PRACTITIONERS GUIDE TO BUILDING RESILIENCE INTO INFRASTRUCTURE NETWORKS

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ABSTRACT

SCIRT (The Stronger Christchurch Infrastructure Rebuild Team) is responsible for rebuilding horizontal infrastructure in Christchurch following the earthquakes of 2010 and 2011.

A challenge faced by asset assessment and design engineers at SCIRT has been to justify to themselves, funders and asset owners, investing taxpayer and ratepayer funds into more expensive but more resilient infrastructure.

SCIRT's response to this has been to develop a whole of life cost methodology that can be used to evaluate rebuild options. The methodology is based on a Net Present Value (NPV) analysis of whole of life costs and takes into consideration capital costs, capital renewals, operation and maintenance costs, and the risks and costs associated with responding to future earthquake events.

This paper presents how the methodology has been developed and applied to the evaluation of wastewater rebuild options and other asset rebuild decisions. The paper examines how the methodology has been refined as SCIRT's focus has shifted from highly damaged areas to other areas that have sustained less earthquake damage, and how the evaluation of options has changed as the rebuild has shifted from a response to a rebuild, with a significant emphasis on returning levels of service across the city.

KEYWORDS

SCIRT, resilience, whole of life, wastewater, NPV, option evaluation, levels of service

1 INTRODUCTION

1.1 SCIRT REBUILD SCOPE AND OBJECTIVES

SCIRT (The Stronger Christchurch Infrastructure Rebuild Team) is responsible for rebuilding horizontal infrastructure in Christchurch following the earthquakes of 2010 and 2011. This includes all Christchurch City Council (CCC) owned buried pipe infrastructure (water supply, wastewater and stormwater), pump stations, roads, bridges and retaining walls.

SCIRT is an alliance formed between three funding owner participants (CCC, Canterbury Earthquake Rebuild Authority (CERA), New Zealand Transport Authority (NZTA)) and five head contractors (City Care Ltd, Fulton Hogan Ltd, Downer New Zealand Ltd, the Fletcher Construction Company Ltd and McConnell Dowell Constructors Ltd). A number of other local organisations have seconded specialist asset assessment, design, planning, project management and construction staff to SCIRT to assist with the rebuild.

The owner participants prepared a guideline document titled 'Infrastructure Recovery Technical Standards and Guidelines' (IRTSG) that sets out the scope of the rebuild. The IRTSG presents the primary objective of the rebuild as being:

"To return the infrastructure networks to a condition that meets the levels of service prior to the 4 September 2010 earthquake within the timing constraints of the rebuild."

And secondary objective is:

"Where restoration work is undertaken, and where reasonably possible and economically viable, greater resilience is to be incorporated into the network."

From these overarching objectives, SCIRT developed it's own noble purpose, which is:

"Creating resilient infrastructure that gives the people security and confidence in the future of Christchurch"

In addition, the rebuild standards that SCIRT needed to work to (CCC's Infrastructure Design Standards (IDS) and IRTSG) required new infrastructure to be designed to '*minimise life cycle costs over the life of the asset'*.

The challenge faced by asset assessment and design engineers at SCIRT has been to develop a methodology for evaluating rebuild options that aligns with the objectives of the rebuild, SCIRT's purpose and CCC's engineering standards.

This methodology needed to be sufficiently robust for SCIRT asset assessment and design engineers to justify to themselves, funders and asset owners, investing taxpayer and ratepayer funds into more expensive resilient infrastructure that isn't at odds with SCIRT objectives and purpose, or guiding engineering standards. It also needed to be flexible and simple enough to be applied to a large number of discrete projects being undertaken by different design teams within SCIRT.

1.2 SCIRT'S APPROACH TO EVALUATING REBUILD OPTIONS

SCIRT's response to this has been to develop a whole of life cost methodology that can be used to evaluate rebuild options. The methodology is based on a Net Present Value (NPV) analysis of whole of life costs.

The methodology takes into consideration capital costs, capital renewals, operation and maintenance costs, and the risks and costs associated with responding to future earthquake events. A key element of the methodology is that it values the resilience offered by different rebuild options by including earthquake related repair and service restoration costs into the NPV timeline. Prior to this a consideration of earthquake risk had not been included in the evaluation of infrastructure options in Christchurch.

The methodology has generated significant interest from local authorities, national infrastructure leaders and visiting academics and post-disaster response practitioners. Although developed for the Christchurch rebuild, the approach can be applied to the evaluating options for renewing assets and for planning new developments in any areas faced with known natural hazards (which may or may not include earthquakes). This is particularly applicable where costs associated with natural hazards cannot be completely mitigated though insurance or more conservative construction standards. CCC has adopted this methodology for evaluating wastewater network options being planned for new subdivisions around Christchurch.

This paper presents how the methodology has been developed and applied to the evaluation of wastewater rebuild options and other asset rebuild decisions. The paper examines how the methodology has been refined as SCIRT's focus has shifted from highly damaged areas to areas that have sustained less earthquake damage, and how the evaluation of options has changed as the rebuild has shifted from a response to a rebuild phase, with a significant emphasis on returning levels of service across the city.

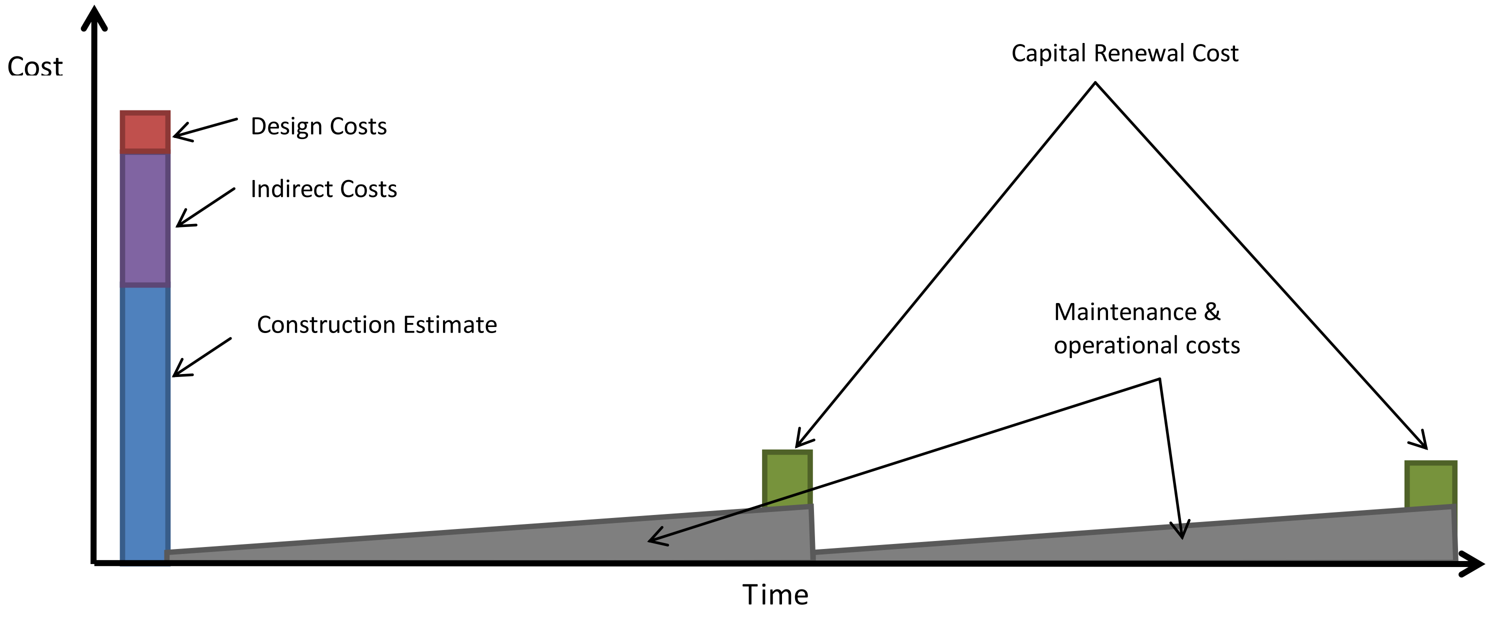
2 WHOLE OF LIFE COST METHODOLOGY

2.1 OVERVIEW

In considering multiple options for rebuild to council infrastructure, SCIRT designers need to evaluate each option on a whole of life basis. An NPV analysis has been used to estimate the whole of life cost of different options to assist in this evaluation. A NPV is a financial calculation that provides the whole of life cost for projects in today's dollars.

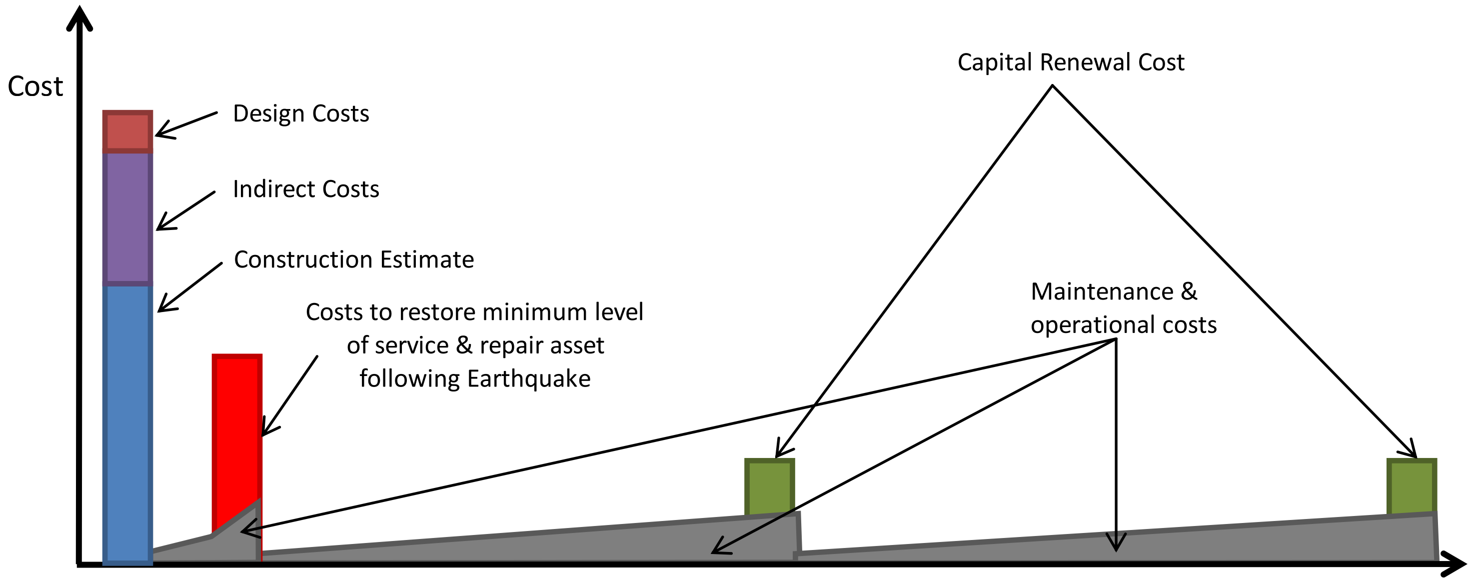
A standard whole of life analysis would contain the inputs presented in Figure 2.1.

Figure 2.1: Typical whole of life costs for a project



To recognise the impact of a future significant earthquake on the whole of life cost of the project, earthquake related costs have been estimated and applied to the timeline of costs based on a review of earthquake risk. Earthquake related costs have been estimated by considering the costs to restore a minimum level of service to the asset and the cost to repair the asset following an earthquake. Figure 2.2 presents how these costs have been incorporated into the timeline of costs.

Figure 2.2: Inclusion of Earthquake related costs in whole of life cost



2.2 INPUTS TO THE WHOLE OF LIFE COST COMPARISON

The inputs to the whole of life cost evaluation are:

1. Total project capital cost (CAPEX) and programme
2. Capital renewal costs and expected asset life of different components
3. Annual operational and maintenance costs (OPEX)
4. Earthquake costs and earthquake risk profile.

The total project capital cost includes the construction estimate (estimate of the physical works costs and onsite overheads), design costs, and indirect costs (asset investigation and assessment, project management, consenting, client project costs).

Capital renewal costs are the costs associated with the partial or full replacement of parts of an asset at agreed time periods (e.g. renewal of certain mechanical components such as pumps every 15 years).

Operational and Maintenance costs are the annual costs associated with operating and maintaining the asset to maintain normal levels of service.

Earthquake costs are those costs associated with a significant earthquake event (generally greater than magnitude 6.0) that is likely to cause liquefaction, loss of service and structural or functional damage to the asset. This includes capital and operational expenditure associated with such an event has been estimated by considering the effort required to:

1. Restore a minimum level of service following an earthquake, and
2. Rebuild infrastructure damaged during the earthquake.

3 THE SCIRT WHOLE OF LIFE COST TOOL

SCIRT has developed a spreadsheet based tool that includes calculations for each of the inputs mentioned above, a whole of life calculation, and an auto populated presentation table that meets the needs of SCIRT funders.

The template spreadsheet and associated designer guideline (SCIRT Designer Guideline 027 - Evaluation of Whole of Life Costs for Rebuild Option Evaluation, which is an instruction paper on how to run the calculation) will be available through SCIRT's Learning Legacy framework which is currently being created.

Comments on different components of the whole of life calculation are provided below.

3.1 TOTAL PROJECT CAPITAL COST (CAPEX)

A cost estimation template for wastewater network rebuild is included in the spreadsheet. The spreadsheet automatically breaks the CAPEX down into different components so that the relative resilience of each can be estimated and compared. This recognises that some components of the network are more resilient than others. An example is a mixed gravity rebuild area where new PVC pipes, resiliently designed pump stations and flexible PE pressure mains offer greater resilience than discrete repairs to earthenware and concrete pipes.

For simplicity and to match the general size of SCIRT rebuild projects (around $10M), the whole of life calculation assumes that CAPEX expenditure all occurs at year zero.

3.2 CAPTIAL RENEWALS

The spreadsheet provides a library of standard rates and renewal frequencies for various components using information collected from CCC and equipment suppliers. Designers insert quantities to estimate capital renewals associated with the different options being evaluated. These then automatically populate a timeline of renewal costs.

3.3 ANNUAL OPERATION AND MAINTENANCE COSTS (OPEX)

The spreadsheet provides a library of standard O&M costs collected from CCC and equipment suppliers. Designers insert quantities to estimate O&M costs associated with the different options being evaluated. These costs then automatically populate a timeline of O&M costs.

It is anticipated that the performance of some mechanical components will reduce over time due to wear, resulting in a gradual increase in O&M costs. This has been reflected by a Performance Reduction Factor which is used to incrementally increase the O&M costs from construction through to renewal.

3.4 EARTHQUAKE COSTS AND RISK PROFILE

3.4.1 OVERVIEW

In the evaluation of wastewater network rebuild options, the relevant earthquake related costs are:

1. First response costs to restore a minimum level of service to customers. This may involve a combination of sewer jetting and sucking, temporary over pumping, the construction of temporary wastewater systems, the completion of temporary emergency repairs to restore service, etc, and
2. Network-rebuild costs to repair earthquake damage.

The spreadsheet tool was developed to make an automatic calculation of these costs for each rebuild option based on the location of the project and the nature of the rebuild works proposed. There still needs to be a sensibility check of the calculated values, drawing on available site specific knowledge of network damage. The values estimated for first response and network rebuild need to be realistic estimates of what costs could reasonably be expected in a future earthquake event.

3.4.2 EARTHQUAKE RISK PROFILE

Advice on the likelihood of a future damaging earthquake has been sought from GNS Science and incorporated into the methodology. Current GNS advice is summarised in Table 4.7, which has been extracted from Section 4.6 of the IRTSG. The scale of the events involved was selected by GNS to be sufficient to cause liquefaction and damage to below ground infrastructure in areas where rebuild works are planned.

This earthquake risk profile has changed over time. From around September 2011 to November 2012, GNS advice was that there was likely to be two earthquakes of magnitude sufficient to cause infrastructure damage within the next 20 years and a possible range to one to four earthquakes over this period. For the purpose of option comparison, SCIRT were instructed to assume these events would occur at Years 3 and 10 on the timeline of costs.

When the earthquake risk profile was revised in November 2012, the client group determined that the evaluation of rebuild options should assume the potential of one event to occur within the next twenty years. This is based on the most likely number of events of 0.72 as reported in Table 4.7 from the IRTSG. For the purpose of net present value evaluation, SCIRT were instructed to assume that this event occurred at Year 5 on the timeline of costs.

Table 4.7: Seismic Hazard Probabilities

Earthquake Sufficient to Cause Liquefaction in Christchurch		Expected Number of Events	
Magnitude Range	Radius (km) from Eastern Christchurch	Next 5 years	Next 20 years
5.8-6.5	10 km	0.142	0.25
6.5-7.0	50 km	0.072	0.17
7.0-7.5	100 km	0.033	0.10
>7.5	200 km	0.052	0.20
Cumulative Total (Average Number)	All events	0.30	0.72
Probability	An event	26%	51%
Cumulate Number Range (95% confidence)	All events	None to 2	None to 3

Note: This table is not intended for application to structures controlled by the Building Act.

3.4.3 FIRST RESPONSE COST ESTIMATE

Wastewater network first response costs have been based on actual maintenance contractor costs (from the 3-waters maintenance contract held by City Care Ltd) to return and maintain wastewater service to different parts of the city following the 2010 and 2011 earthquakes. The costs ranged from $200 to $3,600 per household equivalent unit across different parts of the city.

To predict the first response costs in a rebuilt network, network scaling factors have been applied to the different types of systems to estimate costs. A scaling factor of 100% implies that the rebuilt network will behave in the same way as the original network in a future earthquake event. This means that it will require the same amount of effort (in the form of sewer jetting and sucking, temporary over pumping, temporary wastewater systems, completion of emergency repairs) to restore and maintain service until it is repaired again.

Adopting a lower scaling factor (eg 20% for pressure sewer) is to reflect our expectation that the rebuilt network will be more resilient to a reduction in service following a future earthquake and so will cost less to restore and maintain service until it is repaired. Scaling factors adopted for different types of network are:

- Repaired/Retained/Replaced gravity 100-50% - dependent on whether grade and material have been improved
- Relined Gravity (at the same grade) 80%
- Vacuum sewer system 35%
- Pressure sewer system 20%

The above values were reviewed by SCIRT design engineers and CCC representatives. Observations were also made of the performance of pressure systems in place at the time of the February 2011 event. The sensitivity of changing the scaling factors on the evaluation was also tested across a number of projects to assess the effect of this on the calculated whole of life cost.

3.4.4 NETWORK REBUILD ESTIMATE

The network rebuild estimate is the estimated cost to repair/rebuild the wastewater network following a future earthquake.

The calculation requires a consideration of what damage has occurred to the existing gravity network and what damage could be expected to a rebuilt network. Network rebuild is typically falling into one of two categories:

a. Complete rebuild/replacement of the existing network with a new gravity or alternative system.
b. Part rebuild/repair of the existing network resulting in some saved (unmodified) infrastructure.

a. Complete rebuild/replacement of the existing network

Where the rebuild option involves the wholesale replacement of assets, the estimate of future network rebuild costs makes use of the current rebuild CAPEX. The current rebuild CAPEX cannot be used directly for estimating future rebuild/repairs costs as the rebuild CAPEX is based on rebuilding the current network, which can consist of various pipe materials (eg EW, CONC, AC, RC).

Networks are being rebuilt using (mostly) PVC and (sometimes) RC pipes, which have been found to have performed much better and so the estimate of future rebuild costs needs to consider the actual damage experienced by PVC or RC in similar country to the rebuild area. The spreadsheet tool provides default actual damage percentages for PVC and RC pipe based damage observed across different parts of the city. This information was collected through the extensive CCTV sewer condition inspection programme undertaken by SCIRT.

New enhanced gravity systems and alternative systems (pressure, vacuum) are expected to offer greater resilience than existing PVC dominated networks and so a ‘Relative Performance Scaling Factor’ has been applied to reflect the rebuild option’s increased resilience to future damage.

For a complete rebuild/replacement of the existing network, the future network rebuild cost is estimated by multiplying the current rebuild CAPEX by the Actual Damage experienced by the rebuild pipe material, by the ‘Relative Performance Scaling Factor’. Applying a Relative Performance Scaling Factor of less that 100% means that the CAPEX associated with repairing the network will be less than the rebuild costs associated with the SCIRT rebuild (rebuild CAPEX).

Adopted Relative Performance Scaling Factors are:

- Repaired gravity 90-100+%
- Relined Gravity (as current grade) 80%
- Re-laid gravity (at increased ‘enhanced’ grades) 50%
- Vacuum 40%
- Pressure 20%

The above values were reviewed by SCIRT design engineers and CCC representatives and compared against the performance of a limited number of pressure systems in place at the time of the February 2011 earthquake. The sensitivity of changing the scaling factors on the evaluation was also tested across a number of projects to assess the effect on the calculated whole of life cost.

b. Part rebuild/repair of the existing network (resulting in some saved infrastructure)

Where the rebuild option involves only undertaking discrete repairs to part of the network, the estimate of future damage cannot be limited to a scaling of the rebuild CAPEX. This is because of the risk that a future earthquake could result in saved/repaired pipes sustaining further damage and passing a damage threshold that results in more widespread renewal.

The future rebuild cost of saved network is estimated as the ‘cost to renew the saved assets’ x ‘expected damage to the saved assets’.

4 APPLICATION OF THE WHOLE OF LIFE TOOL

The NPV tool was initially developed and used to evaluate wastewater network rebuild options. An example of the tools application to an early wastewater rebuild evaluation is provided in Section 4.1.

The tool was then applied to evaluate different levels of intervention in the rebuild of gravity wastewater networks. An example of the tools application to this is provided in Section 4.2.

The tool has also been used to evaluate rebuild options associated with water supply renewals, road rebuild, reservoir and retaining wall rebuild, and architectural treatments. An example of the tools application to this is provided in Section 4.3.

4.1 EXAMPLE OF WASTEWATER NETWORK SYSTEM EVALUATION

The example provided is for a wastewater rebuild project in the eastern part of the city which sustained significant structural damage to the network and experienced very high first response costs.

Figure 4.1 presents whole of life (NPV) costs for the different options against a range of earthquake risk scenarios:

1. Direct CAPEX

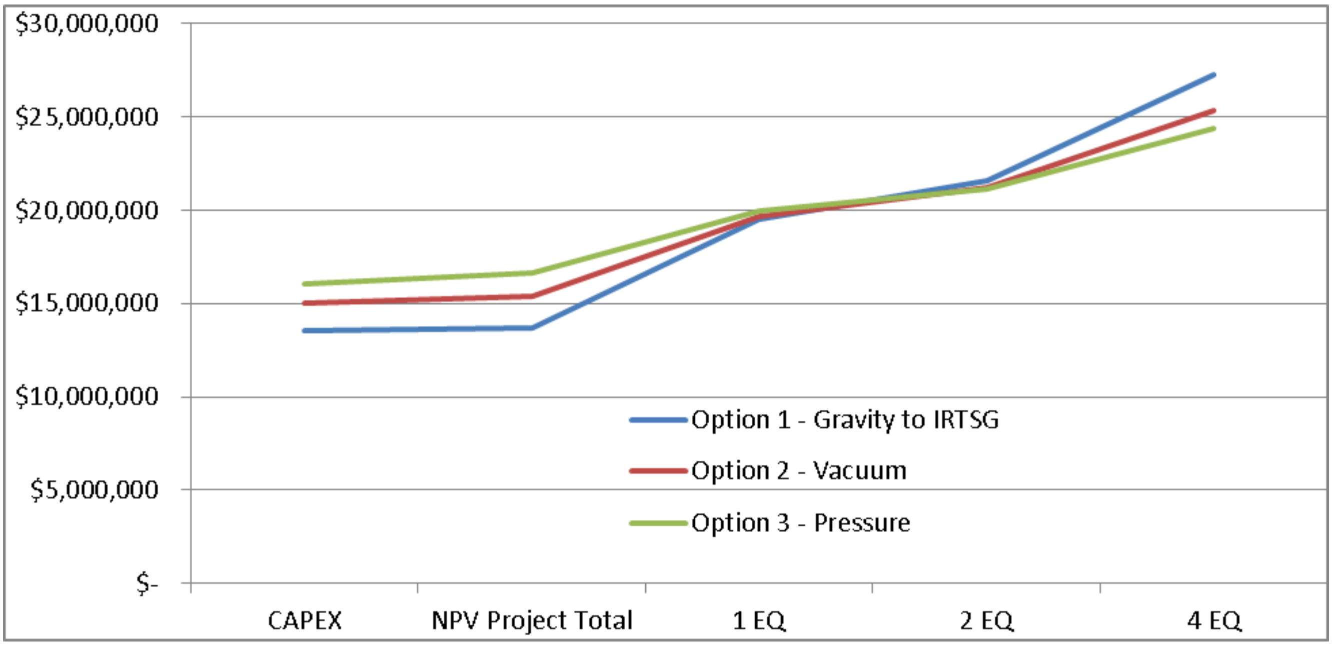
2. NPV project total – whole of life cost with future earthquake related costs excluded

3. One earthquake scenario - occurring at Year 1 on the timeline. This was the lower range of the expected number of events at the time

4. Two earthquake scenario - occurring at Years 3 and 10 on the timeline. This was the relevant earthquake risk scenario at the time and was the cost presented to funders for decision.

5. Four earthquake scenario - occurring at Years 3, 7 10 and 15 on the timeline. This was the upper range of the number of earthquake events expected at the time.

Figure 4.1: Whole of Life Costs for Different WW Network Rebuild Options for different Earthquake Risk Scenarios



The plot shows that for the relevant earthquake risk scenario, (two earthquakes) the whole of life costs of the different options were very similar with the pressure sewer system being marginally lower than rebuilt gravity or vacuum systems. Based on this analysis, funders elected to install a pressure wastewater system in this area.

4.2 EXAMPLE OF WASTEWATER NETWORK REBUILD OPTIMISATION

As the focus of the rebuild moved to areas that had sustained less damage, there was a need to evaluate different levels of gravity rebuild. In these areas pressure and vacuum systems could not be justified due to the reduced amount of damage (with resulting lower rebuild CAPEX) and the lower estimated first response costs.

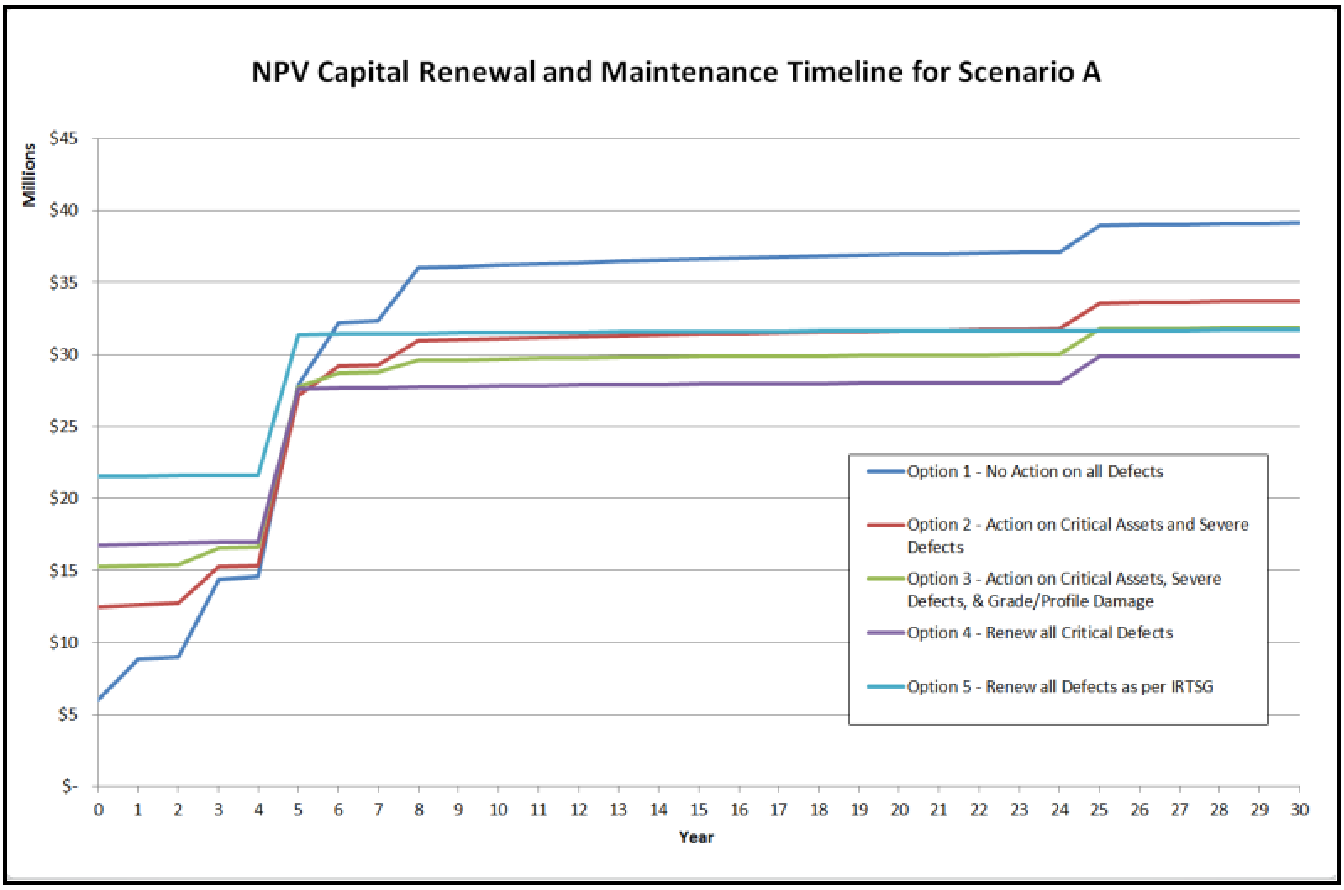
Further explanation on the how this change in focus occurred at SCIRT is described in Section 5 of this paper.

The levels of gravity rebuild range from repairing all defects identified for repair in the IRTSG (using the prescribed intervention points) through to doing nothing (ie leaving all defects behind). Intermediate options include repairing critical damage over the project area or in critical locations only.

In evaluating the different levels of gravity network repair, various risk scenarios have been run to test the sensitivity of the comparison. The different risk scenarios present pessimistic, balanced and optimistic views on when critical damage could fail over the next 15 years. Note that critical damage are defects that have been assessed (thought review of CCTV footage and reference back to a SCIRT designer guideline) as being likely to fail within the next 15 years.

The whole of life cost of different options for different risk scenarios was presented in NPV plots. An example for one of the scenarios is presented in Figure 4.2 below. Scenario A was the pessimistic view. Other balanced and optimistic scenarios were also reviewed.

Figure 4.2: Whole of Life Costs for Different Levels of Gravity Rebuild for Risk Scenario A



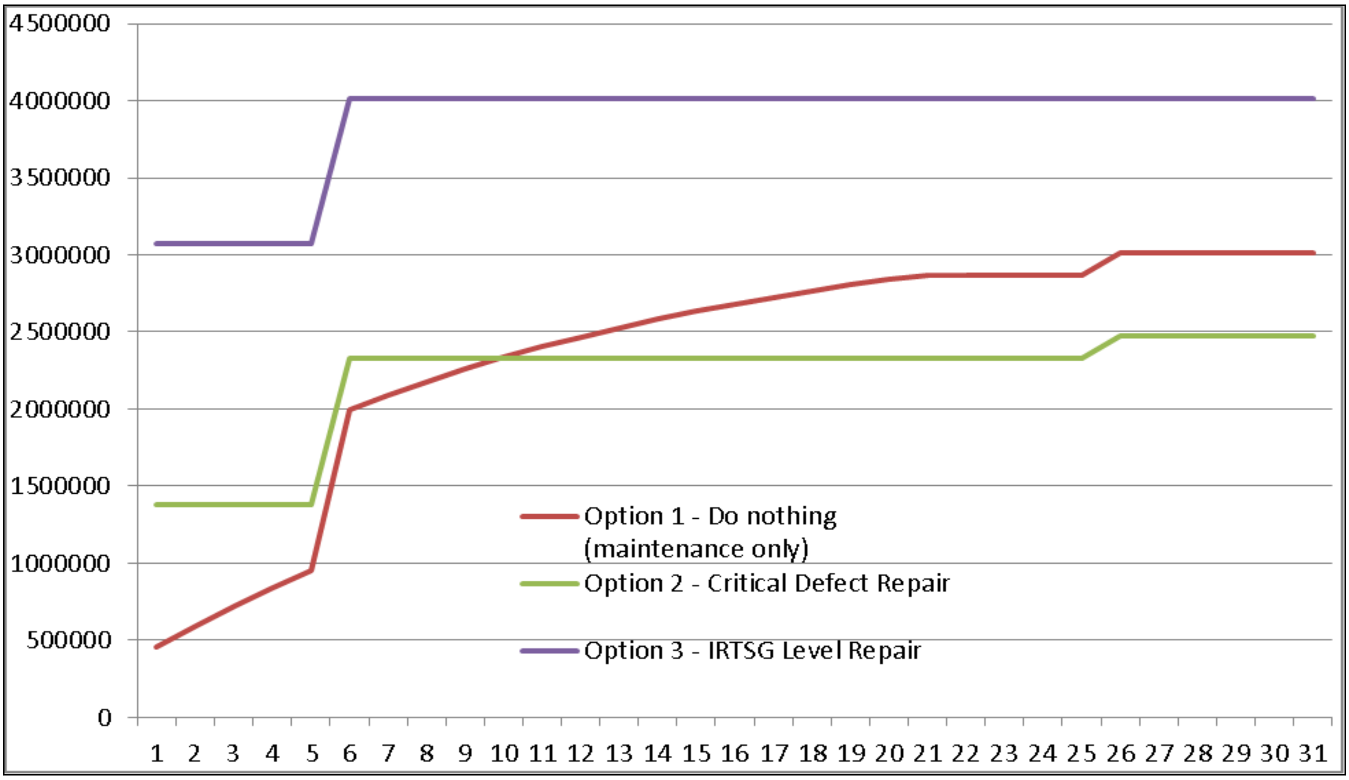
Although having the second highest CAPEX, the option to repair all critical defects was selected on the basis that it offered the lowest whole of life cost under all risk scenarios. Note the step in costs at Year 5 is the result of the assumed earthquake at this point on the timeline.

4.3 EXAMPLE OF OTHER ASSET REBUILD EVALUATION

Although initially developed to evaluate wastewater network options, the rebuild evaluation methodology has been applied to the evaluation of options for rebuilding roads, retaining walls, architectural finishes (paints), reservoirs, and watermain renewal strategies.

Figure 4.3 is an example of the models application to a review of options for making repair to trunk sewers. The 'doing nothing' option assumes that one critical defect fails in an uncontrolled way each year over the next 20 years. The earthquake response is the same for all options due to the discrete nature of repairs on trunk which do not change the overall resilience of the network. Options 1 and 2 both assume the repair of non-critical defects at Year 25 on the timeline

Figure 4.3: Whole of Life Costs for Different Levels of Gravity Rebuild for Risk Scenario A



5 LOS CHANGES

The process for evaluating rebuild options has been refined as the rebuild has progressed to evaluate different types of options.

At the outset of SCIRT, CCC and the other funders created an intervention point based approach to define the scope of the rebuild. This approach, which was presented in the IRTSG, confirmed the way damage was assessed and what defects would be repaired. Under this approach earthquake damage was identified for repair where it passed prescribed damage thresholds. Wastewater options were developed to respond to the degree of damage found and the example provided in Section 4.1 of this paper shows the results of an evaluation of wastewater rebuild options.

The intervention based approach was appropriate where the network had sustained significant structural damage and reduced levels of service, which were costly to return and maintain. As SCIRT shifted its focus to less damaged areas of the city, a new level of service (LOS) approach was developed to get better value from the rebuild.

Under the LOS approach, network LOS were assessed against key performance measures and LOS returned by repairing only critical damage within the network. Comparisons are made back to key LOS within the area when identifying and evaluating options. Key LOS under consideration for the wastewater network have been:

- Current O&M costs and trends
- The nature of current O&M activity and service complaints
- Estimates of changes in dry weather infiltration flow into the network (using a calibrated network model SCIRT developed for this purpose)
- Estimates of the project areas contribution to wastewater overflows (wet weather) to the environment (again using a calibrated network model SCIRT developed for this purpose)
- The age and condition of the network.

Critical damage are defects that are likely to deteriorate and affect LOS within the next 15 years. This approach was adopted to maximise the remaining asset life. Although departing from some of the prescribed intervention points in the IRTSG, the approach aligned with SCIRT primary objective, which is to return LOS to pre-September 2010 levels, provided better value, and is consistent with Council's 'business as usual' approach applied prior to the earthquakes.

As all SCIRT assessment and design effort has now moved to less damaged areas, the LOS approach is now being applied to all SCIRT investigations, assessments and design work. The adoption of pressure and vacuum systems cannot typically be justified in these les damaged areas due to the relatively lower level of structural damage and lower first response costs experienced following the 2010 and 2011 earthquakes. Repair of the gravity network is more appropriate in these areas and the option evaluation methodology presented in this paper has been used to evaluate different levels of gravity rebuild. An example of how this methodology has been applied using the LOS approach is provided in Section 4.2 of this paper.

6 AREAS FOR IMPROVEMENT

The methodology is a fairly crude model but considered by SCIRT and its funders as being appropriate for the comparison of options in this rebuild environment. Some key assumptions and limitations of the current model are:

1. The NPV model is generally used for evaluating investment decisions over a long time period. Questions have been asked over the suitability of using an NPV model for evaluating council expenditure options. A better model has not been found than can be readily applied over the large number of projects that SCIRT is delivering. However other benefit/cost methods might be more applicable to large infrastructure evaluation in a business as usual setting.
2. The outcomes of the NPV are highly dependent on the discount rate and evaluation period. A discount rate of 8% and evaluation period of 30 years have been used based on funder advice. A lower discount rate would have made options with relatively high CAPEX but lower future expenditure (these are generally the more resilient options) more attractive than they are under the current assumptions.
3. A good understanding of O&M requirements and a library of OPEX data is needed to be able for sensibly forecast future expenditure.
4. A key input to the analysis is the local (Christchurch) earthquake risk profile. This risk profile will vary across the country and GNS advice should be obtained on local conditions.
5. This analysis has made assumptions about O&M costs, capital renewal requirements and the expected earthquake performance of alternative wastewater systems (pressure and vacuum). Limited experience was available within the local industry and advice was sought from areas such as Japan and California on the performance of these alternative systems. The network performance scaling factors mentioned in Sections 3.4.3 and 3.4.4 of this paper should be reviewed as further experience in the operation, maintenance and performance of these systems is gained.
6. The evaluation assesses direct costs to council only and makes no attempt to value the economic and social costs associated with future disruptions to service. Being able to value these important factors and incorporate into the analysis would better inform asset owners of the relative merits of different infrastructure options.

7 CONCLUSIONS

This paper draws the following conclusions:

1. The whole of life tool developed by SCIRT has been a useful way to evaluate and present options to funders of the rebuild.

2. The whole of life tool is unique as it valued the resilience offered by different options and provides financial justification for building resilience into infrastructure networks.

3. Although initially developed for evaluating wastewater network rebuild options, it has been applied to evaluating different levels of gravity network repair and for evaluating options for undertaking rebuild on different assets.

4. The model has its limitations but is appropriate for application in an earthquake rebuild environment. It could be refined to make it more appropriate for evaluating long term investment decisions in a business as usual environment. A key improvement would be the incorporation of economic and social costs.

8 ACKNOWLEDGEMENTS

The authors acknowledge the support of SCIRT design staff and asset owner representatives who have assisted in developing and refining this tool, and to rebuild funders who have supported the outcomes.