage systems in the structural domain are examined, namely: 1) Damage inspection; 2) Damage assessment; and 3) Structural improvements for betterment. The proposed PIs designed for 1) and 2) focus on ER and ST phases because damage inspection and damage assessment are assumed to finish by the end of the ST phase. The PIs evaluating structural improvements are applied in the LT phase as those operations are conducted predominantly along with the long term restoration plans. The proposed PIs might be of help for exploring opportunities to integrate system resilience into the post-earthquake restoration operations.

7.3.2 Hydraulic domain PIs of sewerage systems

Table 7.3 presents the hydraulic domain PIs for sewerage systems. The post-earthquake PIs of sewerage systems in the hydraulic domain are used to evaluate hydraulic capacity of the impaired sewerage systems after earthquakes. Unlike business-as-usual measurements, they mainly capture the differences in hydraulic performance between pre- and post-earthquake stages. The PIs could monitor the reduced capability of the system and thus underpin the prioritisation of the operational practice in supporting post-earthquake recovery.

Overflow and infiltration/exfiltration are common issues for sewerage systems under normal operation. After seismic ground movement with the potential for associated rising of the underground water table, these issues are exacerbated. PIs can be deployed to discover the underlying issues by comparing the level of overflow and infiltration/exfiltration post-event with normal condition and to elicit potential solutions to the identified issues, based on the performance evaluation results. The proposed hydraulic PIs are defined at component level and applied throughout the post-earthquake recovery process because the hydraulic capability of sewerage systems is a dynamic process and hence needs continuous monitoring.

Table 7.3 Hydraulic domain PIs of sewerage systems

Asset type	Performance Indicators	Phases	Unit
Pipeline	Percentage of catchment base flow over normal wastewater flow (CCC, 2013b)	ER, ST and LT	%
	Percentage of sewage flow velocity over maximum flow velocity (dry/wet weather) (CCC, 2013b)	ER, ST and LT	%
	Volume of infiltration flow (CARE-S, 2006; CCC, 2013b)	ER, ST and LT	m^3
	Volume of exfiltration flow (CARE-S, 2006; CCC, 2013b)	ER, ST and LT	m^3
	Volume of overflow (Matos, et al., 2003; CARE-S, 2006)	ER, ST and LT	m^3
	Number of gravity pipes surcharging (CARE-S, 2006)	ER, ST and LT	number
	Volume of sediments from pipes (Matos et al., 2003)	ER, ST and LT	m^3
Manhole	Volume of overflow from manholes (CARE-S, 2006; CCC, 2013b)	ER, ST and LT	m^3
	Number of manholes suffering overflow (CARE-S, 2006)	ER, ST and LT	number
	Percentage of surcharge within 300mm of freeboard to cover level (CCC, 2013b)	ER, ST and LT	%
	Duration of overflow (CARE-S, 2006)	ER, ST and LT	day

Pump station	Percentage of well water level over normal water level	ER, ST and LT	%
	Volume of overflow in PS (CARE-S, 2006)	ER, ST and LT	m^3
	Duration of overflow (CARE-S, 2006)	ER, ST and LT	day
Lateral	Percentage of sewage flow velocity over maximum flow velocity	ER, ST and LT	%
	Volume of infiltration flow (CARE-S, 2006; CCC, 2013b)	ER, ST and LT	m^3
	Volume of overflow (CARE-S, 2006)	ER, ST and LT	m^3
	Volume of sediments from pipes (Matos et al., 2003)	ER, ST and LT	m^3

7.3.3 Environmental domain PIs of sewerage systems

Table 7.4 presents the environmental domain PIs for sewerage systems. Earthquake events cause physical damage to sewer facilities, resulting in environmental consequences to a varying extent. The untreated wastewater emanating from leakage and/or breakage is a large threat to the environment. Additionally, over-pumping, a specific method used for discharging wastewater from dysfunctional sewer components, may pollute the waterways, groundwater or ground surface. In sum, the discharge of untreated wastewater post-earthquake might contaminate fresh water sources and thus pose a risk to public health. The PIs of sewerage systems developed in the environmental domain are intended to assess environmental effects and identify potential risk of secondary disasters induced by the damaged sewerage facilities.

The proposed PIs of wastewater systems in the environmental domain address the environmental consequences caused by the entire sewerage system. The direct/indirect unintended disposal of untreated wastewater (leakage, breakage or over-pumping) is assumed to occur in ER, ST and LT phases as many disposal issues are addressed after the completion of permanent reinstatement.

Table 7.4 Environmental domain PIs of sewerage systems

Asset type	**Performance Indicators**	**Phases**	**Unit**
System	Volume of direct wastewater discharged into waterways or ground surface	ER, ST and LT	m^3
	Volume of wastewater discharged by over-pumping	ER and ST	%
	Risk of secondary disaster (disease, living area) caused by untreated wastewater	ER, ST and LT	High, medium or low
	Volume of fresh water and/or area of land polluted by wastewater discharge	ER, ST and LT	m^3 or m^2

7.3.4 Social domain PIs of sewerage systems

Table 7.5 presents the social domain PIs for sewerage systems. To evaluate post-earthquake social consequences of sewerage systems, the PIs for the social domain are established to scope the aspects related to customers' expectations and general wellbeing. In particular, the provision of access to temporary sanitary services (e.g. portable toilets and chemical toilets) is highlighted herein as it is a predominant method to supply residents with sanitary facilities in the ER phase. It allows for the disposal of domestic sewage waste and helps to satisfy the community's wellbeing under time pressure. The proposed PIs can, in turn, assist in setting of service standards (Cardoso et al., 2002).

Therefore, a sewer system is evaluated as a whole instead of individual system components. All the proposed PIs are customer-oriented and need to be assessed throughout the entire post-event recovery process, except for the ones regarding permanent repairs/renewals which only happen in ST and LT phases.

Table 7.5 Social domain PIs of sewerage systems

Asset type	**Performance Indicators**	**Phases**	**Unit**
System	Number of complaints (CARE-S, 2006)	ER, ST and LT	number
	Number of temporary sanitary facilities provided	ER and ST	number
	Percentage of customers without service to network	ER and ST	%
	Percentage of customers served by temporary sanitary service	ER and ST	%
	Number of customers moving out of properties unconnected to sanitary service	ER and ST	number
	Number of households suffering odours issue (CARE-S, 2006)	ER, ST and LT	number
	Number of properties affected by blowbacks	ER, ST and LT	number

7.3.5 Economic domain PIs of sewerage systems

Table 7.6 presents the economic domain PIs for sewerage systems. The PIs proposed in the economic domain mainly investigate expenditures on mitigating earthquake-induced disruption and returning sanitary services both temporarily and permanently after earthquakes. They could break down the gross expenditure based on different recovery operations in Christchurch. 60 % of the recovery costing for three water infrastructure (fresh water, wastewater and storm water) that has occurred is paid by central government of New Zealand through CERA, with the remainder covered by the CCC earthquake response and recovery costs (CAG, 2012; CCC, 2013a). The PIs could aid in the comparison of cost in different earthquakes and also for budget allocation for future reference.

The developed PIs examine the costing that occurs in the entire restoration process, namely: ER, ST and LT phases. It is assumed that immediate hazards are cleaned up by the end of the ER; therefore, the cost on the removal of immediate hazards only happens in the ER.

Table 7.6 Economic domain PIs of sewerage systems

Asset type	Performance Indicators	Phases	Unit
System	Cost of removal of immediate hazards	ER	NZ$
	Cost of mobilisation of equipment, crew and material for repair actions	ER, ST and LT	NZ$
	Cost of temporary solutions needed (portable toilets, chemical toilets, over-pumping)	ER and ST	NZ$
	Cost of repair crew working for extra hours	ER, ST and LT	NZ$
	Percentage of restoration cost over normal maintenance costs	ER, ST and LT	%
	Cost of new assets (CARE-S, 2006)	ST and LT	NZ$
	Cost of asset replacement and renovation (CARE-S, 2006)	ST and LT	NZ$

The PIs further calculate the excessive expenditure caused by earthquake over business-as-usual maintenance cost, which is a way to economically measure the severity of effects sustained by wastewater systems after seismic events.

The PIs proposed herein only focus on the direct costs incurred during the post-earthquake restoration process. The author is aware of the indirect costs (i.e. business and other non-system costs) that are naturally associated with the restoration process and could dramatically increase the overall restoration expense and affect the implementation of the restoration plans. However, this aspect is beyond the scope of the thesis.

7.4 Chapter summary

In answer to the Objective 3b of the thesis (Section 1.2), this chapter demonstrated a set of PIs which intends to measure the functional consequences associated with the impaired sewerage systems in post-earthquake recovery phases, namely: emergency response, short-term recovery, and long-term restoration. This set of PIs aims to guide a holistic evaluation of hydraulic, environmental, structural, economic and social consequences that have arisen after the earthquake-induced damage to sewerage components (including pipelines, PSs, manholes and council-owned laterals). Each type of sewer components is examined for the abovementioned domains. The proposed PIs are deployed to track asset performance and functionality to be compared with the expectations of asset managers and customers.

CHAPTER 8

PIPELINE RESTORATION MODULE: RESTORATION MODELS OF SEWERAGE PIPELINES

8.1 Introduction

This chapter presents the serviceability restoration module embedded in the decision support framework for restoring sewerage systems post-earthquake. The module aims to predict the time required to restore sewerage systems after an earthquake, based on a range of variables related to seismic hazards, asset attributes, and reconstruction operations, through a statistical approach selected in this chapter.

Section 8.2 presents a database used for this analysis that was produced by combining two existing databases recording the reconstruction practises of the CSS after the Canterbury recovery. This section, additionally, introduces the candidate statistical models and approaches to be examined and the prediction measures to be implemented. In Section 8.3, the candidate models and approaches are tested and compared using two types of validation datasets spatially selected from the produced database. According to the comparison prediction results, variable importance is ranked and relevant variables are interpreted in conjunction with observation in field. The limitations and applications are discussed in Section 8.5.

This chapter is based on the following journal paper:

Liu, M., Scheepbouwer, E., and Gerhard, D. A statistical model for estimating restoration time of sewer systems after earthquakes. Journal of performance of constructed facilities. (In review).

8.2 Data and statistic models adopted

8.2.1 Database description and processing

The restoration database analysed in this research is constructed by combining two databases, namely: combined completed repair database and completed renewal database. Both are dated 21 January 2015, that is, the two databases record the sewerage pipes that have been repaired or renewed since the September event until that date. More information regarding the two databases can be found in Section 5.4.1. Although a full analysis will be possible when repairs and renewals are complete, it will be valuable to investigate now the implication of the collected data so far.

The two databases, jointly owned by the CCC and SCIRT, contain the records in relation to the sewer repairs and renewals conducted by SCIRT rebuild contractors and the pipes repaired by CCC sewer maintenance teams as part of business-as-usual rehabilitation program. By no means, based on the evidence (e.g., CCTV footage) collected in field, one can distinguish the earthquake-induced physical damage from non-earthquake-related faults. Therefore, it is hard to affirm whether the conducted reconstruction operations are or are not earthquake-triggered. In this analysis, all repairs and renewals carried out after the February event are assumed as earthquake-related restoration operations.

There are 9,693 records in the completed repair database, each represents one repair operation that has been carried out in the field by teams from either the CCC or SCIRT since the September earthquake. In the Canterbury recovery, a repair operation is defined as the repair of a pipe for less than its full length and any pipe segment replaced that is less than 6 m. in length. The completed renewal database documents 3,177 new pipes that were installed after the September event to replace the damaged sewer pipelines in the CSS. Renewal operation in the Canterbury recovery refers to the relining of a pipe over its full length between manholes or replacement with new materials for 6 m or longer following new design and construction specifications. The renewal operations have been conducted by use of new PVC (150 to 375 mm diameter) or RCRR (450 to 600 mm diameter) pipe. The term ‘renewal’ is used instead of ‘replacement’ to clarify that any new pipe will not be a simple exchange and instead will be selected and installed based on revised design and construction rules.

After combing the two databases, it was found that many repairs/renewals had the same coordinates, which was because multiple repairs/renewals were executed on the same/neighbourhood pipelines sharing identical coordinates. This is due to multiple earthquake events affecting the same coordinates after the prior repairing/renewal. Cautioning that the repair times of different sewer pipes with the same coordinates might be interrelated and thereby affect statistical modelling, the author summarises the combined database by choosing the maximum repair duration as final repair/renewal time and averaging other distinct pipe characteristics (e.g., depth). After data processing, the restoration database with 4,648 records were structured that represent the pipes that have been repaired/renewed after the February earthquake.

8.2.2 Variable definition

Based on observations in the field, and according to expert opinion, eight variables that might potentially affect sewer restoration time were selected and presented in Table 8.1. They are classified into three categories: 1) asset attributes (diameter, length, depth, and soil type); 2) seismic hazard parameters (PGV and LRI); 3) restoration operations (pipe type and operation type), all of which could influence the restoration process of sewerage pipelines post-earthquake to a certain extent.

Table 8.1 Definition, mean and standard deviation (S.D.) of the candidate variables considered in this analysis

Variables definition	Median	Value range	Interquartile range
Restoration time, day (y_t)	983	From 7 to 1530	779-1220
Diameter, mm (x_d)	225	25 different diameters from 60 to 1500	160-200
Length, m (x_l)	31.2	From 0.2 to 1229.5	6.4-68.8
Depth, m (x_{de})	1.8	From 0.2 to 6.5	1.2-2.5
Pipe type (x_{pt})	NA	Gravity and pressure	NA
Soil type (x_s)	NA	Loam, sand, hill soil, and complex	NA
Restoration operation (x_r)	NA	Repair and renewal	NA
Peak Ground Velocity, PGV, cm/s (x_{pgv})	62	From 10 to 82	56-62
Liquefaction Zone (x_{liq})	NA	0, 1, 2, 3, 4, and non-liquefaction zone	NA

In this study, restoration time (y_t) serves as a dependent variable. It is defined as the time differences between the February earthquake (February 22, 2011) and job completion dates recorded in the database, with day as a unit. Due to the unavailability of the data on actual starting date of repair/renewal tasks, the author can only use the date of the February earthquake as a starting date for calculating the pipe restoration time. The restoration duration varies depending on their physical damage, criticality, and operational considerations (e.g., soil dewatering and traffic management). Some restoration work can take a rather long time. For example, one pipe experienced restoration time of 470 days after the February quake. This 67.5 m sewer pipe suffered 6 faults as a result of the quake so a repair task was assigned. However, this pipe was connected to a manhole and the rebuilding practice could only be initiated after the manhole had been repaired. After the design and rebuilding of the linked manhole, this pipe sustained further physical damage due to the earthquakes in June. Consequently, CCTV inspection was needed to detect the damage state of the pipe while decision-making, design and scheduling in terms of the rebuilding operations on the pipe was conducted. Eventually the rebuilding task was completed in June 2012. Furthermore, the length of the restoration time can also be affected by overall recovery plans (e.g., commercial streets) based on which some projects have priorities, leading to relatively shorter restoration time.

The pipe diameter, length, and depth are generic pipe attributes and they could, by nature, affect the pipe restoration time. The pipe diameter used in the analysis is the external diameter of pipes, measured in mm. The pipe length is measured in meters. The pipe depth is the distance assessed from the middle points of the pipe length to the ground surface.

In this work, the WPH and PGDH are assumed to have an influence on the duration of sewer restoration time after earthquakes. Therefore, the PGV values of the February quake are selected as a seismic hazard parameter representing WPH associated with this event. The LRI map is adopted as a measure of the PGDH. The two seismic intensity measures are introduced in Section 5.4.2.

The type of pipes installed in the system may change the restoration time for sewer pipelines, the pipe type is selected as a variable, with two categorical attributes of gravity and pressure pipes. The two pipe types are main asset types functioning in Christchurch. The installation procedures, techniques, resources required could make a difference in terms of the sewer restoration duration after earthquakes. It is noted that the pipe type installed is selected for analysis and it may or may not be the same as the original pipe type. Due to various reasons, such as the number of faults and locations, decisions to change gravity pipes to pressure pipes are common in the Canterbury recovery, for example the New Brighton area (Liu et al., 2013).

In order to consider the influence that soil types may have on the duration of sewer restoration, the Christchurch soil layer is utilised herein (Figure 8.1). The whole soil map covers roughly 500 km^2 area and the map unit boundaries were compiled based on regions in Christchurch. The map units are coded by combining region name (e.g., Kaiapoi), soil depth (i.e., deep, moderately deep, and shallow), stoniness class (i.e., stony, very stony, sandy) and soil textures (Web et al., 1991). The soil texture includes loam, sand, hill soil, quarry, complex and reclaimed land. For simplicity purpose, quarry areas (0.36 km^2) and one reclaimed land (0.12 km^2) are removed and all soil units are standardised into four categories, namely: loam, sand, hill soil and complex in this study. For instance, soil units of deep stony sand and shallow very stony sand are now in the same soil category of sand.

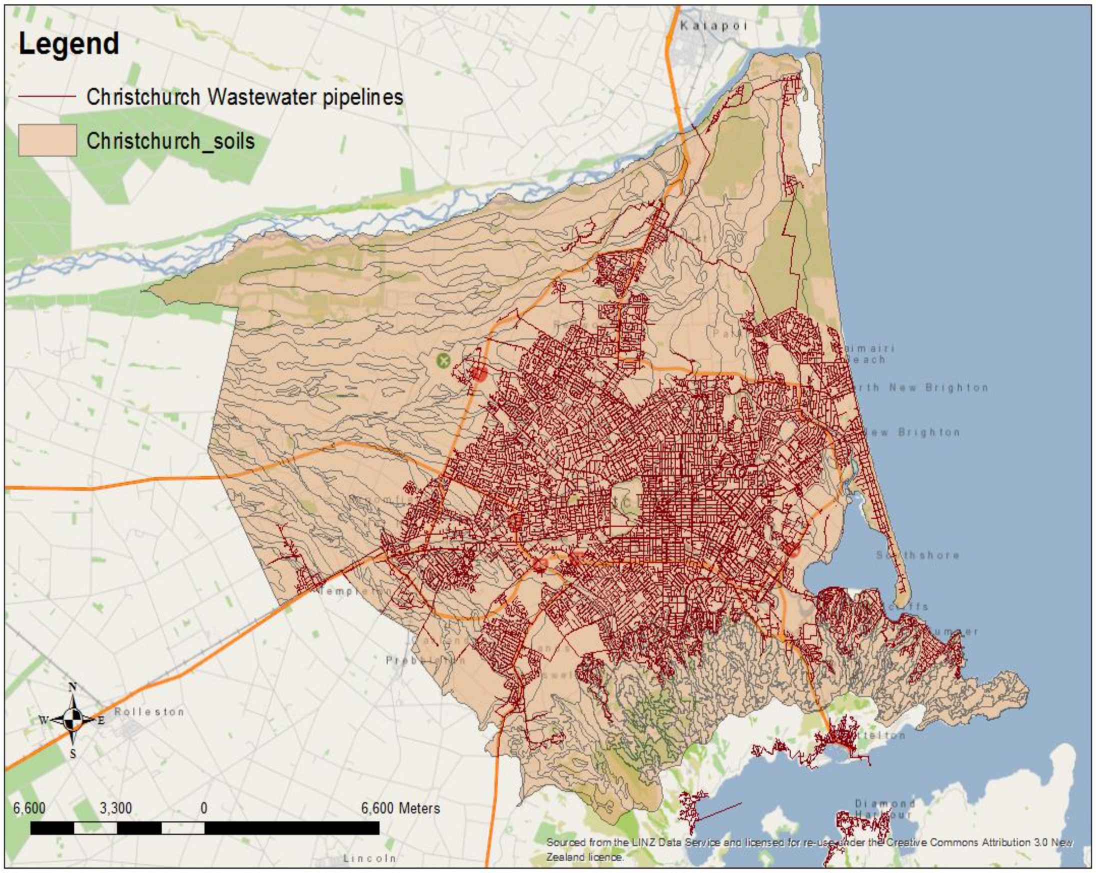


Figure 8.1 Overlap of the soil map and the Christchurch wastewater pipelines

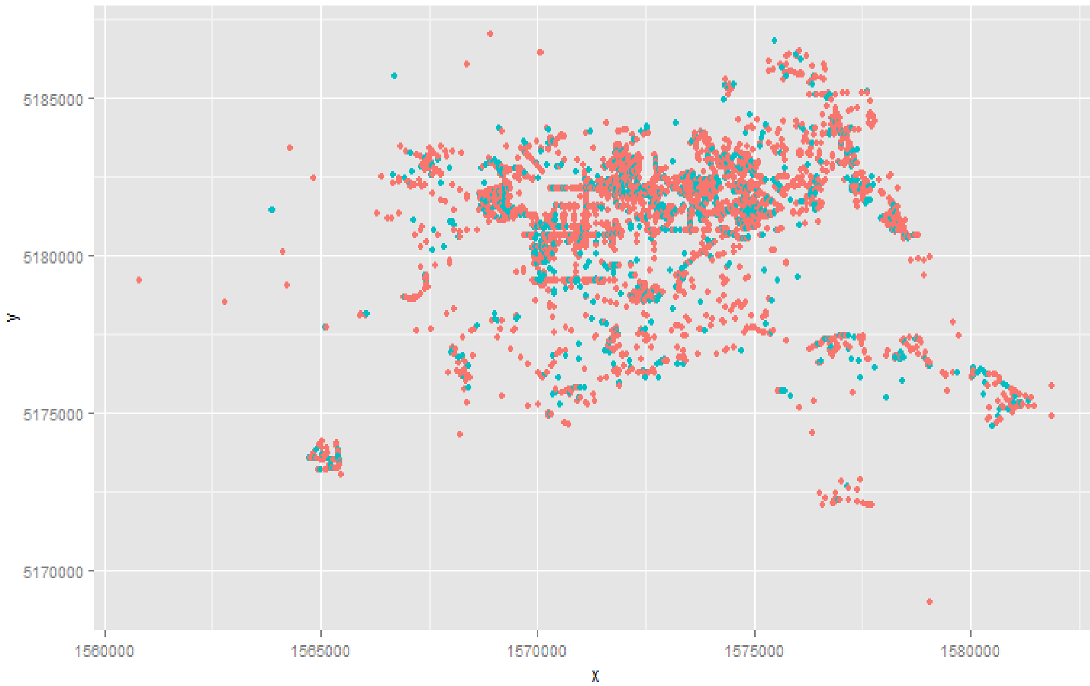
The combined restoration database, PGV value layer, LRI map, soil database are superimposed for obtaining pertinent values for each repair/renewal record in the restoration database. At the end, the restoration database is structured such that one repair or renewal pipe is associated with such information as pipe attributes, pipe type, repair/renewal operations, soil type and seismic hazard parameters.

8.2.3 Model types and prediction measures

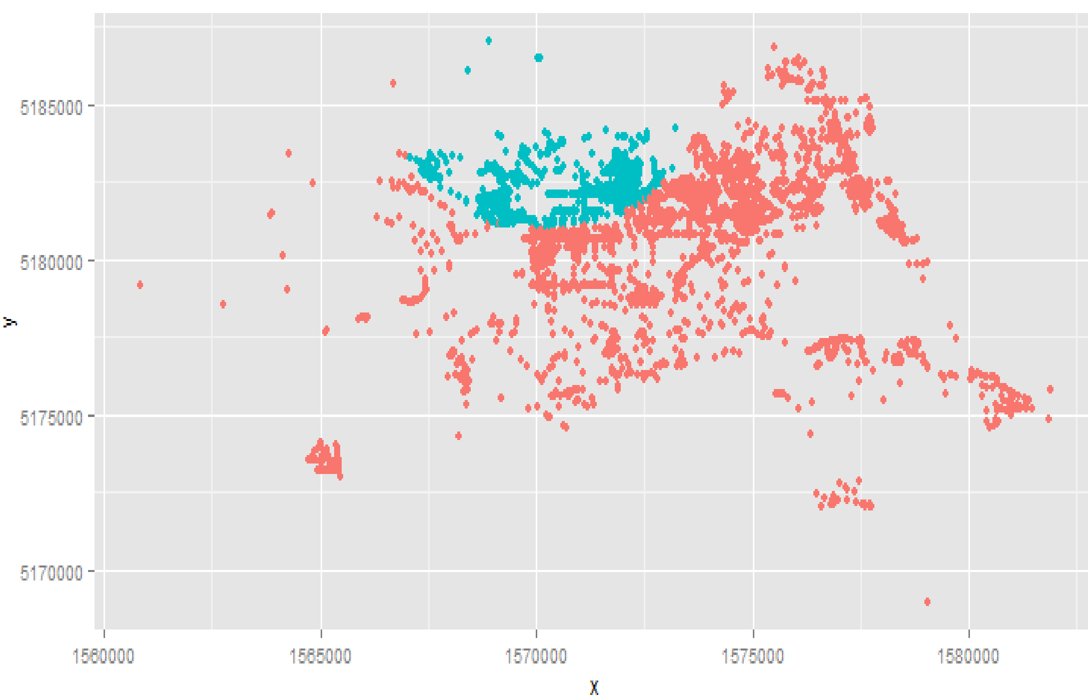
In line with the study objective, and considering the research gaps identified in Section 2.6.1, four statistical models or approaches are investigated, namely: CPH, RSF, AFT, and multiple linear regression model (MLR). The CPH and RSF model the survival functions to capture the probability that a pipe will be repaired after a specified time. The AFT and MLR model are able to directly model pipe restoration time. The MLR model, which provides simplicity, is used to compare how much prediction accuracy could be improved by compromising the simplicity. More information regarding the four candidate approaches are provided in Section 2.6.1. The restoration modelling is implemented in R environment using open-source R software version 3.2.2 (RCore Team, 2015). The R code implemented for this analysis is provided in Appendix A.

The purpose of this Section is to present a statistical approach to predicting the restoration time of sewerage pipelines and to examine the applicability of the method to different geographical areas. The approach is expected to have a robust prediction power, easy adaptability, and practical computability. To this aim, four metrics are calculated and compared herein: 1) AIC value (Akaike, 1970); 2) the square root of the mean squared error (RMSE); 3) mean absolute error (MAE); 4) correct classification rate (CCR). The AIC is defined as: AIC= - 2logL + 2k, where L is the likelihood of the fitted statistical model and k is the number of parameters used in the model. The AIC is used to determine a preferable model in the same model family. The AIC values of different model families (e.g., CPH and AFT) are not comparable because the formulas and calculation of log-likelihood functions for each model family are different. The RMSE and MAE values represent how much difference between the recorded outage duration and the estimated outage time by use of the fitted models. The CCR is defined as the percentage of pipes correctly classified as restored or non-restored over the actual restored or non-restored pipe number. The RMSE, MAE, and CCR are deployed to measure the predictive power of the statistical methods using validation datasets.

Two approaches are used to select validation datasets for analysis herein. One is random sampling, that is, to randomly select 20 % of records from the restoration database as the validation dataset and the rest (80 %) is the training dataset (Figure 8.1a). The other one is out-of-sample approach, aiming to examine the applicability of the proposed statistical approach to a different geographical location. A spatial coordinate from the network is randomly selected and 20 % of the pipes with the smallest Euclidean Distance to this coordinate is chosen to form a validation dataset (930 pipes). The remaining forms the training dataset (3,718 pipes) for building the model. The prediction accuracy of the built model is examined through the validation dataset and the RMSE, MAE, and CCR values are computed. The entire process is repeated 100 times and the values of the prediction measures are averaged. Figure 8.1b gives an example of the partitioning of the training and validation datasets by the out-of-sample approach.



(a)



(b)

Figure 8.2 The partitioning of training and validation datasets by use of: a) random sampling approach; and b) out-of-sample approach

8.3 A statistical approach for estimating sewer restoration time

8.3.1 Model selection and comparison

The author firstly trains the CPH, AFT, RSF and MLR models by use of the random sampling training dataset. The RSF approach is non-parametric; therefore, the CPH, AFT, and MLR models are tested individually in order to select the best fit model for each type of the three models. The process involves distribution and/or variable selection in a stepwise manner, measured by use of AIC values (Akaike, 1970). A preferable model is the one with the smallest AIC value. Categorical variables are treated as dummy variables in R.

For the AFT model, it is assumed that the outage time is in the shape of four distributions respectively: Weibull, exponential, log-logistic, or lognormal distributions. The AFT models with the four distributions are fitted using the random sampling training dataset and the results are shown in Table 8.2. The parameters are selected based on p values below 0.05, showing that they have significant effects on the restoration time.

Table 8.2 Comparison of the regression results for AFT models

Distribution	Number of parameters	Log-likelihood	AIC
Weibull	27	-24263.2	48676.37
Log-normal	27	-24763.1	49676.26
Exponential	23	-25104.9	50301.71
Log-logistic	28	-24604.5	49368.97

The AIC values, log-likelihood values, and number of parameters are presented in Table 8.2, the AFT model with an exponential distribution has the least number of parameters. However, the AIC and log-likelihood values are the highest compared to the models with other distributions. The AFT model following a Weibull distribution has the smallest AIC and log-likelihood values. There are 27 parameters contributing to the total repair time. Therefore, the Weibull AFT model has the best fit amongst the four AFT models considered and is selected for further analysis.

For the CPH and MLR model, the random sampling training dataset is used to fit the models with all variables at the beginning. The outcomes are compared via AIC values to determine a best fit model with the smallest AIC values. Table 8.3 shows the number of parameters and AIC values of the best fit CPH and MLR models. The AIC values of the CPH and MLR models are not comparable.

Table 8.3 Regression results for CPH and MLR models

Model	Number of parameters	AIC
CPH	24	46725.65
MLR	26	38951.59

The interactions between independent variables are captured in training the models by engaging each variable with all other variables (including every categorical variable) so as to test the co-functionality of the two variables. Table 8.4 compares the selected interactions in each model.

In the fitted AFT model with the Weibull distribution, the variable of PGV and LRI are relatively influential. The interactions of the PGV with pipe type, soil type, depth, and reconstruction operation, respectively, are significant in terms of the predicted restoration time. The variable of the LRI interacts with diameter, pipe type, operations, and PGV. This shows that seismic hazard characteristics are the main driver for post-earthquake restoration time represented by the Weibull AFT model.

Table 8.4 Comparison of the interactions captured in the fitted models

	Diameter	Length	Depth	Pipe type	Soil type	Operation	PGV	LRI
Diameter								
Length	* # +							
Depth		+						
Pipe type	# +	*						
Soil type	# +			*				
Operation	* # +		#	# +	# +			
PGV	# +		* # +	*	* # +	* # +		
LRI	*			*		* #	* # +	

AFT model: *; CPH model: #; MLR model: +

For both the CPH and MLR models, the interactions of pipe diameter between five variables (Length, pipe type, soil type, operations, PGV) respectively are captured. Pipe diameter is considered as a surrogate for pipe criticality in the sense that larger diameter pipes serve more population. This means pipe criticality plays an important role in restoration duration. More important pipes are restored earlier than other pipes. Moreover, PGV is considered as important in the fitted CPH model, the interaction of which between depth, reconstruction operation, and soil type are considered as important in the model. Reconstruction operation is another active variable in the CPH and MLR models where the interactions of it between soil type and LRI, respectively are significant. Because reconstruction operation, together with soil condition and/or geographical location of the pipes could determine reconstruction resources (e.g., equipment, crew, budget) and procedures that are needed and all these in turn affect the length of restoration time.

In the three models, the interactions of diameter and length, diameter and operation, PGV and depth, PGV and soil type, PGV and operations, as well as PGV and LRI are mutually captured. This means that their co-functionalities are considered as statistically significant in predicting restoration time of sewerage pipelines after an earthquake when applying the three models. In particular, the variables of diameter and PGV are the most active parameters in the models.

8.3.2 Random sampling prediction results

The author then uses the fitted four candidate models/approaches, namely: AFT, CPH, RSF, and MLR, to predict sewer restoration duration using the random sampling validation dataset. The RMSE and MAE values for each of them are computed and compared with the purpose of measuring predictive accuracy. The calculated RMSE and MAE for the four candidate approaches are presented in Table 8.5.

Table 8.5 Comparison of prediction results for four candidate methods

Model	**RMSE**	**MAE**
AFT-Weibull	374.4374	298.2953
CPH	370.6315	295.3628
RSF	299.7696	174.1792
MLR	354.1645	287.2095

In Table 8.5, it can be seen that the method of the RSF has the lowest RMSE and MAE values and thus outperforms other candidate models. The RMSE and MAE values of the two survival models (i.e., AFT and CPH models) are close but larger than the ones of the MLR model. This means that introducing survival models to estimate sewer restoration time do not lead to an improved predictive accuracy. Having a simple linear regression model for prediction has the potential to provide reasonable outcomes while reducing computational complexity. The RSF, in particular, yields the best prediction accuracy of the models examined and is 39 % more accurate than the MLR model.

While the RMSE and MAE values calculated by averaging prediction differences on the model as a whole, the CCR shows prediction performance as a function of restoration time. The CCR is referred as the percentage of pipes that are correctly classified as restored or non-restored by the model over the total number of pipes to be restored. For the AFT and MLR models which can directly estimate the restoration time, the calculation of the CCR is quite straightforward and that is, given a certain date after the earthquake, to sum up the number of correctly classified pipes divided by the total number of pipes, 4,648 pipes in this case. The CPH and RSF, however, model the survival functions to capture the probability of a pipe will be restored after a specified time. In this research, it is assumed that a pipe with greater than 50 % of restoration probability is classified as fully restored and one with below 50 % is grouped to non-restored. The CCR values as a function of restoration time of the four approaches after the 100 simulations are illustrated in Figure 8.3. The ranges of confidence intervals are obtained from the minimum and maximum CCR values for every date during the simulations.

Figure 8.3 demonstrates that the model built by the method of RSF provides the best prediction accuracy and the CCR values are greater than 80 %. It means this model could correctly classify the restoration status (restored or non-restored) for at least 80 % of restoration projects with 10 % of uncertainty. For the AFT, CPH, and MLR models, their prediction performance along with the restoration times are similar. They can ensure 70 % of CCR with 8 % of uncertainty when predicting sewer restoration status. In particular, the MLR model seems slightly better than the AFT and CPH models especially after 500 days. This means the usage of an MLR model for prediction when more advanced statistical models are not available could lead to reasonable estimates. The graph also shows that the CCR values are almost 1 within the first 50 days after the earthquake and in the last 200 days of the restoration process. This means the models have very high predictability at these time periods. However, the restoration models have the lowest CCR values during 600 – 900 days after the earthquake.

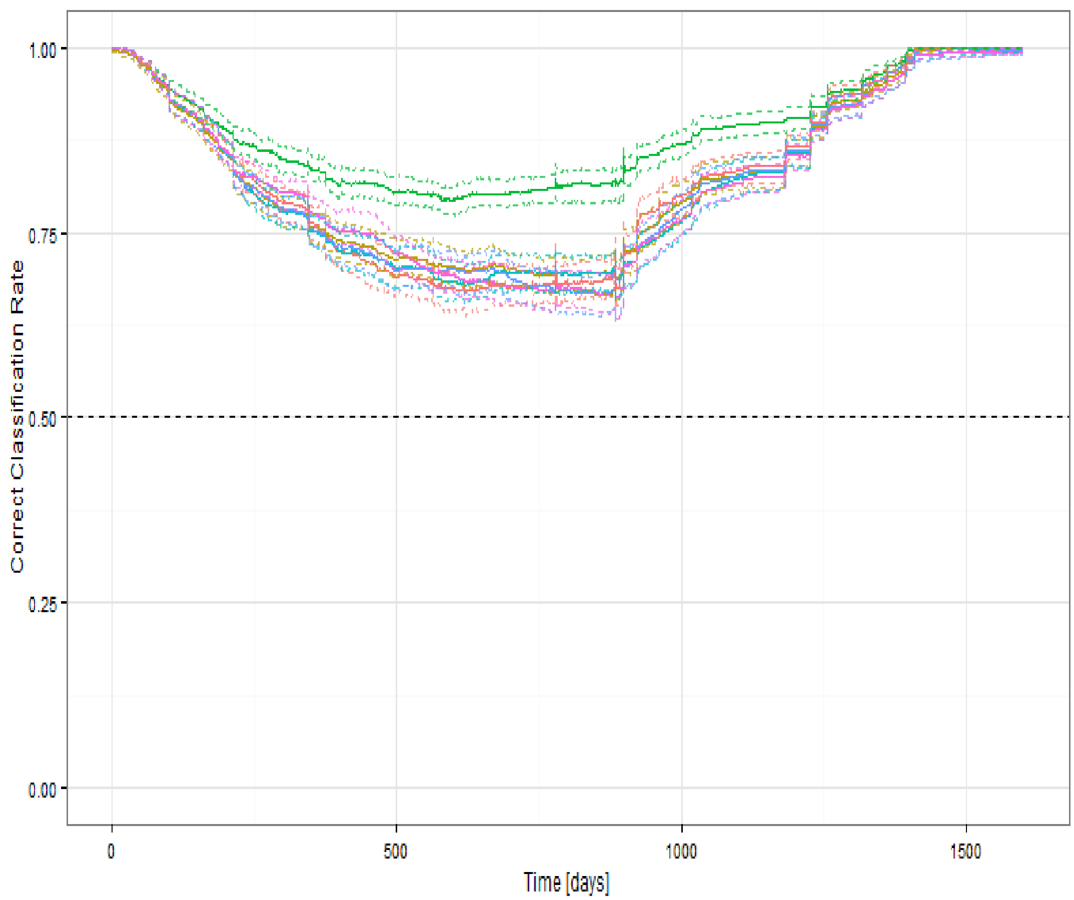


Figure 8.3 Comparison of the CCR for MLR (cream), AFT (blue), CPH (red), and RSF (green) models, using random sampling validation dataset.

The restoration curves for the developed models are compared in Figure 8.4 with the actual restoration rates collected in the field so as to visualise the prediction results. It is shown that the shape of the restoration curve produced by the RSF matches well with the actual restoration rates. However, it slightly underestimates the restoration rates for the first 500 days and overestimates the actual restoration progress for 1000 days after the earthquake by roughly 10 %. As RSF is an ensemble tree method, therefore, there is no predictive equation proposed here. The AFT, CPH, and MLR models show a relatively big discrepancy in the restoration curves, compared with the actual one. Particularly, the shape of the restoration curves produced by the MLR model is similar to the actual one yet with a misestimate of around 20% for most of the restoration process.

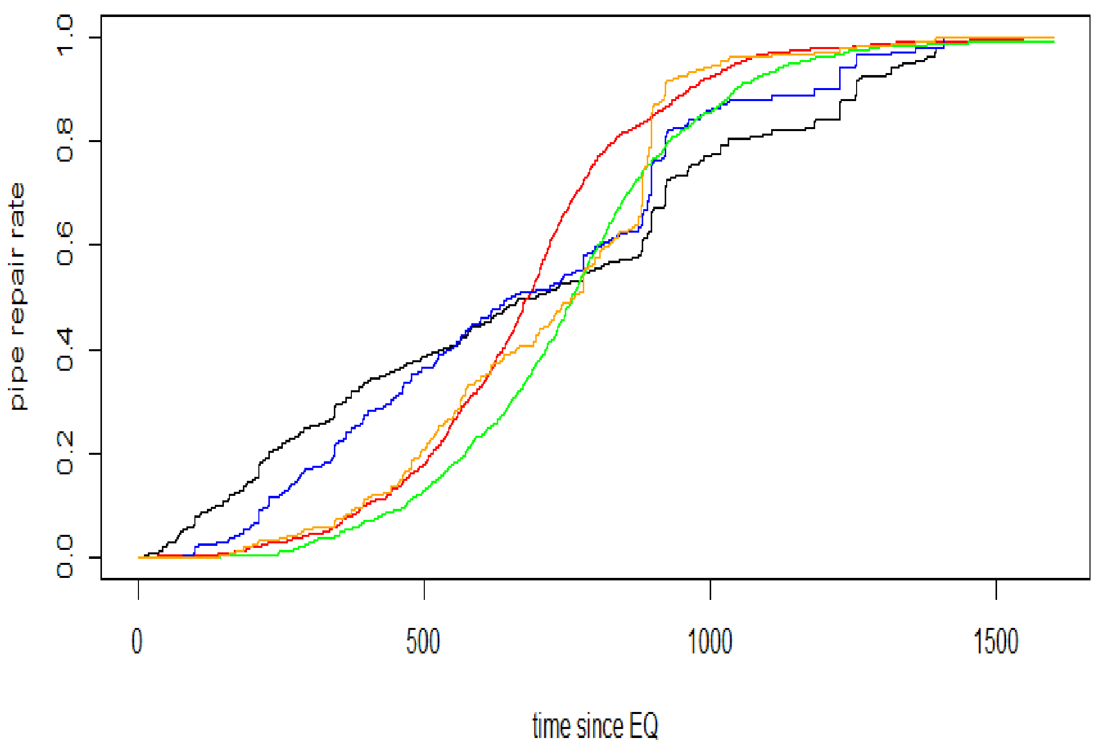


Figure 8.4 Restoration curves for actual restoration time (black), MLR (red), AFT (green), CPH (orange) models, and the method of RSF (blue), using random sampling validation dataset.

8.3.3 Out-of-sample prediction results

The aim of this subsection is to examine the predictive performance of the four candidate restoration models when applied in different geographical locations. The out-of-sample validation dataset is used for analysis herein. The RMSE, MAE, and CCR values of each candidate model are calculated and the simulation is run 100 times. The average RMSE and MAE values for each candidate models are tabulated in Table 8.6 and the CCR values, with confident intervals are plotted in Figure 8.5.

Table 8.6 Comparison of the RMSE and MAE for four candidate models

Model	RMSE	MAE
AFT-Weibull	465.3413	399.2515
CPH	493.7391	409.6673
RSF	483.1532	386.694
MLR	480.3484	407.5399

Table 8.6 shows that the RSF model does not have obvious advantage in prediction using out-of-sample data, although it has the smallest MAE value. The AFT model has the smallest RMSE value. The RMSE and MAE values of the CPH and MLR models are similar but larger than the ones of the AFT model. The Figure 8.5 compares the CCRs of the candidate models using the out-of-sample validation dataset. For visualisation purpose, this figure only presents the CCR of the MLR, AFT, and RSF models as the CPH model's CCR is highly similar to the AFT. The AFT and MLR models behave similarly in terms of correctly classifying reconstruction status and seems better than the RSF in the first 600 days. The RSF, however, has higher CCR afterwards. The CCR of the RSF keeps above 60 % for the whole restoration process. The confidence interval of each model captures a large amount of prediction variance, and are as large as 20 %.

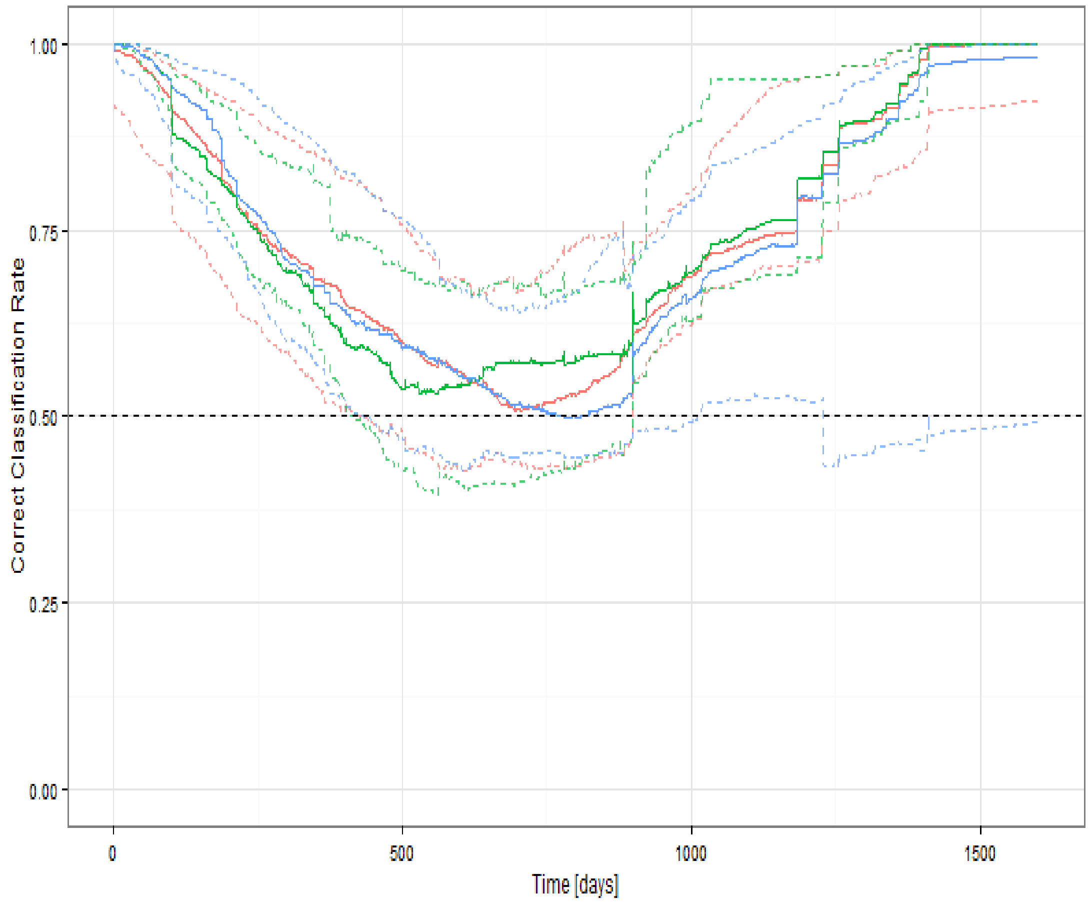


Figure 8.5 Comparison of the CCR values for MLR (red), AFT (blue), and RSF (green) models, using out-of-sample validation dataset

It is found that there is a fracture at around 900 days in Figure 8.3 and 8.5. The CCR lines seem like two segments jointed at the restoration time of 900 days. This is due to the fact that there is a design guideline regarding decisions on sewer reconstruction (restore or not) conceived and released by the SCIRT in October 2013 (SCIRT, 2013). The aim of the guideline is to avoid repairing non-critical defects (details in Section 6.2) and maximise cost efficiency of rebuilding outcomes. The guideline calls for the consideration of 15-year remaining life of sewer assets where appropriate. Therefore, after October 2013 (approximately 900 days after the February earthquake), the sewer reconstruction started following a different trend that is shown in the two Figures.

The restoration curves of the candidate models using the out-of-sample validation dataset are plotted in Figure 8.6, together with the actual restoration rate. It is shown that there are large differences in terms of the predicted restoration rates and almost all models overestimate the restoration rates, except for the MLR model for the first 400 days. The RSF model shows a good agreement in the first 300 days.

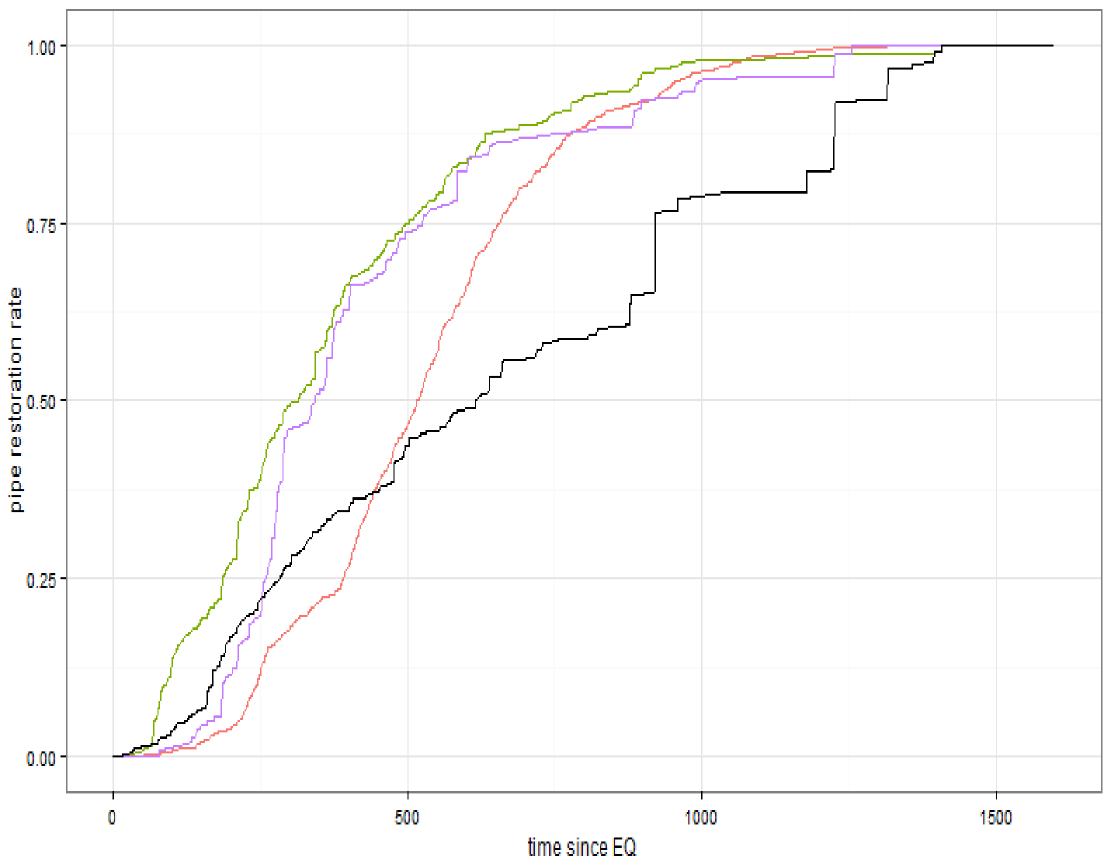


Figure 8.6 Restoration curves for actual restoration time (black), MLR (green), AFT (red), CPH (green) models, and the method of RSF (purple), using out-of-sample validation dataset.

8.4 Variable importance and interpretation

In order to test the importance of the dependent variables, the method of the RSF is applied in the sense that the RSF has the capability to test the significance of individual covariates to a response variable while keeping other covariates constant through partial dependence plots (Hastie et al., 2011). The variable importance rankings gained by the RSF using the random sampling or out-of-sample validation datasets are the same (Figure 8.7). The variables that have been used more frequently as splitting variables to build regression trees are considered more important and believed to have more influence on predicting sewer restoration duration.

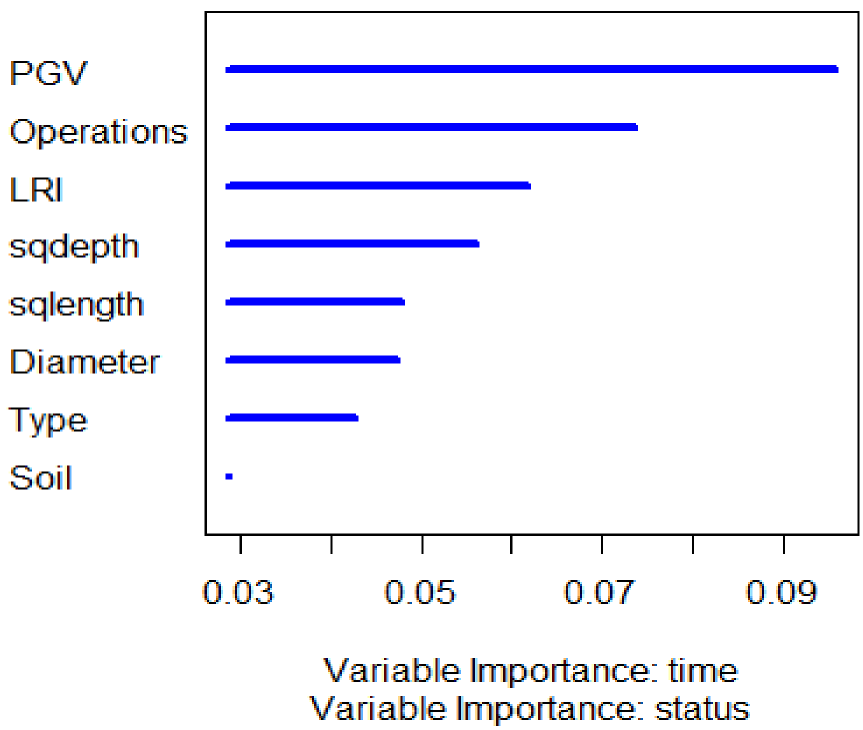


Figure 8.7 Variable importance in prediction sewer restoration time after earthquakes

Figure 8.7 demonstrates the importance of the variables considered in the RSF model in this study. The chart indicates that PGV values have the most significant effect on predicting the length of sewer restoration time. This is reasonable because transient ground motion is the main trigger for physical damage to large-scale networks and the stronger ground shaking are more likely to cause more severe damage which then requires more time for restoration. As expected, restoration operation is a very important variable in estimating the restoration duration. Which strategies (repair or renewal) to use, what procedures to follow, and what ancillary resources are needed have high influence on the duration of restoration process. Additionally, the unit restoration time for different types of restoration operations could vary because of the nature of different reconstruction techniques. LRI values stand relatively high ranking in terms of variable importance from the prediction results. This can be explained by the fact that extensive liquefaction and associated lateral spreading were observed in Christchurch following the CES along the Avon River and other waterways where sewer reticulation was modestly installed. Thus, the LRI is ranked highly in altering sewer restoration times. As for such pipe attributes as depth, diameter, and length, it is understandable that deeper, larger, or longer pipes need more time to restore. Pipe type (i.e., gravity and pressure) and soil type are the least influential on the duration of sewer restoration.

The understanding of the variable importance could be of benefit in determining key factors affecting the length of restoration time and drawing decision makers' attention on data collection and acquisition in an effort to predict restoration time after earthquakes. Based on the timeframe of data availability, the variables considered in this analysis can be obtained pre-earthquake, short period post-earthquake, or long period post-earthquakes. Pipe depth, diameter, length, and soil type are sewer asset characteristics that are attainable prior to earthquakes. It would be ideal if they are collected and recorded in system inventory databases so that they can be directly used to predict sewer restoration time after the occurrence of an earthquake. The variables of PGV and LRI are available after an actual earthquake happens. The empirical data can be gauged by distributed ground motion stations and/or various measurement techniques (e.g., LiDar sensors) after a short period of time after earthquakes, depending on measure accuracy required. They play a crucial role in predicting restoration duration; therefore, timely data acquisition could facilitate the estimate of restoration time. Pipe type and restoration operation need some deliberation. Which type of pipe to install and which operation to choose are determined in line with overall recovery plans and relevant specifications, considering a range of pertinent factors, such as criticality and budget. This normally takes a long period of time after earthquakes. Therefore, to shorten the deliberation period, decisions on sewer reconstruction practices should be made in advance, based on the nature and state of the physical damage. The pre-defined restoration practices can be applied to predict the restoration time of sewer pipelines after earthquakes.

Identifying important variables can help highlight more influential variables in predicting restoration time, in particular, under the condition of data unavailability. The seismic hazard measures are very important especially the PGV values. The restoration operations (pipe type and operation type) are critical in restoration duration prediction. The operation type is ranked the second most important amongst all variables whilst the pipe type is the sixth. Therefore, more effort should be invested in data acquisition in terms of reconstruction operation type (repair or renewal). The asset attributes (depth, diameter, length, and soil type) are located moderate important positions. They should be gained from the inventory database. The soil type may be removed if the attainment needs extra resources in the sense that the importance of the soil type is very low.

8.5 Limitations

A statistical model for predicting sewer restoration time is useful given the lack of research in this subject area. The literature review demonstrated no statistical restoration model has been developed for sewer systems, in particular for post-earthquake context. Thus, four candidate models/approaches were examined herein and validated using two validation datasets, namely: random sampling and out-of-sample validation datasets. The RSF predicts the restoration time of the random sampling validation dataset very well whilst the prediction accuracy for out-of-sampling validation dataset is not ideal. One possible reason might be the respective rebuilding priorities of different geographical areas which are not included in this analysis due to data unavailability. In the Canterbury recovery, some suburbs like Burside and Fendalton, had high priorities in accordance to the overall recovery plans. Therefore, the sewer restoration time of the pipes within these areas by average are shorter than in other areas as the restoration time commences with the February earthquake. This is a limitation of this work. Two solutions have the potential to address this issue. One is to introduce recovery priority of each geographical area as a dependent variable to be tested for developing restoration models. The priority of each area should be assigned to each pipe that needs reconstruction. The second solution is to investigate start date of each restoration task and calculate pipe restoration time by use of the start and finishing dates of restoration tasks so that the effects of awaiting time could be reduced.

In this analysis, it is assumed that the restoration resources are unconstrained and there is no extra waiting time for crews to travel to work, for reconstruction materials to arrive and for budget to be allocated. Additionally, the unit crew number per task and crew professional levels are assumed as uniform. This is because of a paucity of detailed information and data relative to restoration resources. The author notes, however, in reality, the contractors and/or time for crew's traveling from home to work and resting during work, material and machinery's transporting, dewatering operations depending on the ground water table levels and traffic cleaning and management play an indispensable role in restoration time and should be accounted for in developing restoration time. Although the dependent variables in relation to restoration resources could reflect the real situation of post-earthquake sewer restoration, whether the inclusion of the variables could improve prediction power of proposed models needs further investigation.

The applicability and generalisability of this study could be challenging for various reasons. Firstly, although some variables (e.g., asset attributes) are recognised and used worldwide, due to the size of the CSS, the numeric ranges of these attributes (e.g., diameter) are limited. The application of the restoration model in a larger scale city, like Auckland, might be misleading as the size of Auckland sewerage system and individual facilities are bigger than the ones in Christchurch in general. Secondly, the variable of LRI is a qualitative scale and defined according to the LRI map created based on the liquefaction phenomenon in Christchurch. The generalisation of the LRI in the restoration model needs a universal definition of the severity of liquefaction hazard, in conjunction with expert judgement. Lastly, the variable of reconstruction operation types (repair/renewal) is significantly affected by post-earthquake decision making and often case-specific. Thus, keeping the decisions on sewer reconstruction consistent in other cities or countries could help apply the restoration model. In conclusion, in order to apply the restoration model to other cities or counties, based on the results of random sampling validation process, adding the data regarding asset attributes, seismic hazard parameters, and reconstruction operations of the targeted areas could significantly improve the prediction accuracy of the restoration model.

8.5 Chapter summary

In answer to the Objective 3c of the thesis (Section 1.2), this chapter presented a statistical approach for predicting sewer restoration time in the aftermath of earthquakes. Four candidate statistical models or approaches, namely: AFT, CPH, RSF, and MLR, were compared, finding that the RSF approach shows the best prediction power for estimating restoration time of the sewer pipelines within the same areas. The usage of the RSF in different geographical areas may have inherent limitations. Furthermore, key variables that have a significant influence on predicting the restoration duration of sewer pipelines were identified in preparation for future seismic events.

CHAPTER 9

CONCLUSIONS AND FUTURE WORK

9.1 Introduction

This chapter summarises the objectives, main findings and contributions of this thesis in Section 9.2 and the future research directions identified in Section 9.3.

9.2 Contribution summary

The process of restoring impaired sewerage systems post-earthquake to regain normal capability and serviceability presents both opportunities and challenges. The opportunities are for decision makers to upgrade the system facilities and enhance system resilience while rebuilding/repairing the system components. The challenges faced are to make rational decisions under pressure and take effective and efficient actions to implement them for accomplishing predefined recovery targets.

In view of the contributions undertaken by SCIRT and the limited platforms/tools supporting decision-making in sewerage systems recovery after earthquakes available in literature, the key questions have been identified are: 1) how to document and reuse the practices and experience that have been deployed in support of the post-earthquake recovery of the sewerage system in Christchurch; 2) how to provide rapid yet reliable information support for decisions on sewer recovery for future earthquakes.

The findings and contributions made in the thesis are given in line with the identified research objectives.

Objective 1: To investigate, document and review the decision making process conducted for sewerage network recovery in Christchurch

In answer to this research objective Chapter 3 was composed. The object (i.e., the CSS) and the motivations (i.e., the CES and the associated damage to the CSS) of the decision making process for recovering the CSS were investigated. The organisations involved in the post-earthquake restoration of the CSS and the rebuilding strategies undertaken by SCIRT were documented. Furthermore, the decision making process on sewer recovery was scrutinised and reviewed in detail.

The findings allow for a better understanding of the institutional structure of the local and central authorities responsible for sewerage recovery in Christchurch, thereby facilitating the exploration of the informational needs for decision making conducted by the recovery authorities from nationally and internationally. The documented decision making process provides an exemplar for recovery authorities facing decisions in relation to sewer recovery after disasters. Furthermore, it demonstrates how data can influence decision making and the close relationship between data collection and decision making on sewerage system recovery. It is hoped that the findings could encourage increased financial investment in post-earthquake data management.

Objective 2: To identify information requirements for the decisions in relation to post-earthquake sewerage network restoration

In answer to this research objective Chapter 4 was composed. A combination of research approaches, including archival study, observations, and semi-structured interviews were employed for collecting data and evidences by engaging with participants involved at various tiers in the post-earthquake recovery and reconstruction, specifically the Christchurch recovery.

Six salient CSFs for strengthening post-earthquake infrastructure recovery were identified. They were categorized into three groups, namely: governmental requirements, technical requirements, and information requirements. In particular, the governmental needs include the establishment of a recovery vehicle and a flexible funding plan while technical needs involves the selection of a recovery driver, determination of a prioritisation methodology and a standardized data collection and management mechanism. The information requirements for infrastructure recovery post-earthquake refer to: 1) physical and functional impacts on infrastructure systems; 2) hydraulic, structural, environmental, social, and economic consequences that may arise from the impaired infrastructure systems; and 3) estimated sewer restoration duration of post-earthquake recovery.

The various requirements identified herein enable decision makers to concentrate on key aspects when project-managing post-disaster recovery operations for infrastructure systems. Furthermore, they allow for a proactive framework to be built for mitigating potential risk and minimising disruptive loss for future reference.

Objective 3a: To provide tools to assess earthquake-induced physical damage to sewerage pipelines

In answer to this research objective Chapter 6 was composed. The four databases related to the CSS were analysed, namely: 1) Christchurch sewerage network inventory; 2) closed circuit television (CCTV) inspection database; 3) combined completed repair database; and 4) completed renewal database.

The main findings are: a) there should be a threshold of damage per pipe set in order to make efficient use of CCTV; b) for those who are estimating potential damage, care must be taken in direct use of repair data without an understanding of the actual damage modes; c) a strong correlation was found between the ratio of faults to repairs per pipe and the estimated peak ground velocity.

The results disclose the extra benefit that damage data can provide over repair data for wastewater networks specifically for seismic fragility analysis. Moreover, they guide others in the development of sewer decisions after disasters.

Based on field observation and the literature study, a seismic fragility matrix was developed as a simplified fragility assessment tool for identifying seismic fragility of sewer pipelines. Sewer pipes, categorised according to pipe materials and liquefaction zones, are classified into three qualitative fragility groups (i.e., high, medium, and low) in the fragility matrix.

The fragility matrix could be of specific use for buried pipelines, for the definition of scorecard approaches and/or vulnerability indexes and/or rapid screening approaches (as the ones widely available for buildings e.g., FEMA 154).

Fragility functions and fragility curves were produced for sewer gravity and pressure pipelines sorted by pipe materials and liquefaction zones. It was assumed that the fragility functions follow a lognormal cumulative distribution in a form of three-parameter fragility functions. The fragility functions were developed using a maximum likelihood estimation by correlating PGV with damage ratio (defined as number of faults per km) for SGP and with repair rate, defined as number of repairs per km for SPP. Furthermore, the proposed fragility curves of SPP were compared with those defined for WPP in the international literature, showing a reasonably good agreement on the RRs of SPP. However, it is shown that the fragility functions defined for WPP slightly underestimate the number of repairs on SPP due to the large number of SPP nearby waterways damaged by severe liquefaction and associated lateral spreading during the Canterbury earthquakes. By comparing DR of SGP and RR of SPP, it is concluded that fragility functions derived for SPP underestimate the physical damage to SGP.

The developed fragility functions can be directly applied to quantitatively estimate earthquake-induced physical damage to sewer pipes given a ground motion level for the preparation of rebuilding program. Furthermore, they can assist in seismic risk mitigation of sewerage pipelines before earthquakes.

Objective 3b: To provide tools to evaluate hydraulic, environmental, structural, economic and social impacts that have arisen from the malfunction of sewerage systems

In answer to this research objective Chapter 7 was composed. Built on the experience and learning of SCIRT in reinstating the resilience of the CSS, a set of PIs was proposed for assessing loss of wastewater service and the induced functional impacts in three different phases: emergency response, short-term recovery and long-term restoration. The developed PIs aim to evaluate holistically the structural, hydraulic, environmental, social and economic consequences that might arise due to the earthquake-induced physical damage to sewerage components. This includes sewer pipelines, PSs, manholes and council-owned laterals.

The proposed PIs are deployed to quantitatively evaluate post-earthquake states of sewerage system components for tracking asset performance and functionality to be compared with the expectations of asset managers and customers. Moreover, they enable asset managers to disclose the underlying issues in the recovery practices and elicit potential solutions to the identified issues, based on the performance evaluation results.

Objective 3c: To provide tools to predict the time required to restore the damaged sewerage systems

In answer to this research objective Chapter 8 was composed. A database combining pipe attributes, seismic hazard characteristics, restoration operations, and pipe restoration time was created and analysed. Statistical analysis was conducted for determining a statistical approach to estimating the time required to restore sewerage systems after an earthquake and for testing the adaptability of the proposed approach to other areas.

Four candidate statistical models/approaches, namely: AFT, CPH, RSF, and MLR, were compared and validated using two types of validation datasets spatially selected in Christchurch. The random sampling validation process shows that the model built by use of the method of RSF outperforms other models and provides 80 % of correct classification rate. The out-of-sample validation process concludes that the usage of the RSF in different geographical areas may have inherent limitations. Based on the prediction results, the important variables were identified, ranking as PGV, restoration operation, pipe depth, liquefaction zone, diameter, pipe type, pipe depth, and soil type. The serviceability restoration curves with confident intervals were also plotted.

It is of benefit to acquaint both decision makers and local community with the restoration time estimates. Based on the sewer restoration time estimate, decision makers could better allocate rebuilding resources (e.g., crew, budget) for action and distribute portable and chemical toilets for providing temporary sanitation service. The logistical arrangement (e.g., number, location) of the distribution of the temporary sanitation facilities, to a certain extent, depends on the estimated reconstruction time. From serviceability viewpoints, local community can be informed of the time needed to restore their service so that they can better prepare for the lack of sanitary service.

Objective 4: To develop a framework for supporting decision making on sewerage system restoration after earthquakes

In answer to this research objective Chapter 5 was composed. A framework was proposed for supporting the decisions in relation to wastewater system recovery after earthquakes. The decision support framework is comprised of three modules, namely: (a) PDM (Chapter 6), (b) FIM (Chapter 7), and (c) PRM (Chapter 8). The proposed decision support framework, through the PDM, assesses and estimates the earthquake-induced physical damage to the wastewater systems. Given a certain level of seismic hazards, the framework could assess and/or predict the number of faults or repairs sustained by the sewerage system components, categorised by component attributes (e.g., material). Then, the FIM are utilised to evaluate the functional impacts on the impaired wastewater systems and to estimate the expected consequences on the community, environment and economy, by means of the set of

PIs established in Chapter 7. Finally, accounting for the pre-earthquake asset conditions of the different components and the post-earthquake time and financial constraints, the PRM of the decision support framework can estimate the time to restore the sewerage service after earthquakes.

The decision support framework could provide decision-makers with pertinent knowledge and information when, for instance, selecting repair/reconstruction strategies and allocating resource in the move towards an effective and informed reinstatement of sewerage systems after earthquakes. In addition, the proposed decision support framework can be potentially used to support system upgrade and maintenance by guiding system rehabilitation and to monitor system behaviours during business-as-usual time. In conjunction with expert judgement and best practices, the framework can be applied to assist sewer asset managers to target resilience enhancement as part of asset maintenance programmes.

9.2 Identifying future research

9.3.1 Fragility analysis

In Chapter 6 fragility functions of sewer gravity and pressure pipes were presented. As mentioned before, there are limited physical defects detected in severe liquefaction zones because the CCTV inspection cannot be extensively conducted in the area due to restricted accessibility. New fragility functions should be developed once the data in relation to the physical damage to sewer pipes in these zone will be available. In this way, the new fragility functions, together with the ones developed in the thesis can be utilised to estimate in different states of liquefaction zones and non-liquefaction zones. Moreover, when observation data/evidence regarding pipe damage modes is available, fragility functions should be classified with respect to distinct damage modes/mechanisms. The advancements could be made towards prediction of the type of physical damage to sewer pipes.

9.3.2 Functionality evaluation

Chapter 7 demonstrated a set of PIs for evaluating the functional impacts and hydraulic, structural, environmental, social, and economic consequences caused by the earthquake-induced physical damage. In line with the research objective 3b, the set of PIs is intended to be applied in the post-earthquake circumstance. Further advancements in a systematic, multiple-context, performance evaluation framework for sewerage systems could be pursued by developing a comprehensive series of PIs to examine sewerage system performance at both business-as-usual time and post-earthquake context. These PIs are desired to combine the PIs that have been produced in this thesis and the ones designed for daily maintenance, such as annual financial budget.

9.3.3 Restoration prediction

The literature review revealed that no statistical restoration model has so far been developed for sewer systems, in particular for a post-earthquake context. Thus, four candidate models/approaches were examined herein and validated using two validation datasets, namely: random sampling and out-of-sample validation datasets. The RSF predicts the restoration time of the random sampling validation dataset very well whilst the prediction accuracy for out-of-sampling validation dataset is not ideal. In order to apply the restoration model to other cities or counties, based on the results of random sampling validation process, adding the data regarding asset attributes, seismic hazard parameters, and reconstruction operations of the targeted areas could significantly improve the prediction accuracy of the restoration model.

In this analysis, it is assumed that the restoration resources are unconstrained and there is no extra waiting time for crews to travel to work, for reconstruction materials to arrive and for budgets to be allocated. Additionally, the unit crew number per task and crew professional levels are assumed as uniform. This is because of a paucity of detailed information and data relative to restoration resources. The author notes, however, in reality, the contractors and/or time for crews traveling from home to work and resting during work, material and machinery transporting, and traffic management play a significant role in predicting restoration time and should be accounted for in developing estimates of restoration time. Although the dependent variables in relation to restoration resources could reflect the real situation of post-earthquake sewer restoration, whether the inclusion of the variables could improve prediction power of proposed models needs further investigation.

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Appendix A - R code for developing restoration models for sewer pipelines

```
library(googlesheets)
library(dplyr)
gsd <- gs_title("Database")
dat <- gsd %>% gs_read(ws = "Sheet1")

# reformat and summarise data
dat$Type[dat$Type == "Gravity "] <- "Gravity"
dat$Type[dat$Type == "Pressure "] <- "Pressure"


mdat <- dat %>% group_by(x, y) %>% summarize(time=max(Time),
                                  Depth=mean(Depth),
                                  Length=mean(Length),
                                  PGV=mean(PGV),
                                  LRI=sample(unique(LRI), 1),
                                  Diameter=mean(Diameter),
                                  Soil=sample(unique(Soil), 1),
                                  Type=unique(Type),
                                  Operations=unique(Operations))


sdat <- as.data.frame(na.omit(subset(mdat, x < 1590000 & y < 5190000)))
sdat$LRI <- as.factor(sdat$LRI)
sdat$Soil <- as.factor(sdat$Soil)
sdat$Type <- as.factor(sdat$Type)
sdat$Operations <- as.factor(sdat$Operations)
sdat$sqlength <- sqrt(sdat$Length)
sdat$sqdepth <- sqrt(sdat$Depth)
library(ggplot2)
#ggplot(sdat, aes(x=x, y=y, colour=time)) + geom_point()
```

```
library(survival)
library(randomForestSRC)


# separation into training and validation data
# validation data is a random subset (not a specific region)

# specific region for validation
 sdat$isin <- with(sdat, x >= 1575000 & y <= 5177500)
 sdat$isin <- with(sdat, x < 1570000 & y > 5180000)
 sdat$isin <- with(sdat, x > 1575000 & y > 5180000)

reps <- 100

 res <- mclapply(1:reps, function(j){

  sdat$isin <- rbinom(1:nrow(sdat), 1, 0.25)

   # random location choosing neighbours with smallest Euclidean distance, to define a
        random location with 25% validation data
rx <- range(sdat$x)
ry <- range(sdat$y)
cx <- runif(1, rx[1], rx[2])
cy <- runif(1, ry[1], ry[2])
dists <- apply(sdat[,c("x", "y")], 1, function(i) sqrt((cx-i[1])^2 + (cy-i[2])^2))
qdist <- quantile(dists, 0.25)

sdat$isin <- dists < qdist

#   # only short time repairs
sdat$isin <- with(sdat, time > 1000)

   tdat <- droplevels(subset(sdat, isin == 0))
```

```
vdat <- droplevels(subset(sdat, isin == 1 &
                          LRI %in% levels(tdat$LRI) &
                           Soil %in% levels(tdat$Soil) &
                           Type %in% levels(tdat$Type) &
                           Operations %in% levels(tdat$Operations) ))


ggplot(sdat, aes(x=x, y=y, colour=as.factor(isin))) + geom_point()
 tdat$status <- 1



 # linear regression
 linm <- step(lm(time ~ (Type + Operations + LRI + Soil + sqdepth + sqlength + PGV +
        Diameter)^2,                          data=subset(tdat, status == 1)), trace=0)
 vdat$lmpred <- predict(linm, newdata=vdat)


 # random forest
 rsf <- rfsrc(Surv(time, status) ~ Type + Operations + LRI + Soil + sqdepth + sqlength +
        PGV + Diameter, data=tdat)
 prf <- predict(rsf, newdata=vdat[,-3])
 vdat$rfp <- apply(prf$survival, 1, function(x) min(prf$time.interest[x <= 0.5]))


 # survival/Weibull regression
 sr <- step(survreg(Surv(time, status) ~ (Type + Operations + LRI + Soil + sqdepth +
        sqlength + PGV + Diameter)^2, data=tdat, dist="weibull"), trace=0)
 vdat$srpred <- predict(sr, newdata=vdat, type="response")


 sr2 <- step(survreg(Surv(time, status) ~ (Type + Operations + LRI + Soil + sqdepth +
        sqlength + PGV + Diameter)^2, data=tdat, dist="exponential"), trace=0)
 vdat$sr2pred <- predict(sr2, newdata=vdat, type="response")


 sr3 <- step(survreg(Surv(time, status) ~ (Type + Operations + LRI + Soil + sqdepth +
        sqlength + PGV + Diameter)^2, data=tdat, dist="loglogistic"), trace=0)
 vdat$sr3pred <- predict(sr3, newdata=vdat, type="response")
```

```
  cp <- step(coxph(Surv(time, status) ~ (Type + Operations + LRI + Soil + sqdepth +
        sqlength + PGV + Diameter)^2, data=tdat), trace=0)
  scph <- survfit(cp, newdata=vdat)
  vdat$cphpred <- apply(t(scph$surv), 1, function(x) min(scph$time[x <= 0.5]))


  tseq <- seq(0, 1600, by=1)

  err <- sapply(1:length(tseq), function(i){
   rbind(linm=mean((vdat$time <= tseq[i]) == (vdat$lmpred <= tseq[i]) | (vdat$time >=
        tseq[i]) == (vdat$lmpred >= tseq[i])),
        rsf=mean((vdat$time <= tseq[i]) == (vdat$rfp <= tseq[i]) | (vdat$time >= tseq[i]) ==
        (vdat$rfp >= tseq[i])),
        sr1=mean((vdat$time <= tseq[i]) == (vdat$srpred <= tseq[i]) | (vdat$time >= tseq[i])
        == (vdat$srpred >= tseq[i])),
        sr2=mean((vdat$time <= tseq[i]) == (vdat$sr2pred <= tseq[i]) | (vdat$time >= tseq[i])
        == (vdat$sr2pred >= tseq[i])),
        sr3=mean((vdat$time <= tseq[i]) == (vdat$sr3pred <= tseq[i]) | (vdat$time >= tseq[i])
        == (vdat$sr3pred >= tseq[i])),
        cph=mean((vdat$time <= tseq[i]) == (vdat$cphpred <= tseq[i]) | (vdat$time >=
        tseq[i]) == (vdat$cphpred >= tseq[i])))
  })
  return(err)
 }, mc.cores=5)

save(res, file="bscverror_inter_res.rda")

load("bscverror_res.rda")

ares <- array(unlist(res), dim=c(6,1601,reps))
aq <- apply(ares, c(1,2), quantile, probs=c(0.025, 0.5, 0.975))
matplot(t(aq[2,,]), type="l", ylim=c(0,1), lty=1)
matplot(t(aq[1,,]), type="l", ylim=c(0,1), lty=2, add=TRUE)
matplot(t(aq[3,,]), type="l", ylim=c(0,1), lty=2, add=TRUE)
abline(h=0.5, lty=2)
```

```
sm <- stack(as.data.frame(t(aq[2,,])))
sm$time <- rep(1:1601, times=6)
sm$model <- as.factor(rep(c("lm", "rsf", "s1", "s2", "s3", "cph"), each=1601))
sm$lower <- stack(as.data.frame(t(aq[1,,])))$values
sm$upper <- stack(as.data.frame(t(aq[3,,])))$values

sms <- droplevels(subset(sm,  model %in% c("lm", "s1","rsf")))

ggplot(sms, aes(x=time, y=values, colour=model)) +
geom_line() +
geom_line(aes(y=lower, colour=model), lty=2, alpha=0.7) +
geom_line(aes(y=upper, colour=model), lty=2, alpha=0.7) +
ylim(c(0,1)) +
theme_bw() +
geom_hline(yintercept=0.5, lty=2) +
ylab("Correct Classification Rate") + xlab("Time [days]") +
scale_colour_discrete("Model") + scale_fill_discrete("Model")


load("bscverror_inter_res.rda")

ares <- array(unlist(res), dim=c(6,1601,reps))
aq <- apply(ares, c(1,2), quantile, probs=c(0.025, 0.5, 0.975))
matplot(t(aq[2,,]), type="l", ylim=c(0,1), lty=1)
matplot(t(aq[1,,]), type="l", ylim=c(0,1), lty=2, add=TRUE)
matplot(t(aq[3,,]), type="l", ylim=c(0,1), lty=2, add=TRUE)
abline(h=0.5, lty=2)
sm <- stack(as.data.frame(t(aq[2,,])))
sm$time <- rep(1:1601, times=6)
sm$model <- as.factor(rep(c("lm", "rsf", "s1", "s2", "s3", "cph"), each=1601))
sm$lower <- stack(as.data.frame(t(aq[1,,])))$values
```

```
sm$upper <- stack(as.data.frame(t(aq[3,,])))$values

ggplot(sm, aes(x=time, y=values, colour=model)) +
geom_line() +
geom_line(aes(y=lower, colour=model), lty=2, alpha=0.7) +
geom_line(aes(y=upper, colour=model), lty=2, alpha=0.7) +
ylim(c(0,1)) +
theme_bw() +
geom_hline(yintercept=0.5, lty=2) +
ylab("Correct Classification Rate") + xlab("Time [days]") +
scale_colour_discrete("Model") + scale_fill_discrete("Model")
```