The financial implication of the three design guidelines used during the Christchurch rebuild

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A thesis submitted in partial fulfilment of the requirements for the Degree of Master of Engineering (Construction Management) in the University of Canterbury

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Abstract

With the occurrence of natural disasters on the increase, major cities around the world face the potential of complete loss of infrastructure due to design guidelines that do not consider resilience in the design. With the February 22nd, 2011 earthquake in Christchurch, being the largest insured event, lessons learnt from the rebuild will be vital for the preparation of future disasters.

Therefore the objective of this research is to understand the financial implications of the changes to the waste water design guidelines used throughout the five year rebuild programme of works. The research includes a study of the SCIRT alliance model selected for the delivery that is flexible enough to handle changes in the design with minimal impact on the direct cost of the rebuild works. The study further includes the analysis and compares the impact of the three different guidelines on maintenance and replacement cost over the waste water pipe asset life. The research concludes that with the varying ground conditions in Christchurch and also the wide variety of materials in use in the waste water network up to the start of the CES, the rebuild was not a 'one size fits all' approach.

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Abbreviations

AC	Asbestos Cement
BOQ	Bill of quantities
CBD	Central business district
CCTV	Closed Circuit Television
CES	Canterbury earthquake sequence
CIPP	Cured in place pipe
CPI	Cost performance index
CRCI	Centre for resilience of critical infrastructure
CRR	Cyclic resistance ratio
DI	Ductile Iron
DPS	Delivery performance score
ECI	Early Contractor Involvement
EW	Earthenware
GDP	Gross Domestic Product
LOS	Level of Service
LRI	Liquefaction resistance index
IPSG	Infrastructure project steering group
IRMO	Infrastructure rebuild management office
IRTSG	Infrastructure rebuild technical standards and guidelines
IST	Integrated services team
ITP	Inspection and test plan

KRA	Key result area
NZTA	New Zealand Transport Authority
NOP	Non-owner participant
OP	Owner-participant
PE	Poly-Ethylene
PVC	Polyvinyl Chloride
RCRRJ	Reinforced concrete rubber ring joint
RUL	Remaining useful life
SPI	Schedule performance index
SSC	Scope and standards committee
SCIRT	Stronger Christchurch Infrastructure Rebuild Team
TOC	Target Outturn Cost
WSC	Work Scope Change

Chapter 1 – Introduction to study

Background

Natural disasters around the world are increasing and according to the United Nations, during the 10 years from 1992 until 2012, 4.4 billion people were impacted, USD 2 trillion of damage occurred and 1.3 million people were killed as a result of natural disasters (United Nations Office for Disaster Risk Reduction, 2015). It is becoming more important for funding organisations such as insurers, local councils, central governments and transport organisations to accurately understand the cost of repair to infrastructure. Accurate costing requires not only knowledge of the cost of initial repairs but also of the repercussions of the chosen repair methodology on future maintenance costs. Structural solutions may be more expensive than 'quick fixes' but seen over a longer term they may still be the better choice. Funders could be mostly concerned with the initial repair expenditures. The asset owners may need to have a more long term view, balancing capital and operational expenditure (Pelling, Ozerdem, & Barakat, 2002).

Literature review

New Zealand is located on the boundary of the Australian and Pacific tectonic plates and experiences about 30 earthquakes a year of magnitude greater than 6. Most of these earthquakes are centred on the tectonic boundary along the east coast of the north island and the west coast of the south island. Christchurch is New Zealand's second largest city and the largest on the south island. The Canterbury plains experience about 1-2mm of movement per year as a result of the collision of the two plates. Christchurch was considered a moderate seismic zone in a country with high seismic activity because historically the earthquakes affecting Christchurch were as a result of distant faults (Kenneth, et al., 2014)

Since the start of the CES in September 2010, Christchurch has recorded 12,778 earthquakes in and around the region. During this period the most significant earthquakes included the Mw 7.1 on the 4th of September 2010, the Mw 6.2 on the 22nd of February 2011, Mw 5.6 and Mw 5.6 separated by 80 minutes on the 13th of June 2011 and the Mw 5.8 and Mw 5.9 separated by 80 minutes on the 23rd of December 2011 (Nicholls, n.d.). During the February 22, 2011 earthquake, 185 lives were lost in Christchurch as buildings collapsed along with thousands of homes being extensively damaged.

The city also suffered significant damage to its vital infrastructure many inner city businesses were disrupted for a prolonged period as the CBD was cordoned off to allow demolition of critically damaged buildings to proceed. The land damage suffered in Christchurch was particularly unique; nowhere else in the world had liquefaction been repeatedly experienced across such a great expanse (van Ballegooy, et al., February 2014). In Christchurch most of the liquefaction occurred in the eastern suburbs, where nearly 400,000 tonnes of silt mixed with waste water and caused a significant health risk (Heiler, Moore, & Gibson, 2012).

The total cost of damage is estimated to be around 10% of New Zealand's GDP (Parker & Steenkamp, 2012) and the Christchurch earthquake is ranked as one of the most expensive natural disasters since 1950 (Doherty, 2011).

Disaster recovery projects are comparable with major infrastructure projects (Koria, 2009) and to date major infrastructure projects have a history for incurring cost overruns, which are often due to ineffective risk management and the lack of accountability (Flyvberg, Bruzeluis, & Rothengatter, 2003).Alliance contracting is used as a procurement model where organizations work collaboratively by sharing responsibility and risk (Eriksson, 2010). The risk associated with the unknown scope of works (Eriksson, 2010), the urgency to reinstate damaged infrastructure post disaster as quickly as possible (Koria, 2009) and the risk of further seismic activities made an alliance an ideal procurement model.

Horizontal infrastructure, due to its often linear extent, can be vulnerable to geological hazards and is therefore at an increased risk of suffering damage in a natural disaster. (Free, Anderson, Milloy, & Milian, 2006). This loss of infrastructure causes a significant impact on the physiological and economic impact on communities. The reconstruction of these projects should aim to reduce the vulnerability of societies through building back better infrastructure (Palliyaguru & Dilanthi, Managing disaster risks through quality infrastructure and vice versa, 2008). A lack of resilience in infrastructure could lead to ongoing disruptions, poor recovery following a disaster and also increases the likelihood of permanent loss of the infrastructure (Hudson, Cormie, Tufton, & Inglis, 2012).

Due to the diverse range of topics covered in this research more detailed literature reviews are included in chapters 2, 3, 4, 5 and 6.

Aim and objectives

During the rebuild programme of Christchurch's horizontal infrastructure, three different design guidelines were used for designing the repairs to the waste water network. These design guidelines were refined throughout the duration of the rebuild the repair works moved from the worst affected eastern suburbs to the lesser damaged western suburbs. The initial design guideline was based on number of breakages in pipes and lead to the replacement of entire pipe lengths if a certain number of breakages occurred. This was followed by a level of service approach. The subsequent guideline looked at deferring repairs to damaged pipes with at least 15 years of remaining asset life (Heiler, Moore, & Gibson, 2012). The final design guideline allowed for an asset to be repaired using a value approach.

The main aim of this research is to evaluate what the implications were on the asset life using each of the three design guidelines for asset owners. With the value of the waste water repair works estimated to be 65% of the $2,2 Billion infrastructure rebuild programme, this will be the main focus. The main objectives therefore are:

- Evaluate the financial performance of the SCIRT alliance model
- Develop a method to compare the RUL for each of the design guides
- Discuss the comparison of the remaining asset life of each design guide
- Give recommendations concerning design guidelines post disaster.

Methodology

The infrastructure rebuild programme in Christchurch has been selected for a case study because an alliance form of contracting has to date not being used for disaster recovery projects. According to Yin it is acceptable to use a single case study for research (Yin). The methodology used for the research includes a qualitative analyses of the alliance model and the design guidelines used during the rebuild. It also include quantitative analyses of the financial performance of projects delivered during the rebuild programme of works as well as the financial implication of the three design guidelines used.

Lessons learned from the horizontal infrastructure rebuild programme in Christchurch will be used as a case study for the financial impact of different design guidelines for the design of the repairs of waste water network. This is in line with the objectives of the World Conference on Disaster Risk Reduction in 2005 and will assist with decision making for future disaster risk reduction (United Nations, 2005).

Research structure

This thesis includes three chapters been used as the basis for journal articles covering the objectives of the research. A brief summary of the chapters is as follows:

Chapter 2 discusses the alliance procurement model used to deliver the rebuild works. This chapter concludes that this multi-client multi-contractor alliance is different to more commonly used “classes” of alliances, in the procurement of design services, the introduction of a DPS to provide price tension between the NOPs that ensures value for money for the client organisations, while the gain/pain incentive ensures collaboration across the delivery teams. It also has an independent TOC development with no price influence from the delivery teams.

Chapter 3 analysed 288 projects constructed during the SCIRT rebuild with varying levels of ECI input. The financial performance of projects undertaken across the alliance programme with varying levels of ECI input indicates that there is a significant improvement in cost performance and cost accuracy of TOC projects with ECI input, whether informal or documented.

Chapter 4 evaluates the 3 design guidelines. The chapter discusses how the repair works varied from completely rebuilding the network in some parts to other parts where no or little amount of repairs are required as the existing network provides varying levels of resistance to the natural disaster.

Chapter 5 evaluates the application of the design guidelines across the city and in particular in relation to land damage caused by liquefaction.

Chapter 6 compares the financial implications of the 3 design guidelines used during the rebuild on the indirect cost of the waste water network. Depending on the design criteria for determining earthquake damage, the financial implication of the rebuild could have significant implications for the asset owners in terms of RUL and maintenance cost over the life of the asset.

Chapter 2 Christchurch rebuild, New Zealand: alliancing with a difference

Botha P.S, Scheepbouwer E, Christchurch rebuild, New Zealand: alliancing with a difference.

Proceedings of the Institute of Civil Engineers Management, Procurement and Law volume 168 June 2015 Issue MP3 Pages 121-129

Introduction

Immediately following the September 2010 earthquake a programme of works managed by the local City Council was established to repair the broken infrastructure. This programme was referred to as IRMO. In effect, the city was sub-divided into four geographical areas called "pods" each being allocated to a reputable national construction company who in turn engaged a design consultant to provide the necessary professional services. The programme worked well and provided an instant response for what now could be described as a modest amount of earthquake damage. The SCIRT alliance was subsequently formed to deliver the programme of works for the rebuilding of Christchurch's horizontal infrastructure. The horizontal infrastructure to be repaired by SCIRT includes the water supply reticulation and reservoirs, waste water reticulation and pump stations, storm water reticulation and pump stations, roading networks for both Local Council and National Roads Agency include bridge repairs and retaining walls. These networks are commonly referred to as asset types in the SCIRT rebuild programme.

In addition to being able to incorporate a substantial portion of IRMO projects either in construction or well advanced in the design the model had to effectively manage the high risk associated with the unknown scope of work involved in disaster recovery projects, the pressures on schedule performance, co-ordination of resources and a need to have access to ECI during the detailed design phase to reduce risk by providing constructability input. (Song, Mohamed, & AbouRizk, 2006) This made alliancing an ideal procurement model (Department of Treasury and Finance, 2006) , (Eriksson, 2010).

SCIRT has been setup as a *multi-client, multi-contractor alliance* to deliver the programme of works associated with the rebuild. The programme of works is made up in a large number of smaller projects. This chapter discusses the commercial framework of the SCIRT alliance.

Methodology

The form of alliance developed for the delivery of the infrastructure rebuild has some unique features and Data has been collected through the studying of the alliance agreement and the most recent versions of the management plans. Certain clarifications on the interpretation of the commercial framework as well as the history of the formation of the alliance has been sought by interviewing members of the management and commercial teams within the alliance.

The results from the data collection were compared with available literature on alliance contracts and the differences identified were discussed in this chapter.

The SCIRT Alliance Model

The SCIRT alliance model has been developed to ensure competitive tension by providing the client organisations with value for money.

Alliance Structure

An alliance structure has been created to assess, manage, co-ordinate, prioritise, design, estimate and deliver the various work packages associated with the rebuild of the Christchurch Infrastructure programme. The management team responsible for the above functions is referred to as the IST. The SCIRT alliance structure is shown in *Figure 1 SCIRT Alliance Structure.*

The alliance was created between Central Government, Local Government and NZTA as the OPs and 5 of the major construction companies in the New Zealand civil construction industry as the NOPs.

The NOPs were the same companies that were involved in the IRMO programme. These construction companies formed a Joint Venture which then entered into the alliance with the OPs. A senior executive member of each organisation is represented on the alliance board. The function of the alliance board is to oversee the rebuild programme while the daily management has been delegated to the management team embedded in the IST and oversees the various services required to deliver the programme. In order to prevent price fixing and ensure fair trade practises are being followed as well as to ensure price tension between the delivery teams, the setting of the TOC for each project is done by a dedicated estimating team in the IST and independent of the delivery teams.

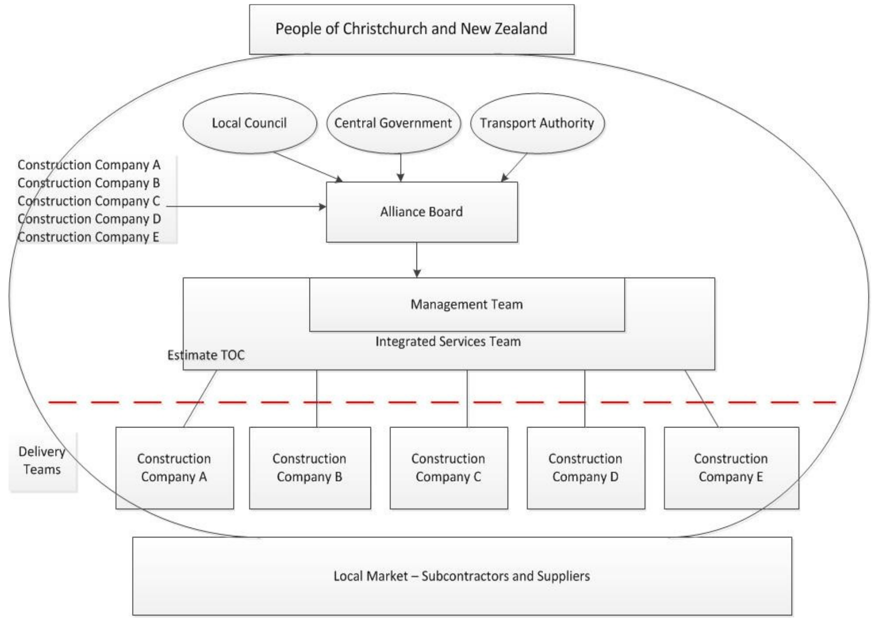

Figure 1 SCIRT Alliance Structure

Commercial Model

Reimbursement of the alliance services will be paid progressively across several categories within the alliance structure as follows:

The actual cost to deliver each project is fully reimbursable with a pain/gain incentive also known as a 3-limb payment structure (see Table 1). Each project will have a TOC, which is the estimated Limb 1 cost to deliver the project. The Limb 2 component for each project is a fixed amount calculated as an agreed percentage to compensate for corporate overheads and assumed profit on the original TOC value. The Limb 2 component for each project will be adjusted when the TOC value is revised through approved WSC. Approved WSC impact on the variance between the actual cost and TOC, which in turn impacts on the Limb 3 component (see *Table 1*) Limb 3 is the aggregated TOC overruns and underruns across the programme of works with 50% share taken by the OPs. The remainder is distributed amongst the delivery teams based on the share of completed TOCs assigned to each individual delivery team expressed as a percentage of the Programme TOC.

The NOPs provide a significant proportion of the resources and services required for the IST to function and are reimbursed actual costs as well as a Limb 2 margin (see *Table 1*) on these costs. The Limb 2 calculation does not apply to any goods and services provided by the OPs.

Each delivery team's off-site overhead TOC is set annually based on the expected turnover for each delivery team for the following financial year. This TOC includes for all staff required to run the business effectively i.e. safety quality and environmental management, commercial, communications teams etc. but excludes any project specific staff such as supervision and project managers. Reimbursement for the cost of the off-site overheads is also paid under a 3-limb commercial framework.

Competitive tension between the delivery teams has been built into the alliance model, with the performance of each delivery team's actual costs measured against the TOC for each individual project adjusted to reflect their performance against the non-cost SCIRT KRA's. This ensures the OPs get value for money, but also provide the ability for benchmarking of each delivery team against other teams. Projects are allocated based on performance; those delivery teams that perform best are allocated a greater share of work than those that perform poorly.

Earned value analysis is undertaken monthly to provide a measure of actual cost and schedule performance of each project but importantly serves as an early warning tool for cost overruns and delays

Table 1 3-Limb payment explained

Target	TOC	TOC established by the SCIRT estimating team and verified by the independent estimator
Payment	Limb 1	Net actual cost reimbursed
	Limb 2	Margin ("offsite overheads & profit") Fixed at percentage of TOC [LS]+agreed percentage x IST costs in proportion to NOPs allocation of the ∑TOC (excludes client supplied goods & services)
	Limb 3	If Limb 1> TOC →pain/ limb 1 < TOC → (gain) If pain = NOPs will pay 50% x pain less a bonus to a max of 10% based on KRA performance

		If Gain = NOPs retain 50% x gain plus bonus to a max of 10% on KRA performance Final distribution in proportion to NOPs allocation of TOCs completed as % of overall programme.

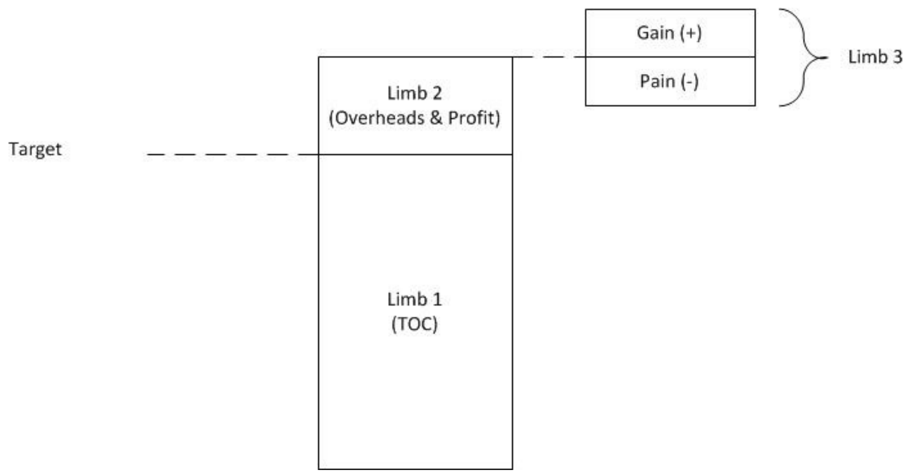

Figure 2 payment model explained showing the difference between Limb 1,2 &3

Project Lifecycle

The project lifecycle in SCIRT is a linear process with a nine point "gate" structure (the gated structure is shown in Figure 3), commencing with asset assessment to determine the extent of damage to the asset. Should the damage be earthquake related, a project is defined and both a design and delivery team are appointed to work towards achieving the most cost effective solution in terms of whole of life cost. Following the completion of detailed design, an Independent and first principles TOC estimate is undertaken within the IST and verified independently through a parallel pricing exercise by a client appointed independent estimator. Final allocation for construction by a delivery team follows TOC completion through a process that is described later in this chapter.

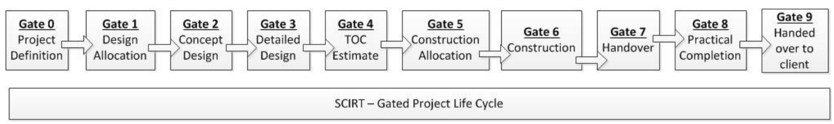

Figure 3 Gated project structure used in SCIRT

Design Services

Four design teams have been established in the IST offices, these teams are a combination of multiple local design consultancy companies in Christchurch that were selected through a tender process. In the SCIRT alliance model, design services for each project is procured from one of the four design teams in accordance with the procurement management plan which outlines a competitive process based on cost performance and abilities of each design team, whilst design cost is reimbursable on a time and cost basis.

SCIRT encourages innovation in design and is allowed to seek departure from the client's design standards and specifications through what is referred to as SSC. This is a committee made up of the various asset owners from the OPs and representatives from central government and NZTA. In order to get approval for a departure during design, the particular lead designer submits a paper with a recommendation and a cost estimate, provided by the estimating team, to SSC for consideration.

Once the design for an individual project is completed, the designers produces a full set of “for construction” design documentation including, drawings, specifications, risk register and a BOQ.

Early Contractor Involvement

Alliance contracting provides an opportunity for construction input during the detailed design phase (see Figure 4) through ECI (Queensland Government Chief Procurement Office, 2008). The purpose of ECI in the SCIRT alliance is for the design team and the dedicated ECI manager and project manager from the delivery team to work collaboratively to ensure constructability opportunities, issues and risks are identified and taken into consideration throughout the design phase of each project. Regular interface meetings are held during the design phases including constructability workshops and risk workshops. The particular delivery team’s ECI manager has the responsibility to lead the interface by chairing the meeting and ensuring that the milestone dates is met (SCIRT, 2012)

Once the detailed design is completed the delivery team receives a copy of the "for construction" documentation to review. On every project the delivery team is responsible for confirming the quantities as derived by the designers accurately reflect the physical works as described by the project documentation.

A further objective of ECI in the SCIRT alliance is to inform the development of a TOC for each project. The ECI team is required to provide the estimating team with a comprehensive set of documentation detailing methodology, schedule, and traffic management staging plans, temporary works as well as an inspection and test plan; they also have the opportunity to review the risk register to ensure the estimator is well informed to develop the TOC.

Immediately prior to estimating a TOC a handover meeting is scheduled between the ECI manager and the estimator to discuss and agree the methodology required to construct the project. The key protocol of the handover meeting is that the meeting is open for discussions around methodology, schedule and risk but any discussion regarding cost is forbidden. This is to prevent price fixing and to ensure the independence of the TOC is maintained. The ECI teams do not have access to the priced BOQ until the TOC has been signed off and allocated to the delivery team for construction. This approach satisfies the requirements as set out by the commerce commission to ensure fair trade practises are being followed and no price fixing occurs.

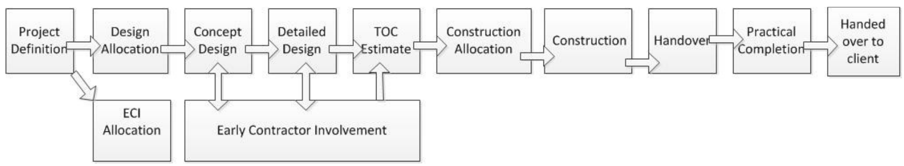

Figure 4 Early Contractor Involvement (ECI) in the project life cycle

Risk

By selecting an alliance model as the procurement option for co-ordinating and managing the city's rebuild, the OPs have expressed their willingness in sharing the risks associated with the programme of works. Risk in the rebuild has been divided in two levels, i.e. programme risk and project risk. An example of a programme risk is the risk of another earthquake causing damage to the newly repaired infrastructure. At the start of the alliance in 2011, the risk of another big earthquake occurring was very high, but over time the geological stresses beneath Christchurch have reduced, consequently the risk of another earthquake causing significant damage also reduces. A change in the design is also a programme risk in that a design change will constitute and adjustment to the original TOC.

The next level of risk is referred to as project risk, these items typically cover risks specific to an individual project such as the risk of trench collapse due to poor ground conditions. Risk on every project is managed with a live risk register that is created in concept design with input from the delivery team, designers, and stakeholder liaison and traffic management staff. The risk register is constantly updated throughout the life of the project. During the preparation of a TOC each risk item is individually assessed and evaluated by means of a first principles approach. Once a TOC has been completed, the resultant provision for risk and opportunity is incorporated into the TOC. The delivery teams are responsible for risk on any quantity discrepancies in the design documentation provided by the designers along with managing the risk during the delivery phase.

Target Outturn Cost for each project

After the detailed design is completed for an individual project, the construction TOC is developed. The TOC is derived using first principles to estimate the value of Limb 1 to construct the project as designed and documented. It includes all the direct cost, based on agreed blended labour and plant rates from each individual delivery team, and market quotes for materials. The TOC also include onsite indirect cost items (supervision and site establishment) as well as an allowance for risk.

One of the benefits of an alliance is the reduction in variations and processing costs of variations or WSCs (Department of Treasury and Finance, 2006). Under this alliance model the TOC can be adjusted for scope amendments that are client instructed or as a result of design changes. Variations in quantities for items on the bill of quantities used to derive the TOC value do not constitute a TOC adjustment.

Monthly Reporting

Each delivery team uses its own company business systems, such as financial software packages and cost reporting structures, to capture the information and to report on the performance of each project. A monthly project progress claim on a life to date basis is submitted by each delivery team for the Limb 1 cost of each project, accompanied by a report with the forecast cost to complete per project (Smith, 2013).

One of the key requirements of the alliance agreement is to report monthly on earned value for each project. Earned value, as an internationally recognised project management tool, that provides an accurate measure of cost and time performance compared to the planned values (Kim, 2009) i.e. the TOC and baseline schedule as developed by the delivery team. Earned value is done by calculating the CPI and SPI for each project.

The IST collates all the information from each delivery team into an overall reporting structure to track and report on the performance of the overall programme as well as forming the basis of calculating the financial performance of each of the delivery team's allocation of future work.

Project allocation

One of the key objectives of the alliance agreement is to reward good performance through future work allocation and applies to both design and delivery teams.

Design team allocation

Design allocation is based on the performance capabilities of each design team as well as the knowledge of the particular asset i.e. waste water design capability or structures design capability within each design team and availability of design resources within each design team. Further to this, the following are also considered for design allocation by the design manager:

Quality – the quality of concept design and detailed design reports, measured based on a modified version of the performance assessment by evaluation system as developed by the NZTA (Topham, December 2012), and also the value of design WSCs. Cost – performance against TOC, the average number of design hours to design $1M of work and the value of innovation captured and assessed on the value register.

Timeless – delivery of reports and designs against target dates, average time to deliver $1M of design.

Delivery team allocation

The default position at the start of the programme was to split the work allocation equally by TOC value between the delivery teams, with five teams the default position was to allocate 20% work by TOC value per delivery team.

The allocation of work is a two-step process taking the following into account:

Part A: Influence of delivery team performance against KRA's and cost performance against TOC for each project.

Part B: Influence of delivery team capacity and other programme context.

Although the delivery team performance model is formal, it provides flexibility to allow an overall "best for programme" decision to be made in the allocating a project for instance if one team is over committed and cannot deliver a project on the scheduled time, it might be allocated to another team who has resource available.

Part A – 5 Non-cost KRA's have been identified in the alliance agreement while a set of KPI's have been developed for each of the KRA's to measure the performance of each team against the non-cost KRA's by calculating a DPS for each delivery team on a 6 month weighted rolling average as follows:

Table 2 Non-Cost KRA's

Key Result Area (% weighting)	Key performance indicator (weighting)
Safety (25%)	Measure of safety engagement /awareness (12.5% Safety initiatives/action (7.5%) Protection of utility services (5%)
Value (30%)	Productivity (12%) Construction quality (9%) Innovations (9%)
Our Team (15%)	Alignment & involvement of team (7.5%) Wellbeing initiatives (3.75%) Developing a skilled workforce (3.75%)
Customer Satisfaction (20%)	Community & stakeholder satisfaction with product (8%) Community & stakeholder satisfaction with communication (8%) Planning & execution of communication strategies (4%)
Environment (10%)	Construction culture & incident/hazard reports (6%) Waste minimisation (4%)

Part B- The cost performance of each delivery team is measured for allocated projects under construction and in handover as aggregated earned value per delivery team/ costs to date and a combined performance score is calculated. The overall performance score is calculated and each delivery team's standard deviation is calculated to determine the change in target work share split.

Discussion

Due to the complexities and high risk associated with disaster recovery projects an alliance has been chosen as procurement model (Department of Treasury and Finance, 2006) and was setup between central and local government in partnership with five of New Zealand's major construction companies to co-ordinate resources and managing the rebuild programme.

The design services for each project are being procured from contracted design consultants that are required to reside full –time in the IST offices, reporting to the management team within the IST. In this particular form of alliancing, due to the complexity of the commercial model and the number of companies involved, it was decided from the outset that the design consultants would not become formal participants of the alliance and therefore do not share in the gain/pain as in the more conventional alliances (Department of Treasury and Finance, 2006).

The delivery teams are however required to provide ECI into the design of each individual project by providing constructability input to ensure the design is optimised to reduce risk, reduction in project cost and improved performance against the schedule through collaboration (Jergeas & Van der Put, 2001), (Osipova & Eriksson, 2011). An objective of the ECI process in SCIRT is to inform the independent TOC development, once the design is completed, to ensure the methodology used to develop the TOC estimate is safe and constructible while all construction risks have been identified (SCIRT, 2012).

The success of this alliance therefore relies heavily on trust and commitment between all parties involved while lessons learned is a key factor in problem-solving and a collaborative approach to proper risk assessment and management on future projects (Davis & Love, 2011). The principal of a two stage ECI process is not too dissimilar to a conventional ECI procurement process where the contract is formally awarded for delivery at the completion of detailed design and price development (Queensland Government Chief Procurement Office, 2008).

In alignment with the SCIRT alliance agreement, good performance will be rewarded through future work allocation (SCIRT, 2011); this was done with the introduction of the DPS. The DPS has been designed to ensure the best performing team in all areas of the programme i.e. safety, value, quality, environmental, cost and stakeholder liaison is rewarded with future work allocation, but also to drive innovation by introducing price tension in a collaborative environment (Teece, 1992). This reduces the reputational risk of the alliance by ensuring that a non-performing delivery team is not exposing the alliance to poor work performance, but also ensures value for money to the client organisations.

Partnering as a procurement model has been developed to avoid disputes and improves cooperation between all parties because the construction industry has long been criticised for its lack of cooperation (Davis & Love, 2011). The DPS is the centre of the commercial model in that future work allocation depends on the DPS performance of individual delivery teams, while future work allocation in turn influence the off-site Preliminary and General which is based on expected annual turnover. The best performing team would, as a result of more work being allocated, be able to successfully grow its business and employ more staff. The Limb 3 calculation is shared in relation to the amount of projects performed as a percentage of the programme of works, which is the same with other forms of alliance contracts (Department of Treasury and Finance, 2006). However the SCIRT alliance agreement rewards good delivery performance through work allocation, which in turn will result in a bigger gain/pain share for the best performing team. Therefore the DPS is creating price tension between the delivery teams while the

Limb 3 gain/pain share incentive ensures collaboration between the alliance participants throughout the project lifecycle (Love, Davis, Robert , & Edwards, 2011).

The development of the TOC independently, from the delivery team, within the IST is based on blended plant and labour rates. These blended rates represent the average plant and labour rates that each of the delivery teams agreed with the Independent Estimator on an annual basis and claim as part of their Limb 1 cost per project. The blended rates for labour used in the TOC build up include all uplift cost such as over time, medical allowances, training, personal protective equipment etc. whereas plant rates include all cost including replacement value and maintenance cost. Material prices are market related as quotations from various suppliers and or specialist subcontractors are being obtained by the IST estimating team during the estimating process. The TOC estimate is a first principles build up, but the actual procurement of the works is a business decision for the delivery team whether to self-perform, the use subcontractors to help ease with resource availability, any specialist subcontractors as well as which suppliers to use. To ensure that the TOC is fair and market related, an independent estimator performs a full parallel estimate for every project based on the same design documentation, using the same blended rates, but not necessarily accepting the same methodology and once alignment is reached i.e. within 2% of the overall value, following a discussion and alignment of assumptions on price variances for activities listed in the bill of quantities, the TOC is reviewed by senior IST management staff and released for construction allocation. The TOC is not a complete open book in that the delivery teams do not have insight into the price build up until the TOC has been allocated after sign off with the independent estimator, but also because it is based on blended rates. Each project is then delivered by one of the delivery teams as on a cost reimbursable basis, with a gain/pain share arrangement while the financial performance of the delivery team is measured against the TOC.

Compensation for physical works completed is based on actual cost incurred by the delivery teams. Each company has its own collective agreement with labour unions, these agreements vary between the employers and as a result there is no consistency between the delivery teams in terms of base wage rates, medical benefits, amount of over time etc. The total cost of employment i.e. including over time etc. is a reimbursable Limb 1 cost for each of the delivery teams. The possible implication of this is that some of the construction companies might have different staff benefits or higher base salary rates which mean that their labour cost might be higher than the TOC allowance for labour and as a result could impact on their performance against TOC.

The same also applies to the procurement of specialist subcontractors and suppliers, which are business decisions for each of the delivery teams, could be different to what is allowed for in the TOC and could potentially impact on the cost performance against the TOC, thus impacting on their DPS.

Conclusions

SCIRT as a multi-client, multi-contractor alliance has been setup to manage the rebuild of Christchurch's damaged civil infrastructure with some significantly different features to the more familiar "classes" of alliance contracts. In this form of alliance, the design teams are on cost reimbursable agreements as opposed to a conventional alliance where the design consultancy is a NOP of the alliance and share in the gain/pain of the overall project performance.

Another unique characteristic of this alliance is to reward good delivery team performance on projects through future work allocation which is achieved by means of the project delivery allocation process. This is done by means of a DPS which is used to evaluate the performance of each of the delivery teams against the construction TOC of each project and the SCIRT non-cost KRA's as agreed by the alliance board. The tension of the DPS and the collaboration of the gain/pain share drive innovation and ensuring value for money for the client organisations.

Within the SCIRT alliance model the development of the construction TOC for each project is an independent process with no price input from the delivery teams.

ECI is included in the alliance model, which means the TOC development is well informed and constructability advice is available during the design and TOC development.

Chapter 3 Relationship between ECI and Financial Performance in the Rebuilding of Infrastructure in Christchurch

Botha Paul, S. Scheepbouwer Eric Relationship Between Early Contractor Involvement and Financial Performance in the Rebuilding of Infrastructure in Christchurch, New Zealand.

Transportation Research Record: Journal of the Transportation Research Board. No 2504, Transportation Research Board, Washington, D.C., 2015 pp.66-72

Introduction

ECI is provided by the delivery teams as a structured process to provide design teams with constructability advice, ensuring issues and construction risks are identified to enable them to be taken into consideration throughout the design process (Ekaterina & Eriksson, 2011). The objective of ECI in SCIRT is to ensure the independent TOC pricing is well informed in terms of a safe methodology and construction associated risks identified are properly assessed. In present research the financial data from 288 projects that are in construction, handover and practical completion are assessed to illustrate the cost certainty of TOC projects that have had ECI.

This chapter provides a better understanding of the financial performance of the rebuild programme.

Literature Review

One of the benefits of alliance contracting is having access to construction personnel during the design phase of the project to help make more informed decisions to optimise the design and managing risks through a collaborative approach by all parties involved (Department of Treasury and Finance, 2006).

To date major infrastructure projects have a history for incurring cost overruns, which are often due to ineffective risk management and the lack of accountability (Flyvberg, Bruzeluis, & Rothengatter, 2003). Commitment to partnering from all parties involved, early involvement of contractors during the design, the identification of risk, trust and relationships have been identified as key factors for mitigating risk and also the success of TOC projects (Chan D. W., Chan, Lam, & Wong, 2010), (Davis & Love, 2011), (Chan, Chan, & Lam, 2012).

Methodology

A quantitative analysis on which this chapter is based was done using the actual monthly financial data of 288 projects that are either in construction, handover or practical completion gates, as at the end of February 2014, in the SCIRT rebuild programme. The results of the analysis have been verified through discussions with the programme's Risk Manager, other members of the commercial and management team and delivery team members in addition to comparing with available literature on ECI and alliance contracting. Other possible contributing factors such as procurement of subcontractors, experience of staff, risk events that may have occurred on site etc. have not been taken into consideration during this analysis.

Early Contractor Involvement in the SCIRT rebuild

In the SCIRT rebuild programme each delivery team has to engage a dedicated ECI manager that works collaboratively with the design teams to provide constructability input into the design to ensure all construction risks have been taken into consideration during the design (Ekaterina & Eriksson, 2011). This is achieved through regular meetings as well as risk and constructability workshops. The interface meetings are led by the ECI manager from the delivery team who is also responsible for ensuring all key milestones are met (SCIRT, 2012).

At the end of the detailed design phase the ECI manager's responsibility extends to ensure that the required deliverables are submitted for consideration by the estimator when pricing the work activities to construct the project. The key deliverables required are methodology, traffic staging details, construction schedule in bar chart format, an updated risk register and an ITP. It is also the responsibility of the ECI manager to review the bill of quantities prepared by the designers to confirm that it accurately reflects the scope of works and also tie in with the proposed methodology to construct the work safely. *(See* Table 3 Key roles and responsibilities during ECI*).*

Table 3 Key roles and responsibilities during ECI

ECI Team member	Responsibilities
ECI manager from delivery team	Lead and chair ECI team interactions Ensuring key dates are met Review of BOQ
Design lead	Identify and communicate design parameters and issues Evaluate input from delivery team and integrate modifications as required to the design and risk register
Delivery lead/ project Manager	Communicate construction methodology and any associated issues Required to evaluate input from designer and make modifications as required to the methodology and risk register

At the commencement of pricing the works and, following the submission of the ECI deliverables and design documentation to the estimator, the estimator, ECI manager and the independent estimator arrange a handover meeting during which the project is discussed and any concerns or differences on methodology are resolved and agreed. During this meeting discussions around methodology, duration and risks are encouraged but any discussion around price is prohibited to ensure the independence of the TOC and to prevent any direct influence from the delivery teams.

The ECI process also provides the delivery team with the opportunity for early construction planning in that it gives an opportunity to understand the project and plan for construction. One of the key deliverables also required for pre-construction planning is the traffic staging information, which is also to be submitted for approval by the local authorities prior to construction commencement to inform the council of potential road closures and detours etc.

In the SCIRT alliance model, construction allocation follows TOC sign off and is based on the DPS. Providing ECI input during the design of each project is no guarantee that the project will be allocated to the delivery team who provided ECI input during the design and TOC gates for each project.

Target Outturn Cost

On completion of the detailed design of a project, the TOC for each project is estimated by a member of the team of resident estimators within the IST seconded to SCIRT from the 5 construction companies.

Each TOC is set independent of any financial input from the delivery teams. The TOC is determined from a first principle build-up using plant and labour rates as agreed with the independent verifier, employed directly by the OPs, and material supply pricing from the market. Each TOC is signed off by the independent verifier once alignment is reached following a parallel estimating process (Office of the Auditor General, November 2013).

Once a TOC has been signed off and the project allocated to a delivery team for construction, a TOC can only be adjusted through an approval process referred to as WSCs. A WSC is only approved for design changes, client instructions and project definition changes. Once the WSC is approved and evaluated, the original TOC value is adjusted and issued.

Defined periods within the programme of works

With the quick transition from disaster to rebuilding the infrastructure, three distinct periods within the programme of works have been identified to date i.e. transition, ramp-up and steady state. A fourth period will occur gradually across the programme which is the ramp-down. During this period staff and contractors will transition out of the rebuild programme back to a "business as usual" environment. Each of these periods has some unique characteristics that have significantly impacted on the financial performance across of the programme of works.

Transition Period

After the signing of the alliance agreement in September 2011, all the projects identified under IRMO that were in design and construction stage were transferred to SCIRT. Projects with designs that were either completed or well advanced were estimated and constructed under the SCIRT alliance commercial model (Office of the Auditor General, November 2013). During the IRMO period, a close relationship was established between contractor and design consultancy, the designs were well informed albeit it mainly for small emergency repair projects; the identified construction risks were well developed and incorporated into the design and construction methodologies identified albeit very informally. These projects were procured on a basis similar to a typical design and construct project, where each contractor had independently engaged and managed a design consultancy to provide the professional design services.

The projects that were transferred to SCIRT with designs that were well advanced were prioritised for construction during the Transition period between October 2011 and February 2012. These projects were mostly water mains although the first of the gravity waste water projects were estimated and delivered during this period. *(See table 2 for average transition period project size)*

Ramp-up period

SCIRT has an obligation to complete the programme of works within a set period of time (Office of the Auditor General, November 2013). In order to achieve this, a certain volume of work was scheduled to be completed per month across the programme. This in turn requires every gate in the process to meet a minimum monthly target. Once the designs of the smaller projects were completed, the prioritisation of catchments was well advanced and the design of larger projects was able to be undertaken. During the ramp-up period, from about March 2012 through to October 2012, a greater number of complex projects were designed than during the transition period. These were typically large diameter pressure mains, waste water pump stations and civil structures such as bridges. In order to meet the programme completion date of December 2016, a minimum monthly construction spend was required. Resource availability and competency of construction personal are constraints for resourcing a natural disaster recovery programme (Chang & Wilkonson, 2012). Due to the increase in project size, a lack of resource from delivery teams while the systems and procedures in the IST were still being developed, ECI input during the design was limited. During this period there was very little formal risk and constructability workshops etc. as everyone was focussed on constructing the work packages in the field. As a result the design and TOC development of the projects during the ramp-up period were not well informed.

During this period the programme as a whole across all delivery teams suffered a significant blow out against TOC for each project. Because of the pressure to demonstrate progress and give the people of Christchurch confidence in the rebuild, projects during this period were designed and priced with a less than optimal constructability input. This meant that some designs were at risk of being incomplete and the independent TOC development was uninformed as to the correct methodology and associated risks all because of minimum ECI. The ramp-up period also saw a significant increase in project size which occurred during a time when the SCIRT business systems and reporting structures was still being developed *(See table 2 for average ramp-up period project size)*. Due to the pressure of constructing the increased volume of work during the ramp-up, the delivery teams had to increase their workforce which led to inexperienced staff (Chang & Wilkonson, 2012) being brought into the concept of alliance contracting. Other factors such as procurement of subcontractors and suppliers have also contributed to the financial performance of some of the projects during this period.

Steady state

As the staff became more familiar with the SCIRT processes and business systems were developed, ECI input became a formalised and documented process. During the current steady state period, from November 2012 to date, there has been an increased focus from SCIRT on improving the constructability input into the design and informing the independent TOC development through as per the ECI guidelines (SCIRT, 2012).

Projects designed during this period, had risk workshops and constructability workshops that are being attended by the nominated ECI team to provide constructability input into the design and ensuring that all construction risks have been identified and mitigated in the design where possible. During the current steady state period, a formal handover meeting and site visit is scheduled by the delivery team with the estimator to ensure that the methodology and risks are understood and taken into consideration for TOC development. Discussions are permitted around methodology, risk and duration but discussions on cost remain prohibited. *(See* Table 4 Average project size (in millions) per period in the SCIRT programme*)*

Table 4 Average project size (in millions) per period in the SCIRT programme

Programme Period	Number of Projects	Mean ($) Project size 000	Std. Deviation 000
Transition	55	591	1,507
Ramp-up	94	2,027	2,931
Steady-State	139	3,792	4,188
Total	288	2,604	3,635

Data Analysis

The month end financial data as at the end of February 2014 was analysed taken into consideration all 288 SCIRT projects from all 5 delivery teams that are in construction, handover and practical completion. The available data consist of project number, project name, programme period, delivery team name, design team name, gate the project is currently in, TOC completion date, date deliverables were submitted, original TOC value, revised TOC value (adjusted after approved WSCs), cost live to date and forecast final cost, pain/ (gain) *(see figure 4 for pain/(gain) calculation)*. All statistical analyses were performed using SPSS version 20.

A normality test of the % pain/ (gain) as the dependant variable per period of projects with deliverables submitted has been performed and was found to be approximately normally distributed using the Normal Q-Q plot. A univariate analysis of variance was calculated and the estimated marginal means of the % pain/ (gain) per period in the programme were analysed in order to assess the financial impact of ECI input in to the estimate of the TOC for each project. *(See* Equation 1*).*

$$\% \text{ Pain/(Gain)} = \frac{\text{Forecast Final Cost} - (\text{Original TOC} + \text{approved work scope changes})}{\text{TOC}}$$

Pain = Positive %
Gain = Negative %

Equation 1 Pain/(Gain) Calculation

Results

Financial Performance of the SCIRT programme

From the calculation of the average pain per period of the SCIRT programme, it is evident that the programme performed differently throughout the duration of the rebuild. During the transition stage in the early stage of the programme the programme performed really well with a (1.62%) gain. During the current steady state, the programme is showing a significant improvement in the financial performance against TOC albeit slightly in pain of 0.86%. *(See* Table 5 Estimated average gain/pain per period of the programme*)*

Table 5 Estimated average gain/pain per period of the programme

Programme Period	Number of Projects	Mean Pain/(Gain)	Std. Error of mean	95% Confidence Interval	
				Lower Bound	Upper Bound
Transition	55	(1.6%)	4.8%	-11.1%	7.6%
Ramp-up	94	12.0%	3.7%	4.7%	19.2%
Steady-state	139	0.9%	3.0%	-5.1%	6.8%

The difference in pain/(gain) between the transition stage and the ramp-up is 10.4% while the difference between the ramp-up and steady state is 11.1% *(See table 3),* with an average of 10.75% financial improvement of projects with ECI input during design and price development. The large variance in the upper and lower bound of the mean pain/gain is indicative of the big variance in the performance of some individual projects. There are various other factors that are not related to ECI such as procurement of subcontractors and suppliers, project management and also the costs associated with realised risks that significantly impact on the financial performance of projects.

Financial impact of projects with ECI deliverables submitted

ECI during the transition period was interactive and informal, which was as a result of the designs being developed during the IRMO arrangement. The design of these projects were completed during the IRMO period where the designers were reporting directly to the construction company. When these projects were transferred to the SCIRT programme for estimating and construction, there was no requirement from the IST to submit the ECI deliverables for the estimate to be completed. Communication with the estimator was also encouraged during the transition period and although some projects did not received formal deliverables, the communication with the estimator was informative.

During the ramp-up some projects have started before the design and TOC was completed. As a result very little effort from the delivey teams was put in to properly inform the design and TOC estimate as they were under pressure to start constructing the projects in order to maintain confidence in the rebuilding of the citys' damaged infrastructure. There was also no requirement during the ramp-up to get the deliverables submitted prior to the TOC being signed off, nor was there any communication with the estimator. Towards the end of the ramp-up period the ECI guidelines were released combined with the instruction from the IST that no construction activity is to start priot to the finalisation of a TOC.

During the steady state period the TOCs are not allowed to be released prior to the deliverables being submitted and any differences with regards to the methodology have been resolved. However, at the start of the steady state there were some projects that were already being estimated that did not receive deliverables on time.

For the analysis in *Table 6* the estimated marginal mean of projects with ECI deliverables submitted were analysed as per the 3 periods in the programme to date. For this analysis the date the deliverables was uploaded onto the SCIRT document control system was compared relative to the date the TOC was signed off and released through the TOC gate for construction allocation. From an estimating perspective deliverables submitted late is the same as no deliverables submitted, but from a project perspective deliverables submitted late still indicates that pre-planning of construction has been undertaken for the project.

Table 6 Estimated marginal means of the pain/ (gain) of projects with ECI deliverables relative to TOC sign off date

Programme period	ECI Deliverables submitted	Number of Projects	Mean % Pain/ (Gain)	Std. Error of the Mean	95% Confidence Interval	
					Lower Bound	Upper Bound
Transition	Not Submitted	51	0.2%	4.6%	(9.0)%	9.4%
	Deliverables late	4	(24.8 %)	16.4%	(57.7%)	8.1%
Ramp-up	Not Submitted	59	14.3%	6.5%	1.5%	27.1%
	Deliverables late	27	10.4%	9.5%	(8.5)%	29.4%
	Deliverables on time	8	(0.1%)	17.5%	(34.9%)	34.7%
Steady state	Not Submitted	21	4.1%	4.9%	(5.5%)	13.8%
	Deliverables late	57	2.6%	3.0%	(3.3%)	8.4%
	Deliverables on time	61	(0.3%)	2.9%	(5.9%)	5.4%

The 4 projects in the transition period with deliverables that were submitted late have an average gain of (24.8%) but because of the small sample size the standard error of the mean of 16.4% is large. Considering the upper of 8.1% and lower bound of (57.7%) for these projects it could be argued that pre-construction planning made a significant difference in the performance of these projects.

During the ramp-up, projects that have had no deliverables submitted has the biggest average pain in the programme of 14.3%, while projects during the same period that have had deliverables submitted on time has an average gain of (0.1%) which means that there is an improvement of 14.4% against TOC of projects that have had deliverables submitted on time during the ramp-up period. During the same period there is a 3.9% improvement of performance against TOC for projects in the ramp-up that have had deliverables submitted late and therefore have had the benefit of pre-construction planning.

Projects in the steady state that have had deliverables submitted on time are performing similar to the projects in the transition period with no formal deliverables submitted. The projects in the steady state that have had deliverables submitted late or not at all are in pain and performing slightly worse than the projects in the steady state with deliverables submitted but better than the projects in the ramp-up.

The combined estimated marginal mean pain/ (gain) of projects that have not had deliverables submitted or submitted late for TOC sign off during the steady state period is 3.0% while the projects in the same period that have had deliverables submitted have an estimated marginal mean gain of (0.30%) which indicates that there is a 3.3% improvement in performance against TOC on projects where the estimate and design is well informed.

Conclusions

The SCIRT alliance model was developed for all parties to work collaboratively to optimise the design solution through reducing risk by having access to ECI into the design of a project. ECI not only provides constructability input into the design, but also significantly informs the TOC estimate of each project and therefore gives the client organisation price certainty of the cost of the work. It is evident from analysing the financial data that with the programme broken into three distinct periods with varying ECI input into the design and TOC development that projects that have had ECI input during design and TOC setting are performing better financially and provides the client organisations with price certainty. ECI during detailed design and price development also provides early value transfer to the client organisations, through significant improvement of financial performance of projects.

By preparing the ECI deliverables that are required for developing the TOC, the delivery team by definition, is undertaking a substantial component of the pre-construction planning of a project This is evident from the result of projects that have had deliverables submitted late for the TOC development still perform better than projects that have had no deliverables submitted at all.

ECI, whether informal and interactive or formal and documented, provides price certainty to client organisations by providing construction input during the design by identifying the construction risks. Good procurement practises and project management techniques is still required for the successful outcome of construction projects as ECI input into the design and price development is not a guarantee for the financial performance of a project

Chapter 4 Earthquake recovery versus routine maintenance of the waste water network in Christchurch.

Botha Paul S, Scheepbouwer Eric, Earthquake recovery versus routine maintenance of the waste water network in Christchurch.

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Introduction

Immediately following the 22nd of February 2011 earthquake, a desk top assessment of the damage and a cost estimate of the repairs needed was completed and submitted to central government, with the expectation that as more information becomes available on the extent of the damage the estimate will be revised. Immediately following the February earthquake it became apparent that the design guidelines used prior to the earthquakes was inadequate and did not cover earthquake repairs sufficiently as it lacked resilience in the design. As a result the IRTSG was developed by the city council, this design guideline stipulated the intervention criteria for repairing the damaged waste water network which meant if the number of breaks in a pipe exceeded a certain number then the total length of pipe was replaced and it also allowed the use of more modern materials in the rebuild.

One of the first priorities of SCIRT was to undertake asset investigations of the asset types including the waste water network. The waste water network in Christchurch consists of more than 1600km of gravity pipelines. With over half of New Zealand's CCTV resource assisting with the CCTV programme undertaken by SCIRT, the estimated time to complete the investigation was expected to be 4 years from October 2011 when the alliance agreement was signed (Cubrinovski, et al., Performance of Horizontal Infrastructure in Christchurch City through the 2010-2011 Canterbury Earthquake Sequence, 2014). With December 2016 as the planned completion date of SCIRT (Office of the Auditor General, November 2013) and the asset investigation forming a critical component of the programme for informing the design teams, SCIRT developed a range of assessment tools, including visual inspections and a pipe damage assessment tool (Heiler, Moore, & Gibson, 2012). These tools were all used to assist in assessing the damage to the waste water network across the city. As the asset assessment programme progressed and more information on the damage of the network became available, the design requirements were reviewed and adjustments made to the design guidelines.

SCIRT also developed a prioritisation tool for prioritising the repair work by recognising the worst affected areas as the highest priority. Generally, the work commenced with the deeper waste water repairs, followed by the roading, water supply and storm water. Geographically the work started in the eastern suburbs where most of the liquefaction and subsequent pipe damage occurred and progressed towards the least affected western suburbs.

During the second half of 2012, the estimate for the rebuild of Christchurch's horizontal infrastructure was updated based on more accurate information on the damage in the network as well as the cost associated with the repairs. As the investigation works progressed and moved further west, it became apparent that not all the damage required immediate repair actions and as a result significant changes to the design guidelines were developed and approved by SSC. These amendments to the design guideline recognise the remaining asset life of the pipes with the aim of restoring the network to the same level of service as prior to the earthquakes and also offered a significant saving to the client organisations with less repair work included in the rebuild programme of works

In 2013 central and local government signed a cost share agreement for the repair of Christchurch's infrastructure and as a result of this agreement an optimisation process was initiated in 2014. During this optimisation process the design guidelines for the repair of the waste water network was further refined to repair only critical assets where there is value in doing so and if the asset was impacting on the performance of other assets (Trout, 2015). As part of this optimisation process, the IPSG was formed. This group was made up of representatives of the client organisations' asset managers as well as financial advisers from central government and replaced the SSC for all further approvals of technical decisions and amendments to specifications and design guidelines. During the optimisation process a new design guideline (DG43B) as a further refinement to the IRTSG for waste water design was developed by central government which became the basis for their financial contribution for the remainder of the programme of works. The local council also developed a refinement to this design guideline (DG43A-1) that accepted blockages in lower grade pipes as less critical for repairs than the integrity of the pipe. The remainder of the waste water projects designed by SCIRT were designed in accordance with both design guidelines followed by a cost review once the designs were completed. The proposed designs were submitted to the IPSG with a recommendation and if the client organisations agreed to the merit of additional scope added to DG43B the scope was adjusted for construction, or else DG 43A-1 formed the design used for the rebuild of the particular project (Trout, 2015).

The present research will be evaluating the waste water design guidelines and amendments used during the rebuild of Christchurch's horizontal infrastructure rebuild programme. Here the progressive development of the guidelines to recognise the remaining asset life of the waste water pipe network, together with the differences between the design guidelines will be discussed.

Literature Review

According to Alexander Hay, a natural disaster can be shown as the performance levels of infrastructure against time. The performance levels of infrastructure can drop as low as zero during an event with the immediate emergency response bringing the performance level of infrastructure back to a minimum performance capacity. This is followed by a more organised response period to bring the performance levels up to a minimum level of sustainability. It is during the recovery phase that the performance levels are restored to the same routine level as prior to the event. (Alexander, 2014) Figure 5 Timeline showing resilience showing performance of infrastructure

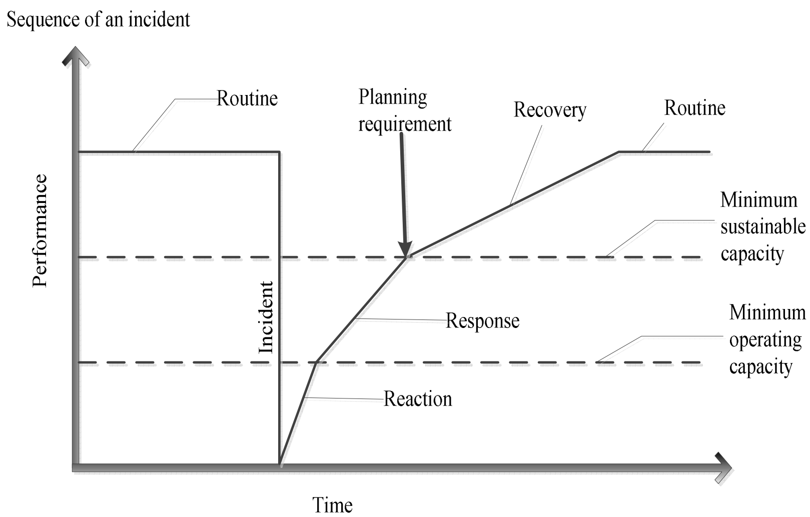

Figure 5 Timeline showing resilience showing performance of infrastructure (Alexander, 2014)

Christchurch has a very flat terrain, with an average slope of 0.1% - 0.2% from the western suburbs towards the east near the coast line. The city's existing waste water network consist of mainly gravity pipes installed in the middle of the road with minimum cover of 1.2m. Due to the flat topography of the land, the grades in the gravity system is significantly less than normal waste water networks with velocities of less than 0.7m/s. As a result of the flat grades traditional maintenance included regular flushing of the network with water from shallow wells. Since 1986, when the drainage board manual was last revised, more robust self-cleaning velocities were introduced. The currently used waste water design guidelines do not eliminate the need for flushing but only encourage more reliance on self-cleaning (Christchurch City Council, 2015).

The pipe materials used in the development of the network include Earthenware, Concrete, PVC and Asbestos and the materials used was reflective of the preferred choice of materials at the time when parts of the network was developed (Cubrinovski, et al., Liquefaction impacts on pipe networks, 2011). During the CES, different pipe materials performed differently with PVC and PE pipe materials performing better in lateral movement, differential settlement and areas of liquefaction than AC and EW (O'Rourke, et al., 2014), (Cubrinovski, Henderson, & Bradley, Liquefaction Impacts in residential areas in the 2010 - 2011 Christchurch Earthquakes, 2014)

The two main earthquake events i.e. the September and February quakes caused significant damage to the waste water network due to its depth. Following the February 22nd earthquake, 40% of the network had limited to no service following the event with damage to the waste water network, mainly consisted of loss in gravity pipe grades, damage to pipe joints and also high levels of liquefaction infiltration into the network. (Cubrinovski, et al., Liquefaction impacts on pipe networks, 2011). The majority of damage to pipes occurred in areas with high levels of liquefaction, with 80% of broken pipes found in areas of high levels of liquefaction (Cubrinovski, Henderson, & Bradley, Liquefaction Impacts in residential areas in the 2010 - 2011 Christchurch Earthquakes, 2014).

The implications of the broken network ranged from increased overflows into the local rivers which led to consent breaches, significant damage at the city's waste water treatment plant with sand and silt entering the treatment plant and also the use of chemical toilets in especially the eastern suburbs where no service was available immediately following the earthquakes.

Methodology

The research for this chapter is based on a quantitative analyses of the different design guidelines approved and implemented during the infrastructure rebuild programme in Christchurch.

Different design guidelines used during the Christchurch rebuild

During the SCIRT rebuild programme a of number wastewater design guidelines were developed, approved and implemented during various stages within the programme as outlined in *Figure 6 wastewater guidelines used during the Christchurch rebuild.*

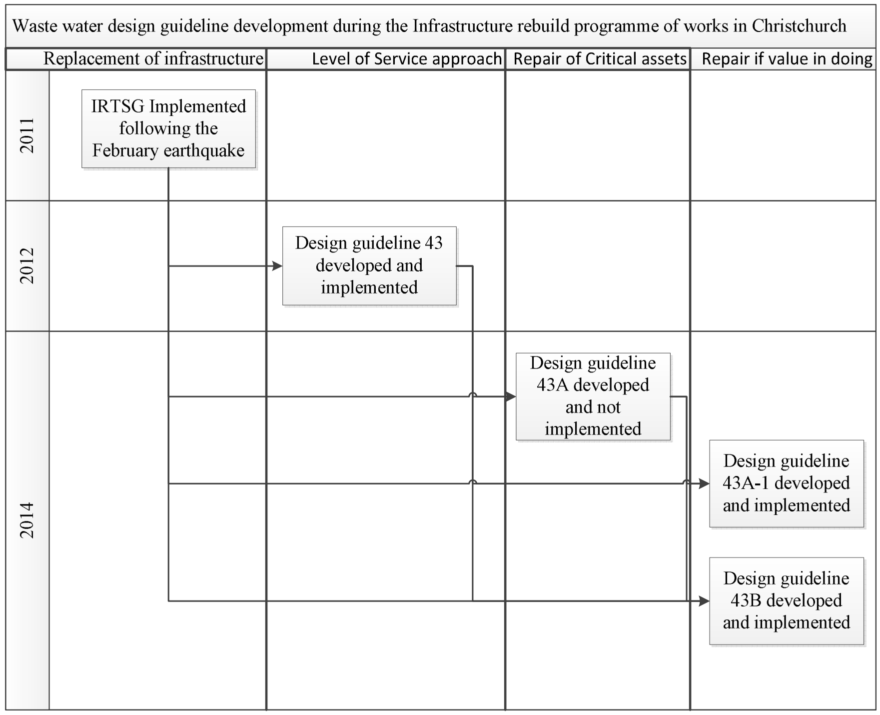

Figure 6 wastewater guidelines used during the Christchurch rebuild

Infrastructure recovery technical standards and guidelines (IRTSG)

The earthquake of the 22nd of February 2011 in Christchurch caused a significant increase in the damage to the city's already damaged infrastructure. A review of the design guidelines used prior to the CES indicated that it did not sufficiently address the repair work to earthquake damage. As a result the IRTSG was developed by the Christchurch City Council and introduced to the rebuild programme in October 2011. The IRTSG was specific in the type of damage that needed repairs i.e. failure in grade or if a pipe length had a certain number of breaks the line was replaced.

Three revisions of the IRTSG were issued, these revisions included refinements to the acceptance criteria of earthquake damage as well as separating construction and service defects identifying during the inspection of the pipe (Heiler, Moore, & Gibson, 2012).

Level of Service Approach

As the waste water network inspections in Christchurch progressed it was realised that not all the damage had to be replaced immediately as the assets still had sufficient asset life remaining. This was recognised by the asset assessment team within the IST who in collaboration with the Christchurch City Council developed a set of design guidelines that was approved by SSC, to provide the designers guidance for assessing earthquake defects in gravity wastewater pipes when utilising asset life where appropriate. This design guideline deferred all defects in the pipe network if the remaining asset life is more than 15 years (Heiler, Moore, & Gibson, 2012).

The design guideline used by the designers for this was SCIRT design guideline 43 as per Figure 6. This document was issued in March 2013, after approval by SSC and revised in October 2013. Approximately 30%

of the network was design and constructed in accordance with this design guideline (Trout, 2015).

Repair of critical assets

Early 2014 design guideline 43A was developed. This guideline, even though not implemented, worked on the basis of addressing only critical repairs that will lead to failure of the particular asset within the next 15 years. This guideline was again developed by SCIRT, and the principals was only applied by SCIRT when approved by SSC.

Repair of assets if there is value in doing the repair works

In June 2013, the cost share agreement between the Christchurch City Council and central government was signed which capped the central government contribution towards the rebuild. This was followed by an optimisation process, initiated by the OPs, and a new set of design guidelines was developed. Design guideline 43 B is very specific in which defects was to be deferred to the maintenance programme by excluding defects pipes with a remaining asset life of more than 5 years from the rebuild programme of works. The local government asset owners developed another design guideline DG 43A-1 as a result of the possible impact on the maintenance budgets of deferred work from DG 43 B. It was agreed between local and central government that the waste water networks will be design in accordance with both design guidelines and at the end of detailed design, only one of the designs will be constructed. The preferred design was selected through a discussion between representatives from both central and local governments based on the cost of doing additional repairs.

These two design guidelines set some parameters around requirements for replacing an asset if it has a remaining life of less than 5 years, the asset was identified as being a critical asset, had a high maintenance cost and was impacting on other assets i.e. may cause localised road failure.

Discussion

The immediate response to the damaged waste water pipes was in the worst affected areas where no service was available. The loss of service was due to the high levels of liquefaction and the pipe materials used for the construction of the existing network. In response to the lack of resilience and to include modern materials in the rebuild, the Christchurch City Council developed and introduced the IRTSG at the start of SCIRT. This guideline provided immediate response to the worst affected areas by specifying the requirements for the replacement of the damaged infrastructure.

The scale of the disaster and the large waste water network placed a significant demand on New Zealand's CCTV resources. This combined with a lack of understanding of the performance of the network across the city meant that a conservative approach in the initial estimate of the rebuild was taken based on the IRTSG. Initially during the rebuild programme, the emphasis was on restoring the service that was lost which resulted in the replacement of some of the pipes without recognition of the remaining asset life.

As the investigation works moved west across the city into areas that experienced much lower levels of liquefaction from the earthquakes and where modern pipe materials such as PVC have been used to construct the original network, the waste water pipes performed better with less damage while service was still available. The reduction in the damage to the network combined with the council's regular maintenance programme, which included the flushing of the waste water network, resulted in the amendments to the design guidelines by taking into consideration the remaining asset life of the pipes.

Conclusions

Each amendment to the IRTSG increased the acceptable remaining asset life of the pipe to be used in the design of the repairs. This resulted in less damage in the network being accepted as earthquake related damage in need of immediate repairs. The implemented amendments to the guidelines therefore became revised damage thresholds of acceptable earthquake damage.

Different damage thresholds applied to different areas in the city because of the varying ground conditions and also different pipe materials performing differently with certain materials performing better than others.

By taking into account the remaining asset life, a considerable saving to the client organisations could be offered by recognising the remaining asset life of the pipes.

Chapter 5 Application of the design guidelines across Christchurch city during the rebuild of the earthquake damaged infrastructure programme

Introduction

This chapter presents information on how the design guidelines, as described in chapter 4, were implemented during the rebuild across the different damaged areas in Christchurch. This chapter also provide support to the financial analyses of chapter 6 in terms of the database and its application in this research.

Background

Christchurch was originally mainly a swamp behind sand dunes, with estuaries and lagoons. These soils overlay the Riccarton gravels, which is also the upper aquifer with artesian pressures. The water tables in the western parts of the city is approximately 5m below the surfaces and gets shallower towards the east where it nearly touches the surface. (Cubrinovski, Henderson, & Bradley, Liquefaction Impacts in residential areas in the 2010 - 2011 Christchurch Earthquakes, 2014).

The first earthquake on the 4th of September 2010 recorded a maximum Peak Ground Acceleration (PGA) of 0.24 g in the CBD. The February

22nd 2011 earthquake recorder several PGAs of between 0.37g and 0.52g in the CBD. (Cubrinovski, Henderson, & Bradley, Liquefaction Impacts in residential areas in the 2010 - 2011 Christchurch Earthquakes, 2014)

The eastern suburbs were the worst hit by liquefaction due to the loose fluvial deposits of liquefiable sand. The high water table combined with the strong ground movement during the earthquakes resulted in high levels of liquefaction (Cubrinovski, Henderson, & Bradley, Liquefaction Impacts in residential areas in the 2010 - 2011 Christchurch Earthquakes, 2014). Buried pipes suffered significant damage in each of the 2 major events (Cubrinovski, Henderson, & Bradley, Liquefaction Impacts in residential areas in the 2010 - 2011 Christchurch Earthquakes, 2014). The damage to the waste water network was caused by loss of grade, broken pipe joints and also liquefaction infiltration (Cubrinovski, et al., Liquefaction impacts on pipe networks, 2011). Significant parts of the city had no service available for up to 3 months following the February 2011 earthquake (Cubrinovski, Henderson, & Bradley, Liquefaction Impacts in residential areas in the 2010 - 2011 Christchurch Earthquakes, 2014).

Immediately following the earthquakes, the primary focus was to restore the services to the worst affected areas. Once the service was restored, an order of priority for the rebuild programme was developed to repair the infrastructure from the worst affected areas to the least affected areas. (Botha & Scheepbouwer, 2016)

Methodology

A quantitative analysis was done using the waste water as-built CCTV database from the SCIRT rebuild programme, which include projects that have been completed and handed over to the Council up to the end of April 2016. The database from SCIRT includes a lot of information for each pipe. The information on the database is captured in the SCIRT GIS system and transferred to the Christchurch City Council asset register software once all the hand-over documentation is completed. At the time of research the rebuild programme is still being undertaken with projects still in construction and as a result the last 8 months of outstanding as-built CCTV data is still to be recorded and verified. Therefore the database is not a complete list of assets assessed and repaired during the rebuild programme of works.

The data includes the original asset register from the Christchurch City Council prior to the start of the earthquakes in 2010. Information from completed SCIRT projects are collected during the as-built process which includes a CCTV inspection of all installed waste water pipes that have been worked on during the rebuild. During the as-built CCTV inspection the information such as repair method etc. are being recorded for each pipe.

At the start of the rebuild, the handover process was not well defined and the information required for SCIRT's own internal records as well as to hand the information back to the Council was not defined until later in the programme. This was due to the initial focus being on getting the construction started as soon as possible to give the residence of Christchurch confidence in the rebuild. As a result the as-built information required was developed after some of the early projects have been completed and as a result some of the information have not being captured correctly. The information captured for each of the pipes on the database are shown in Table 7 & Table 8

Table 7 example of as-built CCTV database information

Project Number	Action	SCIRT ID	Council ID	Status of the service	Pipe type	Date laid	Pipe materials
11130	No action	177019	14234	In Service	Gravity	1/01/1974	RCRRJ
10314	Removed	90015	53950	Removed	Gravity	10/01/1953	uPVC

Table 8 example of as-built CCTV database information

Project Number	Installation Company	Internal Diameter	Pipe length	Shape length	Treatment	Network	Liquefaction Zone	Area Label
11130	Company A	150	21.60	21.60	Lining	WW	1	3-14

10314	Company B	225	22.45	22.39		WW	1	4-11

A detailed explanation of the database is as follows:

Project number

Each SCIRT project has a unique 5 digit number that is allocated at project definition gate (Figure 3 Gated project structure). This unique number is recorded in the document control system and is used to track the progress of the individual project from design through to handover gates.

Action

This is the action taken by SCIRT as recorded for each individual pipe on the database, there are four actions that have been used across the rebuild for all pipes and these are as follows:

No Action

This is used for pipes that have been inspected during the asset assessment and have been included in the catchment of a project. These pipes have been assessed by the designers in accordance with the guidelines and do not meet the criteria for either repair or replacement.

Removed

This is used for pipes that have been removed by SCIRT during the rebuild. These pipes have suffered significant earthquake damage and are beyond repairing as they have lost their serviceability and therefore passed their asset life. Once the individual project is handed back to the City Council the pipes that have been identified as being removed by SCIRT will also be removed from the asset register.

Repaired

This is used for pipes that are able to be repaired during the rebuild. The techniques used for pipe repairs in SCIRT include pipe lining, segment repairs by means of trenchless technology or traditional dig down repairs.

Added

This is used for new pipes that have been installed during the rebuild programme. These pipes are new assets and will be recorded as new on the Christchurch City Council's asset register. There are also instances where new pipes have been installed as part of betterment. The agreement between Central Government and the Council is that if the Council wants to improve the network i.e. increase the pipe size to cater for future population growth etc. then the Council would fund the difference between the original design and the cost of the new infrastructure.

SCIRT ID

SCIRT developed a GIS system and have also created a unique ID for each pipe that has been assessed by the design team. This ID is used for their own internal systems to identify the pipe.

Council ID

The Council has their own unique asset ID which is registered on their asset database in their internal asset management software.

Status of the service

The status of the service is the status at the time of the assessment of the pipe and includes the following:

Abandoned

Pipes that have been removed from the asset register by means of filling with flow able fill are being recorded as abandoned. This often occurs where the existing pipe is below the newly installed pipe. In this instance, the existing pipe is not being removed but being filled up with a low strength concrete mix. This is to ensure that the existing pipe does not collapse over time and create a void that could lead to pipe failures of the newly installed infrastructure.

In service

A pipe is recorded as in service when it is in need of repair or when no action will be taken.

Removed

Existing pipes that have been removed during the rebuild during the excavation where the existing pipe is above the invert level of the new pipe, the existing pipe is marked on the database as removed. These pipes have been taken to landfill sites.

Pipe type

Prior to the earthquakes Christchurch had a gravity waste water network, in most situations the new installations during the rebuild are gravity, in Parklands low pressure is introduced while in Shirley and Aranui vacuum is introduced. These are recorded under pipe type.

Date laid

This is the date the pipe is installed.

Pipe material

During the rebuild, modern day materials were being used for new pipe installs i.e. uPVC, HPDE, Concrete etc. Prior to the earthquakes, the network was considered in reasonable condition even though some of the materials in the network was outdated and no longer being used i.e. Cast Iron, Ductile Iron etc. The materials of the network was recorded on the Council's asset register and made available to SCIRT at the start of the rebuild. Pipes being installed during the rebuild was recorded during the as-built CCTV programme.

Installation Company

The installation company is one of the 5 NOPs who was allocated the project for construction. Pipe assets with no action recorded would not have an installation company name entered against the pipe.

Internal diameter

The internal diameter of the pipe whether new or existing is being recorded. The internal diameter have not always been recorded during the as-built process of the rebuild programme and also not always been recorded on the Council's existing asset register.

Pipe length

This field is used for the length of the original pipe installed.

Shape length

The shape length field in the database is used for recording the length of the repair. If a new pipe was installed then the length of the pipe and the shape length would be the same length. However if the original pipe was repaired by means of a segmental patch repair then the shape length will be recorded as the length of the patch.

Treatment

This is the type of treatment used during the rebuild and include a number of pipe rehabilitation methods such as CIPP lining, Spiral Wounded lining, uPVC fold and form, slip lined and lined patch. For new installation the treatment is recorded as new pipe, while a dig down repair is recorded as a new pipe section.

Network

This is the unique identifier within SCIRT's comprehensive as-built database of all the assets to identify the waste water network within the SCIRT database.

Liquefaction zone

The city has been divided into areas based on the liquefaction resistance CRR settlements and displacements observed following the earthquakes. LRI zone 0 has the lowest CRR value and also experienced the highest amount of settlement in access of 500mm with high levels of liquefaction being observed, while zone 4 has a higher CRR value and less settlement with no liquefaction observed (Cubrinovski, et al., Liquefaction impacts on pipe networks, 2011) (see Figure 7)

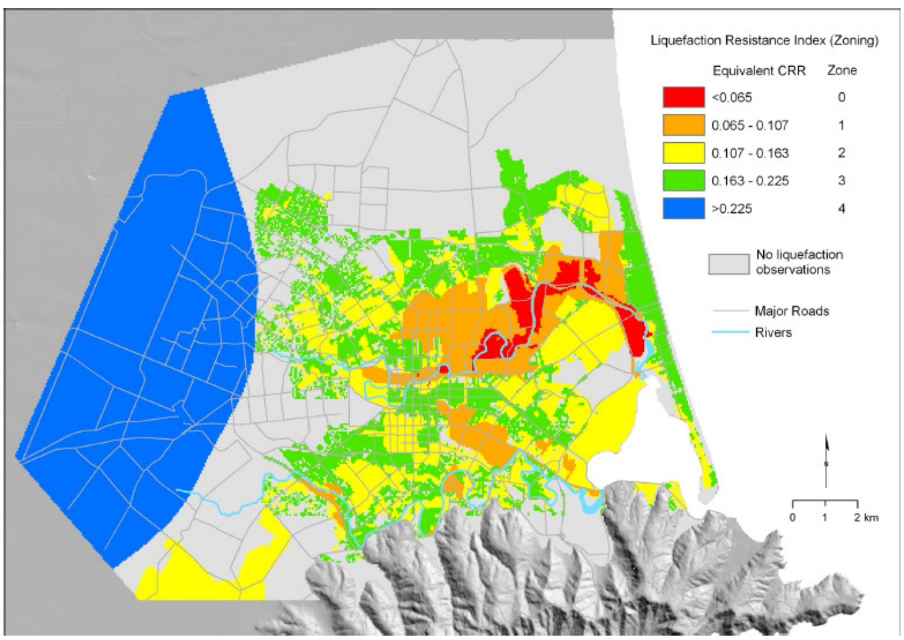

Figure 7 LRI zone at water table depth (Cubrinovski, et al., Liquefaction impacts on pipe networks, 2011)

Area Label

At the start of the SCIRT rebuild programme, the city was divided into 11 main catchments. These catchments were the main identifiers used to identify all the assets within each catchment. For each pipe the original catchment is recorded and is captured on the as-built database.

Data Analysis

As-built information of 11,542 line entries of waste water pipes, recorded on the database, have been analysed using SPSS version 23. For the analyses in this chapter the pipe diameter, design guideline and the damaged area have been used. A frequency test has been performed to calculate the length of pipes repaired. The pipe sizes have been divided into 3 classifications as set out in *Table 9 Explanation of the range of* different pipe sizes for the data analyses.

Table 9 Explanation of the range of different pipe sizes

Pipe diameter classification	Diameter range
Small	<250mm dia.
Medium	250mm to 450mm dia.
Large	450mm dia. to 1600mm dia.

Pipe entries in the early stages of the rebuild do not have nominal diameter recorded because these fields were not filled in during the field verification. These items have been discounted from the analysis.

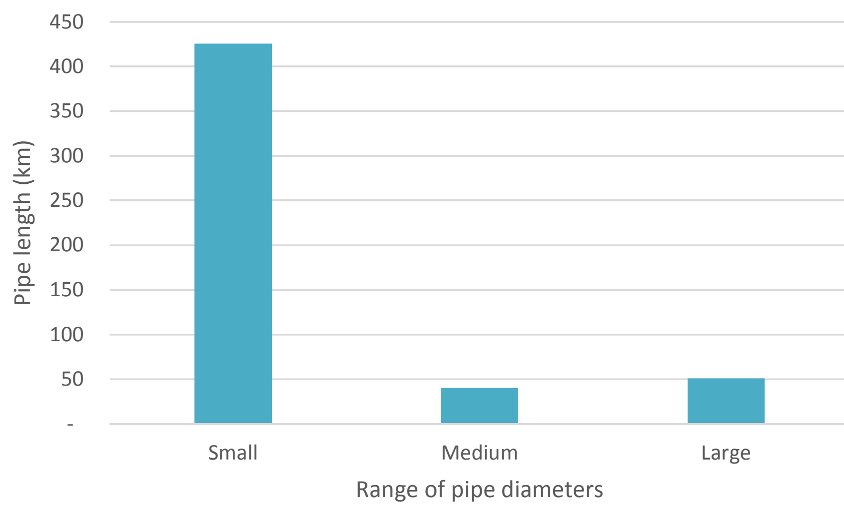

Figure 8 Length of pipes assessed for the different ranges of pipe sizes

From the analyses in *Figure 8 Length of pipes* assessed for the different ranges of pipe sizes the majority of the waste water network i.e. 426km out of a total of 517km pipes assessed are small diameter pipes, with a small number of man truck sewers that make up the large diameter pipes.

Results

Pipe damage in each of the liquefaction zones

For the analysis in *Figure 9* the pipe length assessed in each of the LRI zones have been analysed. The pipes assessed in Zone 0 have been done during as emergency response under IRMO (Botha & Scheepbouwer, 2015). Zone 1 has the majority of pipes assessed as it was the worst affected area of the city where rebuild works was performed.

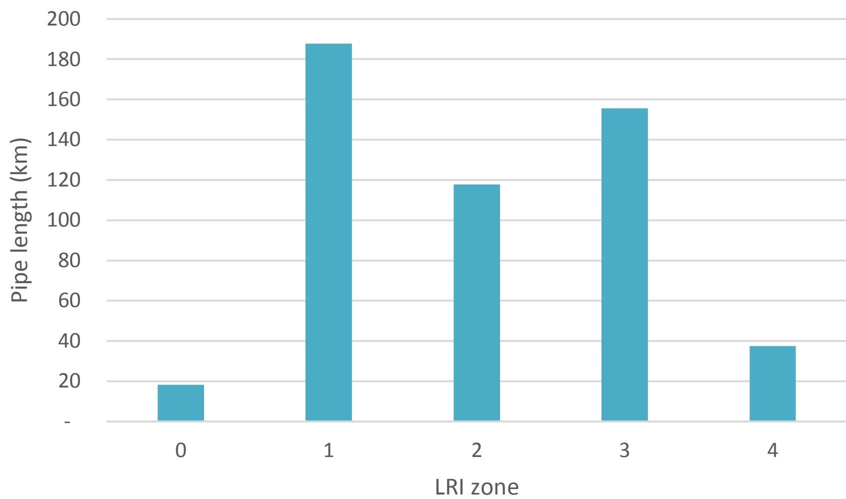

Figure 9 Pipes assessed in LRI zones

At the time of research, 306km of pipe have been assessed in the 2 worst affected areas where rebuild activities were permitted. This equates to approximately 59% of the total of 517km assessed. The pipes in zone 4 is the least amount of pipes with 38km or 7% of the total assessed.

Pipes assessed under each design guideline in the liquefaction zones

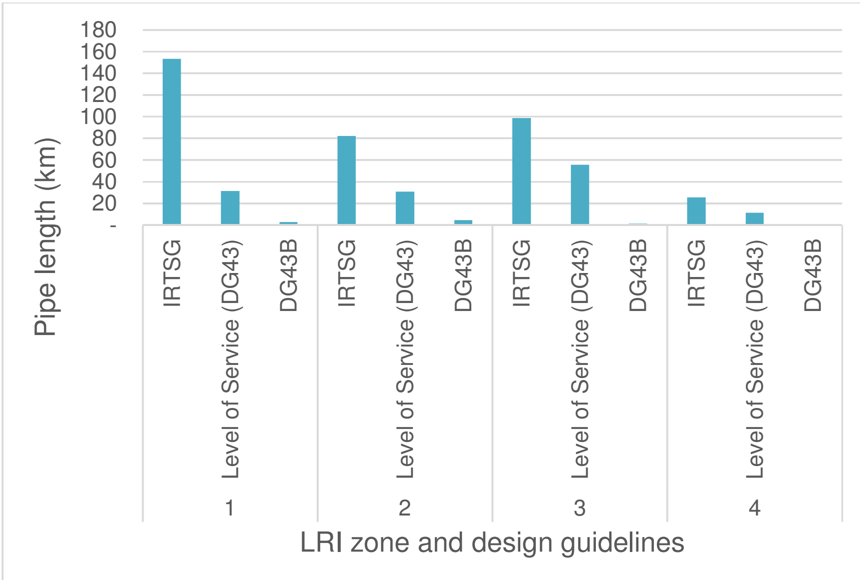

Figure 10 Pipes assessed for each design guideline in each LRI zone

From the analysis in *Figure 10* 153km or 31% of the waste water network was assessed in accordance with the IRTSG in LRI zone 1. Work completed under the IRTSG make up 359km or 72% of the completed waste water work designed and constructed up to the end of April 2016.

Works completed under DG43B make up 9.5km or 1.9% of the total waste water network assessed and completed to date according to the results in *Figure 10*. This is because DG43B was implemented in 2014 and at the time of the research most of these projects were still in construction.

Conclusions

The focus of the rebuild was on restoring the service to the worst affected areas with low liquefaction resistance.

Chapter 6 Financial Implication of the design guidelines.

Introduction

In order to develop an estimate for the reconstruction of the infrastructure, the situation prior and post disaster needs to be compared. For the baseline situation, the asset registers from the asset owners are used to establish the quantum of infrastructure and its condition. As the information from these asset registers is not always up to date, the estimate is therefore based on less than perfect information. Immediately following the disaster an assessment is required to understand the extent of the damage as well as to do an initial estimate of the repair cost. The different assets can be assessed in different ways i.e. visual inspections for assets such as roads can be inspected from the surface to identify the damage. However the deeper assets such as waste water reticulation and storm water pipes are more time consuming and costly to assess by using CCTV inspection methods.

The analyses in this chapter evaluates the CCTV database as described in chapter 4 and compares the financial performance of the design guidelines as described in chapter 3. This then provides the information of the main objectives of the research to better understand the impact of the different design guidelines on the asset life, the repair costs as well as the replacement cost.

Decisions on the cost of rebuilding infrastructure only deal with the direct cost of repairing infrastructure and do not include costs such as the ongoing operational costs or indirect costs, which can be considerably higher than the direct cost (Pelling, Ozerdem, & Barakat, 2002). The operational cost is usually the responsibility of the asset owner and or local government which could ultimately have a financial implication on the end users.

The financial impact of the natural disasters can be divided into direct and indirect costs. Rebuilding of damaged infrastructure is the direct cost, while the operational cost of maintaining the infrastructure is considered to be indirect cost (Ricardo, 1997). The short term period immediately following the disaster provides opportunities for investment through insurance pay-outs, international relief and development aid, but is usually short lived and does not compensate for the secondary losses that can be felt for a long time after the disaster (Pelling, Ozerdem, & Barakat, 2002). Understanding the financial impact of natural disasters will not only help society to understand the magnitude of the disaster but also to identify resource that can assist with reducing the consequences of disasters (Porfir'ev & Makarova, 2014).

Reconstruction provides opportunities to address specific vulnerabilities to future disasters through building back better and to boost social and economic development. Rebuilding infrastructure often plays an important role in sustaining recovery following a major disaster (Palliyaguru, Amaratunga, & Haigh, Developing an approach to assess the influence of disaster risk reduction practises into infrastructure reconstruction on socio-economic development, 2013). Loss of infrastructure, together with the loss of lives as a result of a natural disaster have significant impacts on the psychological and economic impact on communities. It is therefore important that the reconstruction of infrastructure projects aim to reduce the vulnerabilities for the development of communities through disaster risk reduction (Palliyaguru & Dilanthi, Managing disaster risks through quality infrastructure and vice versa, post disaster reconstruction practices, 2008). With regards to damage to infrastructure, improved planning at design stage can reduce losses to more tolerable and affordable levels as well as reducing long-term costs (Hudson, Cormie, Tufton, & Inglis, 2012)

Methodology

For all the analyses in this chapter the pipes that have been installed in LRI zones 1 to 4 prior to the start of the CES have been selected and evaluated to predict the impact of the design guidelines. The actions taken by SCIRT on these pipes have been recorded on the database as one of three options i.e. no action, removed or repaired. The total length of pipes assessed for each action in accordance with each design guideline is shown in *Figure 11*. Pipes in LRI zone 0 have been discounted from the financial analyses in this chapter as no rebuild activities were permitted in this zone. This is because the properties have been bought by the government, demolished but the land has not been developed.

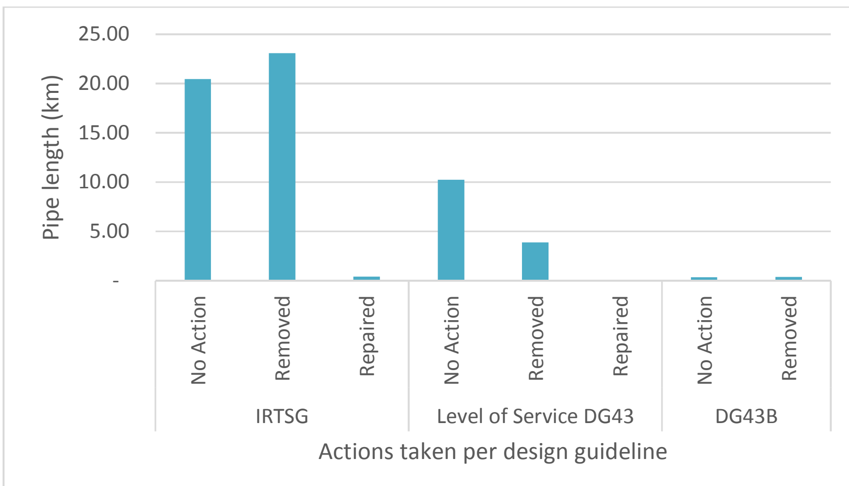

Figure 11 Actions taken by SCIRT

When a pipe has been removed, it has been replaced by another pipe and the action for the new pipe is then recorded as added. From the information available in the database it is not possible to separate the pipes that have been added between betterment and replacement of existing pipes as this information is captured on the SCIRT GIS database. It is also not possible to use the CCTV database to link the pipes that have been removed with the pipes that have been added without the GIS database. This is because each pipe entry on the CCTV database has a unique asset number that feeds into the Christchurch City Council's asset management software. The link between pipes removed and added are established as part of the handover process in SCIRT with the aid of their GIS database. The GIS database was not available for this research and therefore new pipes that have been added have been excluded from the analyses. New pipes that have been installed under each of the design guidelines are therefore not shown in *Figure 11*.

For the data analysis in *Figure 12*Figure 12 the RUL of each pipe has been calculated using the formula in Equation 2*:*

RUL = standard asset life – age of the asset

Equation 2 Remaining useful life calculation

For all pipes installed prior to the CES, the standard asset life is based on the materials used during the initial installation of the pipes *(see Table 10 Standard asset life for pipe materials for pre and post-earthquake pipe installations and repairs).* Standard asset life is also sometimes referred to as the design life of the asset. (New Zealand Asset Management Support, 2006).

During the rebuild modern day materials such as concrete and PVC pipes have been used for the installation of new gravity waste water pipes. Trenchless renewal techniques such as lining were used where the pipe had minor damage but did not fail on grade and was in need of repair works.

During the rebuild modern day materials such as concrete and PVC pipes have been used for the installation of new gravity waste water pipes. Trenchless renewal techniques such as lining were used where the pipe had minor damage but did not fail on grade and was in need of repair works.

Table 10 Standard asset life for pipe materials for pre and post-earthquake pipe installations and repairs (New Zealand Asset Management Support, 2006)

Pipe material used	**Standard asset life in years**
Asbestos cement	60
Concrete	60
Ductile Iron	40
Polyvinyl Chloride	88
Repairs including pipe lining and patch repairs	50

The standard asset life post rebuild for a new pipe installation is determined by the material used, for a repaired pipe it is determined by the materials of the host pipe. In the event of no action taken by SCIRT the standard asset life was the same as prior to the CES.

The age of the assets for pipes installed prior to the earthquakes were calculated from the date the pipe was installed up to the 4th of September 2010. The age of the asset post rebuild has been calculated based on the action taken by SCIRT during the rebuild as explained in *Table 11*

Different pipe materials have varying number of breaks for the length of pipe per year depending on the age of the pipe (Adachi & Singh, 2013). The results from the bathtub curves (Adachi & Singh, 2013) were used to estimate the number of breaks for each pipe up to the date of the first earthquake of the 4th of September 2010. These pipe failure rates were also used to predict the number of breaks over the remaining asset life of the pipes post rebuild for each pipe. Two common repair methods used during the rebuild for repairing pipe breakages are trenchless pipe repairs (patch) or segment replacements where a section of the broken pipe is replaced by means of traditional "dig down" and replace. For this research an estimated section repair cost has been used to estimate the predicted repair cost for pre and post-earthquake repairs depending on the repair method used.

Table 11 Calculating age of asset post rebuild

Action taken by SCIRT	Age of the asset in years
No Action	Number of years from date pipe was originally installed up to date of research i.e. 2016
Removed	0
Repaired	Number of years from date of repair to date of research i.e. 2016

TOC unit rates for replacing pipes from the SCIRT rebuild programme have been used for both pre and post-earthquake replacement costs as they are reflective of the ground conditions and construction standards in Christchurch. According to (New Zealand Asset Management Support, 2006) indirect cost such as design, quality assurance and project management are spread across the various assets as a percentage. For the analysis of the repair and replacement cost only the construction cost has been included in the calculation. This is because the indirect structure of the SCIRT rebuild programme is different to the traditional Council projects due to it being an alliance to accommodate the 3 Limb payment model (Botha & Scheepbouwer, 2015). The replacement cost is also based on the modern equivalent asset (MEA) method, i.e. using modern day materials such as uPVC and Concrete, as described in the New

Zealand Infrastructure Asset Valuation and Depreciation Guidelines (New Zealand Asset Management Support, 2006).

Data Analysis

A quantitative analyses was performed comparing the RUL, estimated repair and replacement costs for the various design guidelines. The results have been compared between pre-and post-earthquake using SPSS version 23 to evaluate the financial impact of each of the design guidelines on the network.

Results

Remaining useful life

From the analysis of pipes installed prior to the earthquakes for each of the different design guidelines in *Figure 12*, the total RUL up to the start of the CES was 45.8 years with an estimated 38.8 years RUL post rebuild. The Christchurch City Council lost an estimated average of 7 years of RUL from the city's gravity waste water pipe network as a result of the Canterbury Earthquake Sequence (CES).

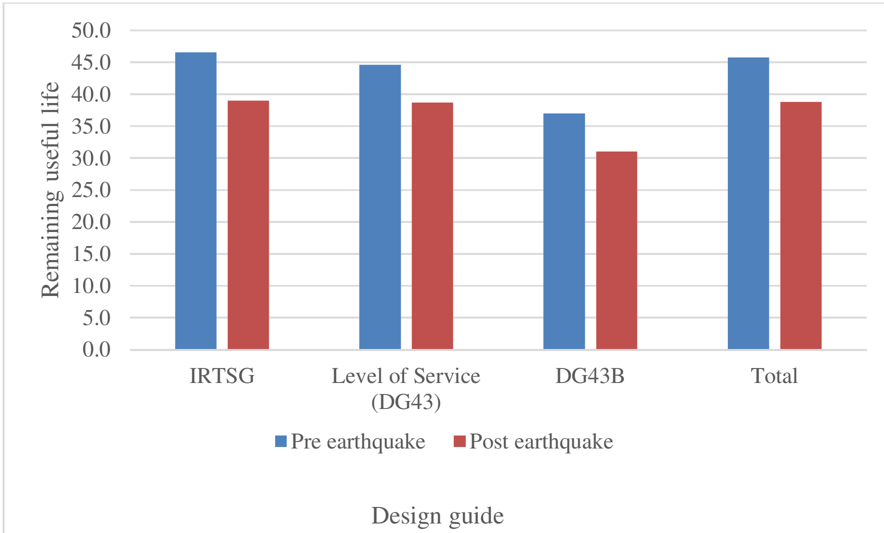

Figure 12 Remaining useful asset life

The IRTSG was introduced at the early stages of the rebuild, with the intention of fixing all the damage in the network caused by the CES, it did not improve the RUL post rebuild. The pipes installed prior to the earthquakes and designed during the rebuild under the IRTSG had a RUL of 46.6 years. Post rebuild these pipes have an estimated RUL of 39 years with an estimated loss in RUL of 7.6 years.

Designs completed in accordance with the Level of Service (DG43) have an average of 44.6 years RUL prior to the earthquakes, with an estimated RUL of 38.7 years post rebuild. These pipes have lost an estimated reduction in RUL as a result of the earthquakes of 5.9 years.

Designs completed under the DG43B design guideline had a useful asset life of 37 years prior to the earthquakes compared to 31 years RUL post rebuild. These pipes have lost 6 years in useful asset life.

Both the IRTSG and Level of Service (DG43) designs have almost the same useful life of 39 and 38.7 years respectively compared to the total estimated useful life of 38.8 years of the network. DG43B have an estimated 7.8 year useful asset life less than the useful life for the network post rebuild.

Estimated cost of repairs

The estimated repair cost comparison between the design guidelines pre and post-earthquake is shown in *Figure 14*. The total estimated repair cost for these pipes up to the start of the CES is $41,8M and is estimated to reduce by $10.4M or 25% post rebuild. The Level of Service (DG43) designs have an estimated repair cost post rebuild of $22,9M which is a reduction of $7,38M or 24%. The DG43B design guideline has an estimated pre-earthquake repair cost of $1,2M and $760K post-earthquake repair cost. This is an estimated 37% reduction in repair cost post rebuild.

There is also a significant correlation between the pipe materials and the cost of the repair works over the useful life of the pipe. According to *Figure 13* the majority of the pipe materials repaired are AC and RCRRJ pipes for each of the design guidelines.

The designs completed under the IRTSG in *Figure 13* below includes 44km of pipes with a combined total of 38.4km of RCRRJ and AC pipes. For the Level of service (DG43) designs, these materials make-up a combined total of 11km out of a total of 14km of pipes assessed. The DG43B design guideline included 0.64km of AC and RCRRJ pipes out of a total of 0.74km of pipes assessed.

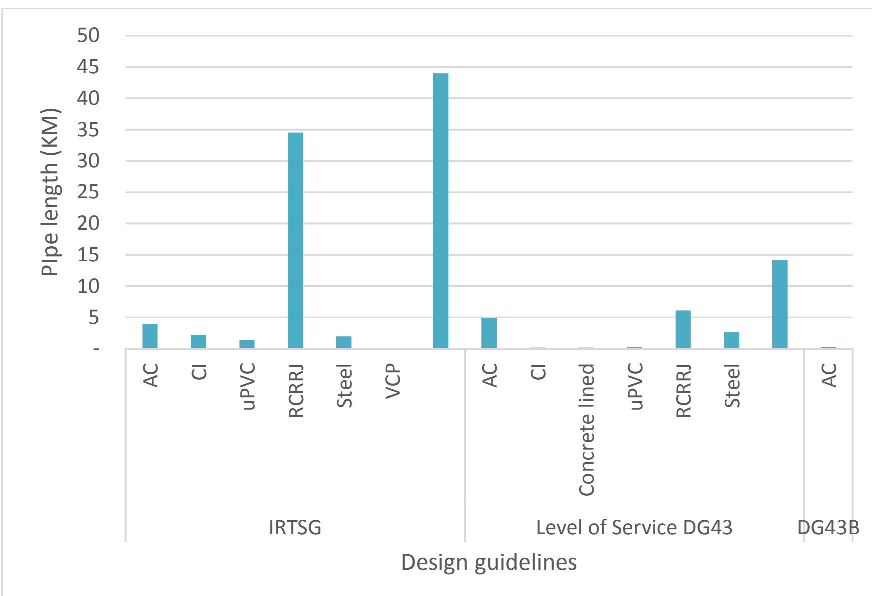

Figure 13 Pipe Materials used

AC pipes is 4.92km or 35% of the total length of pipes assessed under the Level of Service (DG43) design guideline. AC pipes is 0.29km or 40% of the total pipes assessed under the DG43B design guideline. The large AC component of both these design guidelines has a significant influence on the estimated cost of repair works for each of the design guidelines. This is because of the high failure frequency rate for AC pipes as well as the works associated with repairing Asbestos Cement. The repair works includes partial replacement of the AC pipe as well as very expensive disposal charges for AC contaminated landfill sites.

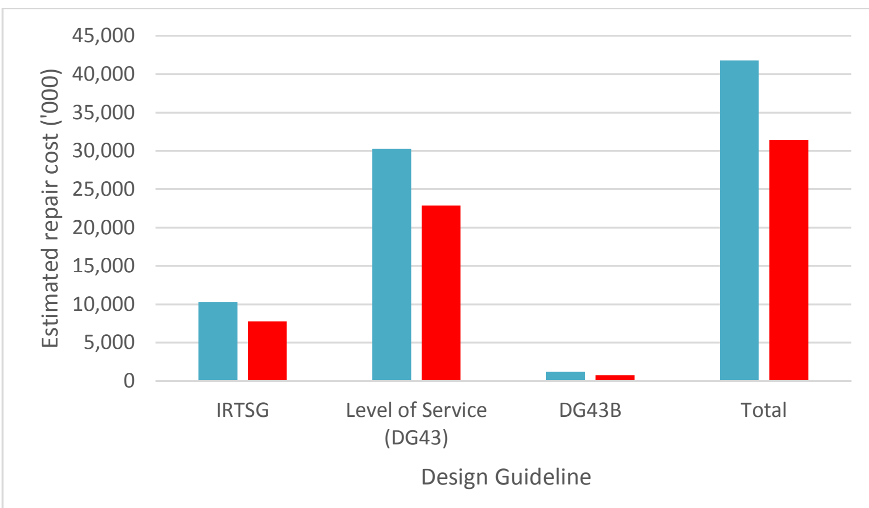

Figure 14 Estimated cost of repair works

The reduction in the RUL of the pipes for each of the design guidelines as indicated in *Figure 12* have an influence on the estimated repair cost from *Figure 14*. This is because the repair cost is calculated based on the RUL of the pipe.

Replacement cost

The replacement cost for each design guidelines is the same pre and post disaster as can be seen from *Figure 15.* This is because the City Council has developed the Construction Standard Specifications which covers the standards for the installation of new pipes. This standard covers standard items such as an approved list materials to be used, back fill requirements and reinstatement requirements etc.

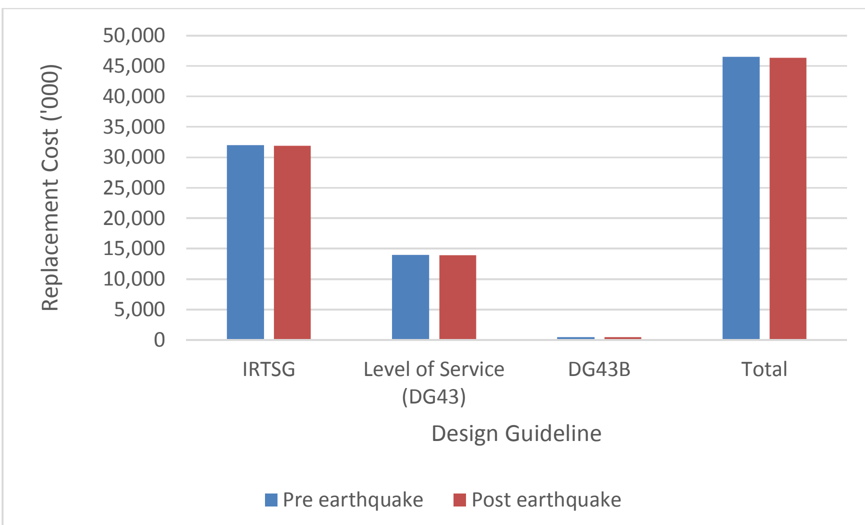

Figure 15 Predicted replacement cost

The replacement cost has been calculated on a $/m rate of pipe installed for each diameter of pipe. Due to the difference in pipe lengths being replaced under each design guideline (see *Figure 11*) the cost varies between the design guideline. The replacement cost for the IRTSG is higher than the replacement cost for both the Level of Service (DG43) and DG43B design guidelines. This is due to the majority of the work completed at the time of the research has been designed under the IRTSG, while projects designed under the Level of Service (DG43) and DG43B are still in construction.

Discussion

The analyses exclude new pipe installations, but include pipes that have been removed or abandoned and also repaired. The repair works reduced the RUL with an estimated 7 years. Both the IRTSG and Level of Service (DG43) design guidelines provide the same useful asset life of 39 years as the total for the network post rebuild. The DG43B design guideline provided the worst useful RUL of 31 years post-earthquakes.

It is estimated that all the design guidelines reduced the repair cost between pre and post-earthquake. The repair cost post rebuild have been calculated over a reduction in the RUL of the waste water network. To assess the impact of the design guidelines on the repair cost a portion of the replacement cost also needs to be added to the post-earthquake repair cost for a comparison of the impact of the design guidelines.

Conclusions

The following conclusions from the results of this chapter can be drawn: The pipe repair works following the earthquake reduced the RUL with 7 years. The 2 design guidelines that have been developed in a collaborative environment between asset owners and designers provided better RUL post-earthquakes.

With the limited amount of data available for DG43B designs at the time of research it is inconclusive that this design guideline will offer a saving in the repair cost post rebuild.

Improved design guidelines that provided resilience in the design as well as the use of modern day materials in the rebuild reduced the estimated repair cost of the network post rebuild.

Chapter 7 Consolidated conclusions and limitations

At the start of the rebuild in Christchurch, aftershocks were still continuing. The associated risks of earthquake damage to repair works combined with the unknown scope of repair works made an alliance an ideal procurement model. The SCIRT alliance not only provided an opportunity to share in the risk but also created a collaborative environment where the designers, asset owners and contractors can work together to reduce risk by having constructability advice available through ECI.

The waste water repair works is estimated to be 65% of the total cost of the infrastructure rebuild, so any changes to the waste water design guidelines could have a significant impact on the financial performance of the projects and ultimately on the rebuild programme. ECI input during the initial (transition and steady state) periods provided constructability advice during the design phase based on the latest design guideline. This ensured that the TOC development was well informed and always based on the latest design guideline. As a result of this, the financial performance of the projects themselves was not influenced by any changes to the design guidelines. ECI input proved to assist in improving the financial performance of the programme.

Waste water design guidelines used prior to the earthquakes in Christchurch had little requirements for earthquake resilience in the design. The initial focus of the rebuild programme in Christchurch was to restore service to the worst affected areas where no service was available immediately following the earthquakes. This required a design guideline that would restore service and also increase the resilience within the network. As the pipe investigations continued into areas with lesser earthquake damage a better understanding of the performance of the existing network in various parts of the city was developed. In zones with high liquefaction resistance the damage to the waste water network was significantly less. Within the collaborative environment the design requirements were adjusted to accommodate different levels of damage within the existing network. The amendments to the IRTSG and the LOS (DG43B) design guideline were developed within the collaborative environment created by the IST. These guidelines were developed by the designers and implemented once approved by SSC, these changes were done based on reviewing the CCTV results as well as input from the estimating team. Both these design guidelines provided an RUL of 39 years which is higher than the DG43B design guideline.

As the investigations continued west into the lesser affected areas, a better understanding of the performance of different pipe materials was developed. The network provided more resilience in areas with lesser ground movement and liquefaction.

This research is limited to works completed and handed over the City Council up to the end of April 2016, with 8 months of as-built data still outstanding. The financial impact of the repair works is limited to the impact of repairs and trenchless pipe lining.

The current research does not include future effects of earthquakes in the estimates of the financial impacts post rebuild.

Chapter 8 Contributions and recommendations for future research

Chapter 7 highlights the conclusions from the research for this thesis. Further this chapter recommends further research to assist asset owners in preparing for possible natural disasters from lessons learnt during the Christchurch rebuild.

Recommendations for future research

It is recommended that the analyses be repeated once all the projects have been completed and handed over the Council to understand the full split of work performed under each design guideline. For this analysis the installation of new pipes should be included for the full financial impact of the design guidelines.

It is further also recommended that the effect of earthquakes be included in the post rebuild analyses to understand the level of resilience provided by the design guidelines.

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