A SEISMIC SHIFT IN DESIGN – EMBEDDING SAFETY, RESILIENCE AND VALUE INTO POST-EARTHQUAKE DESIGNS

Ian Macbeth, Iain Partington, Gavin Hutchison (all Beca Ltd, Christchurch) and John Moore (Christchurch City Council, Christchurch)

ABSTRACT

The post-earthquake 3-waters infrastructure rebuild in Christchurch has provided an opportunity to fully integrate safety in design (SiD) and value engineering into designs. With seismic resilience being fundamental to these designs, there is also a need to balance financial constraints imposed by insurance payments on one hand, with a focus on incorporating whole-of-life safety considerations on the other. These apparently conflicting drivers have emboldened designers to go beyond conventional conservative designs to come up with smart, cost-effective solutions. It has also required clients to be engaged in the journey, sometimes taking them outside their comfort zone. Solutions have utilised unconventional equipment and materials, pared-down structures, novel configurations and innovative repair and remediation methodologies. In some instances, resilience has moved from 'unbreakable' to 'easily repairable'. This paper summarises some of these innovative solutions, using delivered examples from the Christchurch rebuild, as well as one built elsewhere, applying the learnings from Christchurch. It highlights the need to have the right people, from multiple disciplines, involved in projects from the outset; to challenge conventional wisdom in delivering safe, resilient, yet cost-effective, infrastructure for our communities.

KEYWORDS

Safety in Design (SiD), resilience, value, innovation, earthquake, Christchurch, 3-waters infrastructure, water, wastewater, stormwater, pump station, pipeline

1 INTRODUCTION

The Canterbury earthquake sequence has been characterised by a host of big numbers. Since the first earthquake, of 7.1-magnitude at 4:35AM on 4 September 2010 and centred around 40km west of Christchurch, in the South Island of New Zealand (NZ), we've experienced over 14,000 quakes – and counting. The most damaging 6.3-magnitude earthquake on 22 February 2011, centred only 5km beneath a south-eastern suburb of the city, recorded a maximum peak ground acceleration of 2.2g; one of the highest ever recorded. Something like 400,000 Tonnes of liquefied sand and silt have been removed from the streets and sewerage system of Christchurch. Within the 'Four Avenues' of the main city centre, some 1,240 buildings have so far been demolished. The central city cordon was in place, manned by Army personnel, for 860 days. The Crown-designated 'Residential Red Zone'[1] extends over some 830ha and more than 8,000 houses. Around 100,000 houses were damaged, of which some 10,000 have required complete demolition. About 100 wastewater pumping stations have needed to be rebuilt or repaired. Of 1,700km of sewers in Christchurch, more than 500km (c. 30%) were damaged. In the order of 2,000 portaloos and 40,000 chemical toilets were deployed during the earthquake sequence. Approximately 50km of water pipes were damaged. Of the city's 175 water wells, all but 64 have required repair; 22 were irreparably damaged. Vertical ground movement through tectonic uplift and differential settlement has been widespread; ranging from up to 0.5m uplift in the areas of the Port Hills, to 1.0m settlement in areas near the Avon River – highly significant in a flat city predominantly relying on gravity

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[1] The flat land area in the city's eastern suburbs that is subject to liquefaction or the related effect of lateral spreading, along with the Port Hills areas at risk of rock fall or proximity to cliffs; both deemed uneconomic to repair (see Figure 1).

drainage of sewage and stormwater. 1,021km of Christchurch's urban sealed roads (52% of the total) have needed repair. Over half the city's 225 bridges have required repair or complete rebuilds. The cost to repair the city's horizontal infrastructure (i.e. roads, bridges and the 3-waters infrastructure of water, wastewater and stormwater) is estimated to be around $2.5 billion; approximately half of which is in repairing or replacing gravity pipe systems. Overall, it is reputed to be one of the most expensive insured natural disasters in history. Underpinning these bare facts is, of course, the most tragic: 185 people died in the 22 February 2011 earthquake.

Despite all the trauma, damage and disruption, the earthquakes have provided a once-in-a-lifetime, career-defining opportunity for the engineering community. The chance to rebuild a city, creating a lasting legacy of a stronger, modern and world-class urban environment has provided an opportunity that many have relished. Besides locals, scores have come from around NZ and from all over the world to play their part. Based on the collective experience gained – of failure mechanisms, of repair strategies, of the value of multi-disciplinary inputs to design, and incorporating modern materials and techniques – a number of design standards and practices have changed. The significance of the earthquakes on our design environment cannot be underestimated; at a national level, our designs can be considered those completed in the 'pre-Christchurch' world and those 'post-Christchurch'.

This paper focuses on innovative examples of 3-waters (water, wastewater and stormwater) rebuild projects from the city's infrastructure networks. It also provides an example of a project completed in Marlborough; one of the first 'post-Christchurch' projects to apply the learnings in creating safe, innovative and resilient infrastructure elsewhere. Most of the described projects are ones in which Beca Ltd (Beca) staff have been involved. With a long and close relationship with Christchurch City Council (CCC), the owner of the city's 3-waters infrastructure assets, Beca has provided design services for many of the most complex rebuild projects. This has been through either direct engagement by CCC, or by designers working alongside those from other consultants within the SCIRT alliance (described below). A location map of Christchurch, along with the various referenced rebuild project sites is shown in Fig. 1.

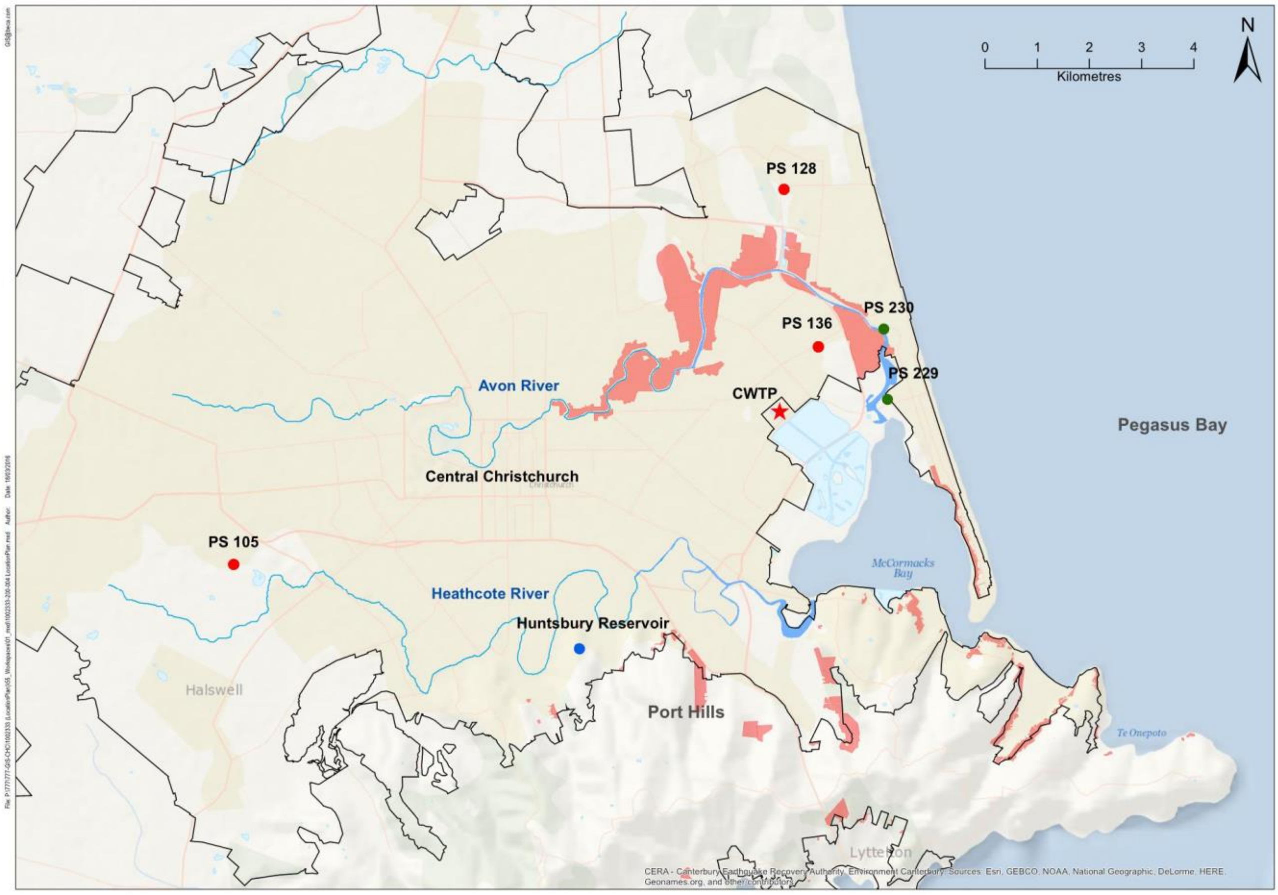

Figure 1: Location plan of Christchurch and the sites referenced in this paper. The olive green area denotes the extent of SCIRT responsibility, while the red areas denotes the residential Red Zone.

Since its creation in mid-2011, the repair, rebuild and replacement of the city's earthquake-damaged horizontal infra-structure has been the responsibility of SCIRT; the Stronger Christchurch Infrastructure Rebuild Team. Its mission is "creating resilient infrastructure that gives people security and confidence in the future of Christchurch." The alliance comprises three asset owners: CCC, the Canterbury Earthquake Recovery Authority (CERA) and the New Zealand Transport Agency (NZTA), along with five non-owner participants: namely, contractors City Care, Downer, Fletcher Construction, Fulton Hogan and McConnell Dowell. Servicing the alliance have been four design teams of consultant engineers and CCC staff; co-located in a dedicated project team environment. Beca staff formed the core of one of the four teams; the Red Team, designing the majority of the pump stations for the rebuild. At its peak in late 2011 – 2014, the design teams totalled around 160 staff (approximately 40 per team), although now ramping down as design works are scheduled for completion in late 2016. By then, SCIRT will have managed more than 700 construction jobs.

A key feature of the SCIRT alliance has been Early Contractor Involvement (ECI). Combining asset owners, designers and contractors in a 'one-team' environment has facilitated construction input into designs, whereby constructability opportunities, issues and risks are identified and taken into account. In doing so, innovation, safety and value have all been enhanced at an early stage for the designs and installations.

Throughout its lifespan, one of SCIRT's objectives has been to foster a learning and sharing culture, both within the organisation and beyond; creating a legacy of knowledge and intellectual property to be shared, not only amongst all the participants, but beyond to the wider industry. To this end, a number of technical papers have been produced on the learnings from SCIRT, such that we now have a significant body of literature and design experience that can be applied in future designs. A select range of SCIRT-derived papers, presented at technical conferences, forms part of the reference list to this paper.

One specific and critical area of infrastructure excluded from SCIRT's remit is the Christchurch Wastewater Treatment Plant (CWTP), owned and operated by CCC. At this site, CCC has had a Standing Agreement with Beca to provide professional services since mid-2008. Because of Beca's history and intimate knowledge of the site, it was rapidly able to deploy staff to the response, recovery and rebuild process, in close collaboration with CCC staff. Experience of this process at the CWTP is referenced in this paper.

Details within this paper have wider reference for territorial authorities around New Zealand, and beyond. The Local Government Act 2002 requires councils to prepare an infrastructure strategy with a minimum 30-year horizon. As noted by McFarlane (2015), a council's strategy must outline how its assets will be managed, including providing for resilience in "identifying and managing risks related to natural hazards and by making appropriate financial provision for those risks." He does point out, however, that it is often difficult for councils to justify resilience improvements against other projects that provide more immediate and tangible benefits. Nonetheless, research shows the massive payback of pre-emptive mitigation measures. McFarlane quotes the example of Orion, central Canterbury's electricity network provider, which estimated the $6M previously spent on seismic strengthening saved $30 – 50M in direct asset replacement costs following the Canterbury earthquakes. There is, therefore, a compelling case for incorporating resilient features into business-as-usual upgrades of infrastructure assets.

2 OVERVIEW OF SAFETY, RESILIENCE AND VALUE IN THE POST-EARTHQUAKE CONTEXT

Before looking at individual project examples, it is worth clarifying the three design cornerstones of safety, resilience and value associated with the rebuild.

2.1 SAFETY

Safety has been of paramount importance throughout the entire post-earthquake period. An immediate challenge was assessing damage in earthquake-weakened structures, with the ever-present hazards associated with further, unpredictable, aftershocks. Then came the challenge of demolishing damaged structures in a safe manner; again, with the spectre of more aftershocks. Designs for new structures needed to incorporate resilient features, whilst considering safe construction methodologies, as well as long-term safe operation and maintenance.

Integrating whole-of-life hazard identification, risk assessment and control methods during design to minimise or eliminate health and safety risks, Safety in Design (SiD) is, at the time of writing, only just becoming a requirement under new legislation in NZ. Since 2012, however, Beca has mandated the application of SiD for all design jobs. This has coincided with the post-earthquake environment in Christchurch, providing an opportunity for SiD to be considered for all of Beca's earthquake repair projects, both in and out of the SCIRT programme. Moreover, conducting SiD workshops during the design process provides an opportunity for all key stakeholders – designers from multiple disciplines, construction representatives and asset owners and operators – to deliberate over a project's 'cradle to grave' safety considerations.

2.2 RESILIENCE

Since the earthquakes, the term 'resilience' has been at the forefront of designers' minds, specifically in relation to the effects of seismic events. Previously, although engineers had taken account of seismic events in designs, with reference to standards such as NZS1170 (Structural Design Actions), it was often without any real experience or understanding of what actually happens to infrastructure in an earthquake. With the benefit of some five years of experience of identified failure mechanisms within the infrastructure networks and consequent design efforts to eliminate or mitigate these in future, that understanding is now greatly enhanced.

As noted by Macbeth, Hutchison & Donaldson (2015), the term 'resilience' is not easy to pin down; 'bouncing back' is a common colloquial definition. In this context, the UK Water Industry Research (2013) offers: "resilience in the water industry can be defined as the ability of an asset or asset system to continue to withstand or to recover from the effects of an exceptional event such that acceptable service levels are maintained and/or restored quickly". Two key points should, however, be stressed here. First, resilience does not necessarily equate to massive, immensely strong, structures and, secondly, resilience needs to consider a system, not just individual elements. Illustrating the latter point, a common failure mode at wastewater pumps stations was the shearing of inlet and discharge piping at wastewater pump stations; whilst the pumps themselves may have remained operable, the system was, at least temporarily, not. Equally, at the CWTP, while the biogas engines (which generate on-site power) survived the 22 February 2011 earthquake, the old galvanised iron water mains supplying the engines' cooling water did not. Without cooling water, the on-site back-up power system could not run. Cooling water is also required for the site's compressors; without them, the site's air-actuated valves could not operate. Over 50 separate repairs were required to the cooling water main to restore service. Having drawn the criticality of the cooling water system into sharp relief, the pipes were replaced with polyethylene (PE) as a priority; proving resilient to the 5.9 and 6.3-magnitude earthquakes on 13 June 2011.

Another specific matter that has not received its deserved attention and accolade is that, whilst damage to 3-waters infrastructure was widespread, subsequently requiring significant repairs or complete replacement of many elements, much of the infrastructure service as a whole was able to be brought back into operation soon after the earthquakes; albeit at reduced capacity and requiring careful nursing by operations staff. For example, following restoration of power and some initial basic patch-up repairs, all of the city's wastewater pump stations were able to kept running to some degree, pumping sewage to the CWTP. Similarly, even with some water bores and reservoirs being rendered inoperative, with the facility to reconfigure the water network through pumps and valves, water supplies to almost all parts of the city were restored within two weeks. Despite the earthquakes exceeding design standards, the resilience of individual elements, combined with the built-in redundancy within systems has proven the inherent resiliency of the city's 3-waters infrastructure; a positive reflection of past designs and NZ's strong design codes. In fact, to some extent, probably the greatest achievement of all in first few months after the 22 February and 13 June 2011 earthquakes was the avoidance of water-borne disease outbreak. As noted by the Canterbury Medical Officer of Health, Dr Alistair Humphrey, "the massive scale of damage to this vital infrastructure in the earthquakes left Christchurch people at risk of major outbreaks of gastrointestinal illness that almost always follows disasters of this magnitude." The fact that this did not occur is testament to the resilience of the system and the "heroic job" done by CCC Water and Waste Unit staff, along with its maintenance contractor, City Care, in "very difficult circumstances" (*The Press* newspaper, 2 September 2011).

2.3 VALUE

Directly after the 22 February 2011 earthquake, engineers dealing with the recovery were advised not to worry about the money, as an empowerment strategy to restore services at the earliest time. That state was never likely to last, and although CCC was of the view prior to the earthquake they had sufficient resources and insurance, events proved that not to be the case for a number of reasons.

CCC is one of 33 contributing members of the Local Authority Protection Programme (LAPP) disaster fund; set up in 1933 following the Napier earthquake two years earlier. The mutual fund accumulates to assist in paying costs of above-ground infrastructure assets damaged by natural disaster. The extent of the damage to the city's above-ground assets revealed that CCC had undervalued some of them and that a full pay-out would exhaust the LAPP fund. This resulted in CCC receiving a global settlement for above-ground assets significantly short of the replacement and repair value in some instances.

In the case of below-ground assets (pipes and wells etc.), responsibility for these costs is shared between central government and local authorities; beyond a threshold, central government will pay 60% of the restoration costs (i.e. taxpayer-funded), leaving local authorities 40% (i.e. ratepayer-funded). Further to this, the Civil Defence and Emergency Management Act 2002 was subsequently interpreted that, where pipes were replaced, funding would be calculated on the undepreciated value of the pipe being replaced, leaving another significant shortfall.

With a limited budget, all design decisions have needed to carefully consider what value they are adding to the system and, moreover, to the ratepayers of Christchurch and the taxpayers of New Zealand. Designers need to balance the resilience of assets against the cost of providing an appropriate level of seismic performance and functionality (Hunt & Hutchison, 2015).

SCIRT’s mode of operation provides a good example. At the outset, a ‘condition-based’ approach was applied: if damage was identified beyond certain specified criteria, it was fixed. Because so much of the damage was underground and not immediately apparent, the ever-increasing scale of the identified repair costs required a new approach. A ‘level of service’ approach has since been adopted, whereby a more global assessment of the networks is taken. The goal is to attain a level of service across the network similar to pre-earthquake levels. In doing so, some non-critical damage is being left unrepaired, with the asset still functioning for its remaining asset life, while funding is directed to repairing more critical assets. More recently, this approach has been further modified, such that some non-critical damage in non-critical locations has been removed from the SCIRT programme altogether; being passed to CCC to repair under its normal renewal programme.

The level of service approach does, of course, require SCIRT designers to not only understand the relative functionality of the pre- and post-earthquake networks, but also understand the implications of any proposed works (Murphy, 2013). It also makes provision for incorporating out-of-scope work or inclusion of elements of resilience or betterment into design solutions. In such cases, the asset owner (CCC, in the case of 3-waters infrastructure) considers the proposed solution, giving approval where a better value solution is demonstrated.

Underpinning SCIRT’s approach is an innovative whole-of-life costing methodology, developed in-house, to evaluate rebuild options. Based on a net present value (NPV) analysis, it considers capital costs, capital renewals, operations and maintenance costs, as well as the risks and costs associated with future earthquake events (Heiler, 2014). A key feature is that it values the resilience offered by different rebuild options, including more expensive, but more resilient, options. Previously, earthquake risk had not been considered in the evaluations. Heiler asserts that the methodology can be applied to any area faced with known natural hazards and is of particular benefit where costs associated with the natural hazards cannot be completely mitigated through insurance or more conservative construction standards.

2.4 INNOVATION

The need to combine the apparently conflicting drivers of safety, value and resilience into rebuild design has inevitably resulted in innovative outcomes. Certainly, if necessity is the mother of all invention, then a natural disaster on the scale of the Christchurch earthquakes has provided that need, in completely upsetting the business-as-usual paradigm. Catalysts for post-earthquake innovations have included scarcity of materials and resources, limited funding, damage to conventional materials, failures of conventional structures and design elements, hothouse working environments and the pressing need to restore functionality to the infrastructure networks to minimise health risks and restore public confidence.

3 WATER SYSTEMS

Typically, repairs to the water supply network following the earthquakes have been relatively straightforward. Within the reticulation, works were typically limited to repair of discrete breaks, or renewal of lengths of main. Widespread use of PE pipe (as is typical for new installations) allowed for rapid renewal, with built-in resilience due to material strength and flexibility. CCC completed repair works to existing well-head and booster stations, whilst SCIRT was tasked with repair and renewals at reservoirs, along with the design and construction of a handful of new water pump stations. The absence of water treatment within Christchurch's aquifer-sourced water supply further simplified the delivery of repair solutions.

One example of a particularly challenging water supply repair project is the Huntsbury Reservoir, built in 1954 and located on the lower slopes of the Port Hills. Prior to 22 February 2011 earthquake, at 35,000m^3, this was the single largest water reservoir in the city's network. On that day, however, its entire contents was lost. Although not confirmed, the loss was likely to be through a combination of cracks in the floor and via the main outlet valve that became stuck in a partially-open position. Hunt, Clifton & Christison (2013) record that damage to the reservoir included a broken inlet/outlet pipe flanged connection, extensive dislocation and cracking of floor slabs, cracking of the roof slab and some movement at wall joints adjacent to the corners of the structure. Damage was concentrated in a 20 – 30m-wide diagonal strip to the extent that base reinforcing was ruptured. Investigations later confirmed a geological shear zone within the underlying basalt, oriented diagonally and directly underneath the reservoir.

Because of its significance in the network, it was critical to restore water capacity rapidly, with a target of a partial restoration by December 2011, in time for peak summer demand. Although other sites were investigated, none were found to be suitable, so the focus was on working with the existing site. Repair of the entire reservoir was not considered feasible, utilising the existing structural system, taking account of the predicted horizontal and vertical movements along the shear zone in the event of a future earthquake. With the time pressure, combined with the need to work with the existing site, an innovative solution was devised whereby two corner trapezoidal sections of the existing rectangular structure would be repaired; maximising the available space on either side of the shear zone. The area of reservoir over the shear zone could be demolished and used for access to the two halves of the 'new' reservoir (see Fig. 2). Whilst providing a lesser capacity, CCC accepted a long-term storage capacity of 15,000m^3 as workable.

Figure 2: Construction activities at the Huntsbury Reservoir site in 2011, with machinery working in the area between the two halves of the 'new' reservoir.

The design required a new floor slab overlaid on the existing concrete slab, a new reinforced concrete foundation and walls adjacent to the shear zone, re-use of the existing perimeter walls of the reservoir and a new reinforced concrete roof. The existing roof column supports were reused, while the new roof slab was designed to allow a crane to operate on it during construction. A design feature of the roof slab was an overlay of a fibreglass-reinforced PVC sheet membrane to prevent leakage into the reservoir due to either post-construction shrinkage at construction joints or seismic cracking. Because the city's water supply is unchlorinated, integrity of storage structures is important to avoid contamination (Hunt, Clifton & Christison, 2013).

Besides the reservoir itself, the connecting pipework design was critical to maintain system resilience. Each half has an inlet/outlet pipe branch connected to a common inlet/outlet pipe, installed below the reservoir floor. Each has an external electrically-actuated isolation valve that closes in the event of an earthquake (via a signal from a seismic sensor), along with a manual isolation valve and a flexible bellows to provide flexibility and minimise transfer of potential loads to the reservoir pipe stub. A butt-welded PE pipe connects the common inlet/outlet pipe section across the shear zone.

Safety during construction was carefully considered. Risks included restricted site access, work within a confined space, restricted working space between the reservoirs columns, the potential for falling debris from the damaged roof and the ever-present dangers associated with further earthquakes – as was experienced with the June 2011 earthquake. Mitigation measures, such as removing loose concrete from the roof's underside, were undertaken and construction proceeded without incident.

Because a demolish and rebuild option was discounted early on, as a result of the identified shear zone, a cost comparison between this and the selected partial reconstruction option was not undertaken. Nonetheless, reconstruction will have provided significant cost benefits over having to demolish the entire structure and constructing a new one in its place. Besides the cost factor, construction of the first stage of the reservoir was completed in less than five months, being commissioned in December 2011, while the second stage reservoir was commissioned in November 2012.

4 WASTEWATER SYSTEMS

4.1 WASTEWATER PIPES

The operational issues associated with the influx of liquefied sand and silt into the wastewater network via damaged pipes were of a monumental scale. At the peak of the post-earthquake response, suction tankers were literally queuing at the CWTP, 24 hours a day, to dump slurries of sand and wastewater, removed from the sewers, into a disused holding lagoon. In terms of overall costs, an unpublished Beca report for CCC records that while CCC's 'business-as-usual' (BAU) operational costs for wastewater over the July 2010 – June 2014 period (i.e. four financial years) totalled $38M, the additional operational costs[2] associated with earthquake response over the same period totalled $232.6M. In the July 2011 – June 2012 year alone, this additional cost was a staggering $119.1M; the majority being associated with cleaning of sewers. ('Initial Evaluation of Christchurch City Council Future 3 Waters OPEX Costs', Beca, 2015).

With 1,700km of sewers, all hidden underground, the scale of the damage assessment programme was nothing short of daunting. Closed circuit television (CCTV) examination was the main method of assessment; Gibson & Triplow (2013) reporting that, at one stage, 95% of all units in NZ were deployed in Christchurch. With sand and silt blocking many pipes, requiring jetting prior to CCTV, progress was slow and costly. To accelerate the assessment process, an innovative methodology was developed by the SCIRT team. The multi-criteria Pipe Damage Assessment Tool (PDAT) was developed to predict the structural condition of pipe assets based on previously completed CCTV surveys in similar situations, in combination with other damage predictors such as pipe depth, material, diameter, direction, local road condition data, proximity to waterways, and sub-catchment

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[2] BAU operational costs include operational repairs to pipework, cleaning and maintenance.

Additional earthquake response costs include cleaning and silt removals; investigations and CCTV inspections, pipework repairs (some up to 6m deep); over-pumping and extra repairs to pump stations, temporary works and network modifications.

area. The fundamental benefit of PDAT is that it reduces the reliance on costly and time-consuming CCTV surveys; a good example of the best-value approach being developed by the SCIRT team. This value is summed up by Mark Christison, then CCC's City Water & Waste Manager, who reported back to SCIRT that "the tools that are being created, along with the risk-based analysis techniques are ground-breaking stuff [which will] accelerate assessment and the entire delivery programme, saving millions of dollars." (M. Christison e-mail to SCIRT General Manager, 18 April 2012).

A key finding of the assessments was that, while some pipe materials were typically more resilient than others (e.g. polyvinyl chloride (PVC) and PE pipes suffered minimal structural defects, but grade defects were common), the underlying ground conditions and proximity to watercourses were at least as significant in determining damage. Liquefiable soils and lateral spread adjacent to watercourses were particularly high risk conditions. Rebuilding the pipe network in the poor ground that lay under much of the east of the city was fraught with uncertainty. Parkinson and Maguire (2013) state that the largest uncertainty was varying soil strengths, which are thought to alter during a liquefaction event. Designing for flexible pipelines based on static soil strength no longer ensured resilience.

Their paper describes the replacement of Pressure Main 11 (PM 11), conveying wastewater from terminal Pump Station 11 to the CWTP. The existing 1200mm dia. concrete pipe had failed in three locations; all joint failures near thrust blocks due to differential settlement between the blocks and the pipe. The 3.6km replacement pipe was to be in glass-reinforced plastic (GRP); providing flexibility, whilst requiring minimal open excavation at any one time. As with other pipeline replacements, because no practicable design would have mitigated against the ground conditions and ground movement experienced, a new pipe route was selected in better ground conditions; a key decision taken at the concept stage, providing huge whole-of-life cost-benefit at little design cost. Specific design features include:

- Use of geogrid and aggregate thrust blocks so that the thrust restraints are of a similar density to the trench embedment, reducing the potential for differential settlement

- Use of 'double bell' rubber gasket couplers at the pipe joints to mitigate against differential settlement along the pipe route, allowing a 1o rotation (equating to 100mm over 5.7m of pipe)

- Pipe joints were positioned for maximum pull-out resistance, rather than compression, since most observed failures in the area were from pipe joints pulling apart

- All joints were wrapped in a geotextile sock so that, if the joint pulls apart, the sock prevents gross entry of liquefied material, allowing the pipe to continue to function even though damaged.

- A composite compacted aggregate raft, reinforced with geogrid, was installed to mitigate against buoyancy effects during liquefaction.

Working in similarly poor ground conditions in the eastern suburb of Aranui, Mirza (2013) describes the design of the 2.9km PM 128 which, being a DN800 PE pipe, is the largest directionally-drilled pressure main in the city (see Fig. 3).

The PM and associated PS 128 replace a gravity sewer and pump station (PS 63) which were both badly damaged as early as the 4 September 2010 earthquake, and scheduled to be abandoned on completion of the new works. The pipe runs along a new route to avoid replacement of the large diameter gravity sewer and taking account of better ground conditions along the chosen route option. During the ECI process, the decision was taken to directionally drill the pipe at up to 3.5m depth, to minimise the risk of clashing with a number of existing services. Having made this decision, the route was further refined to allow for the required drill pits and positioning of associated drilling equipment. The pipe's structural design was based on empty pipe and no side support (related to the directional drilling), as well as the poor ground conditions, high traffic load and high expected groundwater table. PN12.5 class PE pipe was specified for the majority of the route, although PN16 was used at the crossing under the Avon River. A key identified risk was pipe jointing; both butt-welding and electro-fusion joints were used in the installation. Mitigating this risk, numerous meetings were held between designers and the pipe welder to establish the welding parameters and testing of joints was undertaken.

Figure 3: The DN800 PE PM 128 pipe running along Bower Avenue prior to installation by directional drilling.

A noteworthy feature of these two pressure main projects is the level of associated investigation undertaken; trialling of pipe embedment options in the case of PM 11 and PE pipe joint testing for PM 128. The time and effort expended on confirming resilient features based on observed damage is, in itself, a reflection of the now well-understood criticality of the sewer network. Whilst a water reticulation network often allows water to be re-routed, sewers have no such facility, nor means of bypass; a single pipeline failure can cause a whole sewer catchment failure, with consequent public health risks. Hunt & Hutchison (2015) state that it is important to design pipelines to the ground conditions and geotechnical hazards, not just a set of generic civil design standards. While pump stations are typically designed to Importance Level 3, as defined in AS/NZS 1170, design of associated pipe infrastructure has not typically had an equivalent. Offer, Christison & Billings (2015) go as far as to argue that major sewers, and particularly pressure mains (since gravity sewers may function even when damaged), are key assets and should be designed with the same geotechnical rigour as pump stations and treatment facilities.

4.2 PUMP STATIONS

Many wastewater pump stations were damaged and rendered temporarily inoperative as a result of the 2010 and 2011 earthquakes. The greatest damage was incurred in the 22 February 2011 event, characterised by extensive liquefaction and high ground accelerations. Kerr (2013) categorises this damage as comprising one or more of the following:

- Structural damage caused by temporary loss of foundation support due to liquefaction
- Settlement or buoyant uplift of structures
- Differential settlement between structural elements (particularly those founded at different depths; e.g. wet wells and valve chambers) and between structures and their connecting pipes
- Subsequent operational issues, such as increased flows through inflow and infiltration (I&I) in damaged sewers, associated ingress of silt and sand, and consequent accelerated wear.

Fig. 4 illustrates some examples of damage. Of these, Hunt & Hutchison (2015) record that the most troublesome were failures at the pipe connections (see Figure 4B); caused through ground settlement and, in some instances, reversing the grade of gravity inlet pipes. Where discharge pipes failed, repairs were often hampered by their depth; requiring significant temporary works and dewatering.

As noted above, all wastewater pump stations (apart from two which essentially fell into the Avon River) were able to be patched up and operated within a matter of days after the 22 February 2011 earthquake. Longer-term, only two have required complete rebuilds; PS 36 and PS 63, albeit both being amongst the largest pump stations in the entire city and both located in the east (see Fig. 1). These rebuilds are discussed here.

In both cases, Kerr (2013) identifies four fundamental priorities for incorporating resilience into the rebuild designs:

- Site selection
- Foundation design
- Pipe connection detailing
- Site and structure layout and interaction.

Figure 4: Common failure mechanisms at pump stations

***A:** Rotation of PS 36, resulting from differential seismic settlement across the pump station and differences in founding depth for the pump station wet well and building.*

***B:** Uplift of PS 15 (not specifically discussed in this paper) and seismic settlement of the surrounding ground, resulting in differential movement and consequent shearing of the pressure main connection.*

***C:** Differential settlement and shearing between sections of Terminal PS 1 building (not specifically discussed in this paper), associated with differential seismic settlement between one half of the building founded on shallow foundations and the other half at depth.*

***D:** Rotation of PS 63 resulting from buoyancy uplift, lateral spreading and slope instability, total and differential seismic settlement across the site, and differences in founding depths of the pump station elements.*

(Examples A, C and D from Gibson et al., 2013, Example B from Hunt & Hutchison, 2015)

Foundation design aspects are further prioritised by Gibson et al. (2013), summarised in Table 1 at the end of this paper.

Built in 1980, Terminal PS 36 (see Fig. 4A) in Aranui transferred around 16% of the city’s wastewater directly to the CWTP, at a maximum capacity of 700 l/s. On 22 February 2011, it suffered from all of the damage types listed in the bullet points above, reflecting the lack of ground improvements and its asymmetric structure. With complete replacement required, a nearby site was selected for the new PS 136, reflecting both the need to keep the existing station operating and the identification of an old river channel running under the existing site – explaining some of the site’s damage. Ground conditions are such that liquefaction is expected to 10 – 20m depth in an ultimate limit state (ULS) event. Ground improvement, in the form of 600mm diameter continuous flight auger (CFA) piles of unreinforced concrete was chosen. The 410 individual columns are positioned in a rectangular lattice at 1.5m centres, extending approx. 10m around the wet well structure; the configuration designed to mitigate liquefaction and limit the extent of settlement. A key design feature was that the pile depths taper from 6m length under the wet well, reducing towards the periphery of the ground improvement area. Any seismic settlement will be gradual, allowing flexible sewer pipes to bend, rather than imposing a shearing action at the connection points at the structure (Kerr, 2013). Even so, restrained pipes (welded PE in this case) were selected over socket and spigot jointed pipes where expected ground movement exceeded the allowable rotation. The new PS 136 has an increased capacity of 1,000 l/s, with submersible pumps in duty/assist/ standby/standby configuration. It is a substantial structure- the wet well is 9.4m x 8m in plan, founded around 9m below ground level and topped with a 7m-high building. A separate underground valve chamber, as well as a separate control room and a separate generator are adjacent. The pump station excavation during construction is shown in Fig. 5.

Figure 5: Construction work at the base of the wet well for PS 136, showing the tops of the 600mm-dia. CFA piles.

Located in the eastern suburb of Bexley, PS 63 (see Fig. 4D) was built in 1983 as an Archimedes-screw lift station, conveying up to 470 l/s of wastewater to Terminal PS 36. Positioned alongside the Avon River, it was damaged due to lateral spread, exacerbated by its asymmetric structure, resulting in differential settlement. Considering replacement, a completely new site in North New Brighton was selected; partly reflecting catchment changes through the Red Zone, but also positioned at a site with better ground conditions. CFA piles in the same configuration as those at PS 136 were used. The new pump station, known as PS 128, has a capacity of 625 l/s, with three submersible pumps in duty/assist/standby configuration.

Although a new-build, servicing a large new housing development in the relatively undamaged west of the city, PS 105 was designed and delivered by SCIRT at the request of CCC. This delivery mechanism was chosen to take advantage of the pool of expertise, experience and resources available at SCIRT in response to the fast-tracking of the development to accommodate post-earthquake housing pressure. Sited on relatively good ground conditions, the foundations are conventionally-piled, with 44 steel H-piles at 8.5m depth. With a capacity of 560 l/s, incorporating duty/standby/assist submersible pumps, the new pump station has been designed with similar resilient design features used in PS 136 and PS 128.

Common to all three pump station examples, the pumps have been separated into pump bays or dual wet wells that can be isolated to facilitate operational and maintenance tasks without limiting the station capacity. The pump bays are hydraulically designed to minimise silt/sand accumulation. Access platforms have been fitted to facilitate cleaning and inspection of the wet wells. Electrical cabling between standby generators and the pump stations incorporate slack to allow for differential movement between the generator and pump station. All of these features are low-cost additions, greatly adding to the resilience and operability of the pump stations, based on the post-earthquake experience (Hunt & Hutchison, 2015). Inlet pipes to all three pump stations from the last upstream manhole have been over-steepened to mitigate against the effects of differential settlement, reducing the potential for reverse grades to develop in a seismic event. At PS 136, with four pumps and three pressure mains, the discharge pipe manifold is outside the pump station itself, within an area of ground improvement. At

PS 128 and PS 105 on the other hand, the discharge manifolds are positioned within the main structure, providing a single exit point from the structure. The connection is fitted with a proprietary ball-and-socket flexible connection. These features are designed to minimise the risk of pipe failures during seismic events. Tanker coupling points at the pressure mains serving both these pump stations allow bypass pumping or direct tanker discharge in the event of a catastrophic pump station failure. An unusual feature of both these pump stations is a permanently-installed gravity bypass around the station to the pressure main, which is at a lower elevation that the pump station. In the event of a pump station failure, by altering valve positions, wastewater can gravitate along the pressure main; albeit at a lower flow rate than if pumped. This is only possible because of the flat terrain in Christchurch.

4.3 CHRISTCHURCH WASTEWATER TREATMENT PLANT

The CWTP treats all of the city's wastewater, a population equivalent of some 400,000 persons, averaging around 170,000m^3/d. Peak wet weather flows are around 6.0m^3/s. Originally constructed in 1957, various process additions have since been incorporated so that the liquid treatment stream now comprises inlet screening, grit removal, primary sedimentation, biological filtration, solids contact (a form of activated sludge), secondary clarification and 225ha of oxidation ponds, prior to discharging via a 3km-long ocean outfall into Pegasus Bay.

Located in the eastern suburb of Bromley, it is built over liquefiable sands with shallow groundwater; typically 1.5 – 2.5m depth. Significant damage was incurred during the earthquake sequence, particularly on 22 February 2011 and further exacerbated on 13 June 2011. In the first two weeks following 22 February, very little flow was received at the CWTP due to power outages and damage at wastewater pump stations, as well as damage and blockages within the sewers themselves. As network repairs were effected, influent flows to the CWTP were restored, accompanied by massive volumes of sand that had been liquefied and entered the damaged network. This caused immediate and long-lasting problems throughout the entire treatment process, blocking pumps and pipes, reducing process efficiencies and accumulating in tanks.

A further challenge was the structural damage sustained to all four secondary clarifiers, rendering them inoperable. This, in turn, meant the interlinked upstream solids contact tanks were also unable to operate. Built in 2002, the 48m-diameter radial-flow clarifiers comprise 225mm-thick pre-cast, post-tensioned concrete walls and 160mm-thick post-tensioned concrete floors. Each clarifier is fitted with a mechanical scraper mechanism to assist with sludge and scum removal. 5m-deep stone columns had been used as ground improvement during the construction. Being built within the groundwater zone, they were fitted with pressure relief valves in the floor slab to prevent flotation. Despite these features, moderate to severe damage was caused during the 22 February 2011 earthquake due to both ground shaking and liquefaction effects. Although differential settlement was immediately apparent, the full extent of damage was only revealed after the tanks were drained, requiring the adjacent water table to also be pumped down. Uplift forces had caused flotation of all four clarifiers, with moderate to severe deformation and cracking of floors (see Fig. 6). There was an urgent need to return two clarifiers back to service as soon as possible, so the two least-damaged units, Clarifiers 1 and 2, were temporarily repaired and recommissioned. Permanent repairs were then effected on the other two clarifiers.

Six repair options were evaluated, as described by Offer, Billings & Scott (2014), ranging from repairing the existing floor slabs ($0.25M per clarifier), through to complete replacement of clarifiers ($12.6M each). The selected option was to install floor overlay slabs ranging from 450 – 700mm-thick depending on the clarifier (approx. $0.6M each); providing both a cost-effective reinstatement of clarifier structural performance and an enhanced resistance to liquefaction uplift in a future seismic event (Offer, Christison & Billings, 2015). In evaluating seismic performance, it was realised that strengthening the clarifier floor could cause the entire clarifier to float up out of the ground in a future, very long duration, earthquake (2 – 3 minutes). Nevertheless, with no practical alternative available, CCC had no choice but to proceed on this path, whilst acknowledging the possibility of this low risk, but high consequence, event.

Besides the clarifiers themselves, their 1800mm-dia. jointed concrete inlet pipes from the contact solids tanks needed repair, with significant leaking identified as a result of ground movement. Any repair needed to accommodate a similar amount of future movement, measured at up to 120mm over the length of the pipes. Various options were considered, with physical excavation under the clarifier floors quickly eliminated as being too risky in case of further earthquakes. Trenchless repairs of liners or joint repairs were, therefore, shortlisted. Any repair needed to be installed 'live' with the pipe full of water, due to the buoyancy risks to the pipes if dewatered. Of the four shortlisted options, two were ruled out because of access limitations for installation, while another was unable to demonstrate it would withstand anticipated seismic forces. This left the cure-in-place pipe (CIPP) liner. Using a polyester fabric impregnated with a thermo-setting resin and expanded against the existing pipe before curing, it effectively forms a 'pipe within a pipe'. The selected liner, resisting worst-case external pressures from liquefaction, had a wall thickness of 50mm. At 1800mm dia., it remains the largest CIPP liner installed in NZ.

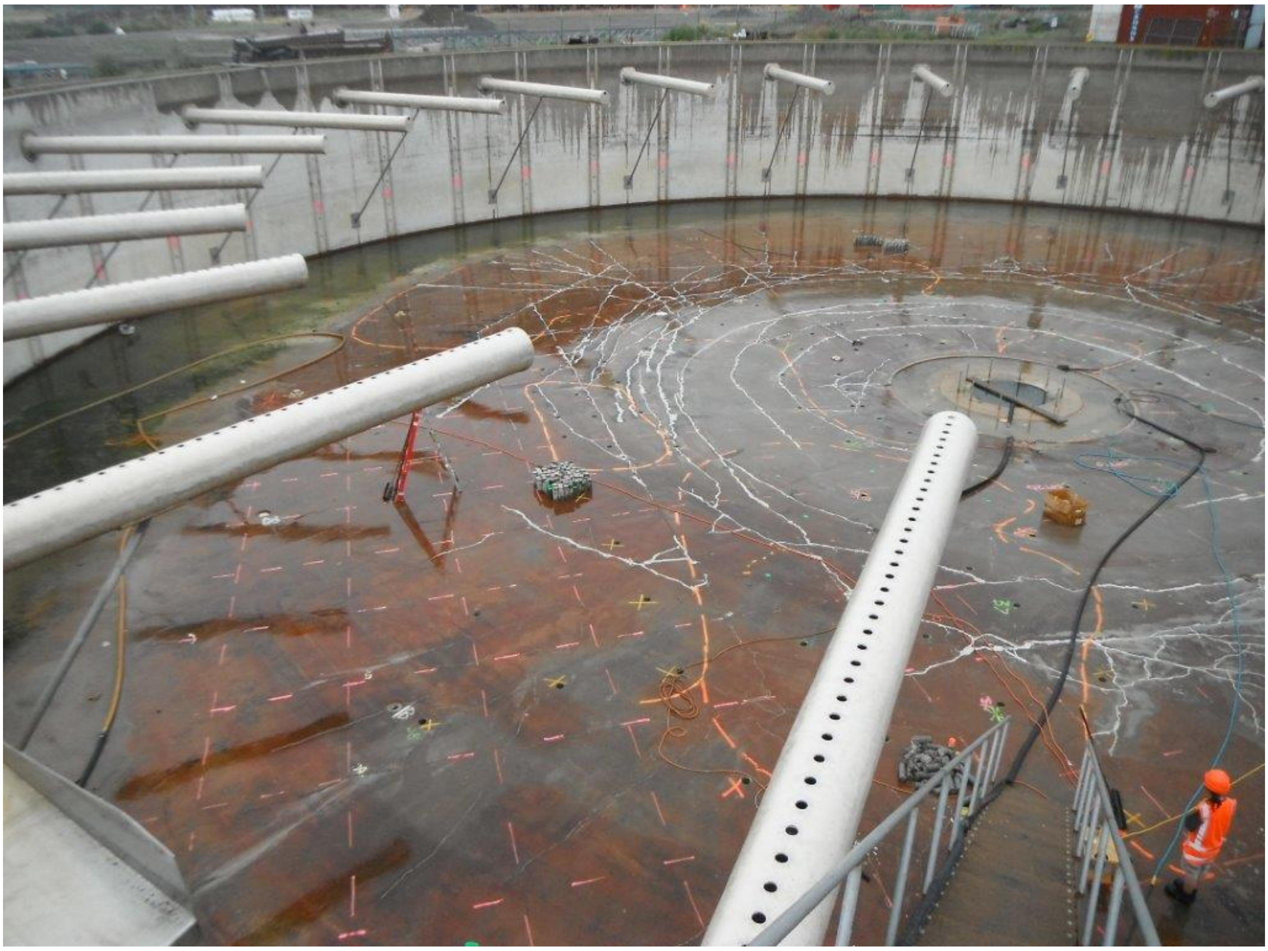

Figure 6: View of the empty Clarifier 3 (with mechanical scraper mechanism removed) showing the inverted floor cone and grout-filled circumferential cracks.

Whilst the clarifiers were off-line, as noted by Offer, Christison & Billings (2015), basic plant functionality was restored within four weeks of the February 2011 earthquake. This reflected the level of redundancy provided by five grit traps and seven primary sedimentation tanks (allowing multiple tanks to be taken off-line for servicing or repair at any one time), the relatively limited damage to the trickling filters, oxidation ponds and ocean outfall, along with the number of treatment process steps at the CWTP. Because of this pre-existing level of plant-wide redundancy, the contact tanks and clarifiers were able to be bypassed completely, yet treatment was maintained at a level that managed the public health risk.

5 STORMWATER SYSTEMS

With the level of vertical ground movement caused by the earthquakes, the largely gravity-drained stormwater catchments in flat, low-lying Christchurch were significantly affected. Particularly in eastern suburbs and those along the lower Avon and Heathcote Rivers, drainage was compromised. Pipes were damaged, liquefied sand blocked pipes and sumps, some properties no longer drained to roads, sumps were no longer at low points, flow paths were altered, the network's capacity was reduced and flooding of roads and property was occurring at high tides – particularly when co-incident with storm events.

Initial response works included:

- Installation of flap gates or simple steel plates, even concrete infilling of some riverside pits, to prevent tidal inflow during high-tide events

- Temporary pumping to manage severe ponding

- Emergency stopbanking to inhibit inundation of low-lying land; much of which is still in place five years later.

Longer-term solutions provide good examples of SCIRT's level of service approach discussed above. The South Brighton area adjacent to the Avon-Heathcote estuary saw 200 – 400mm settlement in the catchment. Simply repairing and/or replacing existing pipes would not restore the level of service. Instead, an element of betterment has been required: a combined pump station (PS 229) and storage basin has been installed. Whilst the catchment can drain by gravity at low tide, the pump station is required to pump stormwater under high tide conditions. The storage basin has been designed to provide flow buffering in a 1 in 5-year rainfall event. In doing so, the system's capacity has been reinstated. In contrast, in the central suburb of Shirley, out-of-scope assets have been incorporated, where works to watercourse and culverts have provided a more cost-effective means of providing system capacity than solely works to the stormwater reticulation (Murphy, 2013).

Softer engineering is also considered: where appropriate, pipelines can be replaced with swales or open drains. Besides providing flood storage, they have ecological, recreational and water quality values. Moreover, they are immune to the common pipe defects of cracking and displaced joints.

The majority of Christchurch's stormwater network is laid in reinforced concrete rubber ring jointed (RCRRJ) pipe. Due to its cost efficiency and comparatively good seismic performance in most areas, this is still the material of choice for most renewals; typically replacing materials such as asbestos-cement, earthenware, and unreinforced concrete that performed less well in the earthquakes. In areas at risk of lateral spread, bank instability or root intrusion, plastic pipes are more appropriate (PE for >DN300 and PVC for smaller) given their durability and flexibility. Whilst more costly that RCRRJ, value is seen in the improved resilience in case of future earthquakes. (Murphy, 2013).

In low-lying areas at risk of tidal inundation during high tides or in low level outlets at risk of silt deposition, non-return valves are being installed on all SCIRT installations. Whilst many existing outlets had flap gates, new installations utilise in-line check valves, such as WaStop® check valves, eliminating the observed issues of breakage and loss of function due to debris accumulation seen in the flap gates. These valves are also unobtrusive, being inside the pipe, provide flushing qualities and have a longer asset life (Murphy, 2013).

The specific example of PS 230, described by Hutchison & Mirza (2013), provides a good illustration of the combination of SiD, value and resilience in a single SCIRT project. Since the earthquakes, the northern Owles Terrace stormwater catchment, draining to the lower reaches of the Avon River, has been unable to convey surface waters during high tides or storm surges. A pump station was required, meeting an agreed level of service of a 1 in 50-year flood event, combined with a 5-year high tide. The approach was to provide a design that was transferable to other locations with similar drainage issues, reducing overall programme costs. Key challenges were to convey the flow volume to the pump station and to construct the pump station in poor ground conditions with the combined risks of lateral spread, buoyant uplift and seismic settlement.

Solving the conveyance issue was relatively straightforward: pumping capacity needed to be close to the existing gravity outfall. Constructing the pump station itself required more lateral thinking, with concepts discussed with geotechnical and structural experts, along with contractors in ECI workshops. The innovative solution developed utilises a horizontally-mounted axial-flow pump. Rather than a conventional wet well of approx. 5m depth, requiring significant ground improvements, the horizontally-mounted pump station is 2.5m deep. This orientation has enabled another innovative feature; the wet well structure is a lightweight pre-cast concrete box installed with minimal ground improvement. The pre-cast box is of a standard design, fixed to a concrete base, with the benefits of minimising site construction time (providing cost and safety benefits) and enabling removal of the box to facilitate re-levelling following a seismic event. A removable pre-cast concrete lid is positioned over the box, incorporating McBerns safety access lids for access and pump removal (see Fig. 7). The standard box is based on a $1m^3/s$ design flow, adjustable through benching to reduce flows, or installing parallel pump station modules where higher throughput is required. Utilising a raft foundation with a light, shallow structure limits differential settlement following a seismic event and, should it eventuate, excavation around the structure allows it to be lifted and re-levelled within a short period. The station is designed to settle with the surrounding ground, accommodating movement, rather than resisting it.

Figure 7: The near-complete horizontally-mounted PS 230 installed in the road verge at Owles Terrace.

It is understood that, while horizontally-mounted stormwater pumps are used in Europe, the only other examples in NZ date from the 1970s. Identified overall cost savings were \$3.6M, compared to a conventional pump station design, achieved through reduced pump station construction costs and reduced requirement for stormwater network upgrade. Overall, the project has achieved the objective of balancing affordability with an appropriate level of resilience (Hutchison & Mirza, 2013).

6 AND BEYOND CHRISTCHURCH…

With the design of much of the Christchurch infrastructure now complete, designers are now turning their attention to business-as-usual projects, informed by their learnings from the rebuild. One of the first examples to have been completed is the Vernon Street Pump Station in Blenheim, Marlborough, at the north of the South Island, as described by Macbeth, Hutchison & Donaldson (2015).

Located in an industrial estate, the pump station is owned and operated by Marlborough District Council (MDC), pumping a combination of sewage and industrial wastewaters; largely derived from wine-making. Growth in the estate required replacement of the previous pump station, with a key requirement being to protect the new wet well and equipment from the corrosive effects of the winery wastewater. The previous concrete wet well and pumps had been severely corroded; the wastewater pH during the wine harvest being 4.5 or lower. Another critical design consideration was the need to commission the new pump station before the March 2015 grape harvest. Ground conditions at the site had previously been assessed as having high liquefaction potential in an earthquake, with 180mm and 300mm settlement predicted in Serviceability Limit State (SLS) and ULS events respectively. Despite dissimilar project drivers compared to the SCIRT projects, the similar underlying ground conditions enabled a number of the SCIRT-developed resilient design principles to be applied in this project.

Having won the consultancy services in mid-2014, Beca considered high-level design options; essentially whittled down to a larger-capacity concrete wet well similar to the existing or a proprietary GRP wet well with conjoined valve chamber (similar to GRP units used in SCIRT projects). The latter option had not previously been considered by MDC. A cost comparison of the two options indicated a saving of almost 20% in favour of the GRP unit. Besides cost, GRP's inherent resistance to corrosion and the reduced site works programme added to the attractiveness of this option.

Based on the Christchurch experience, various design features were incorporated to mitigate against the predicted effects of seismic events:

- A simple concrete base, 'over-sized' in comparison to the wet well and valve chamber plan area, acts both as a cost-effective foundation and a counter to buoyant forces through the addition of mass, and as an anchor acting against the surrounding backfill.

- The wet well invert has been lowered by 150mm and the last length of inlet pipe over-steepened by a similar amount to allow for the anticipated differential settlement between the inlet pipe and the base of the wet well (i.e. settlement of pipe within the non-improved ground beyond that underlying the wet well)

- Flexible pipe connections have been provided at the interface with the wet well structure and slack has been provided in the cables connecting to the pump station. Gibault joints have been provided for the pressure pipe connections to provide an easy-to-repair 'fuse' if differential settlement exceeds the capacity of the pipe or jointing system

- The conjoined valve chamber, housing the pumps' discharge valves eliminates the potential for differential settlement between the two structures and reduces the number of pipe penetrations in the structures that could break due to ground movement

- Minor rotation of the pump station (<3°) during a significant earthquake could occur; unlikely to affect the mechanical performance of the pump station. Some elements, such as the concrete surface slab, may need to be replaced if this rotation occurred.

A key benefit of the GRP option is that the structure was able to be fabricated in a well-controlled factory environment and transported to site as a complete unit, pre-fitted with pump guiderails and duckfoot bends, valve chamber valves, piping access ladder and hatches (as illustrated in Fig. 8). In combination with the simple ground improvements, site works were, consequently, greatly reduced: constructing formwork, placing reinforcement, dewatering, and equipment fit-out. This provides a safer working environment, with less time required for workers in a below-ground confined space. Moreover, the civil works and wet well fabrication were able carried out in parallel, reducing the overall programme for the time-critical installation. Once delivered, the wet well was lowered into place and secured in a single day, with the system commissioned two weeks later – ahead of programme and under budget.

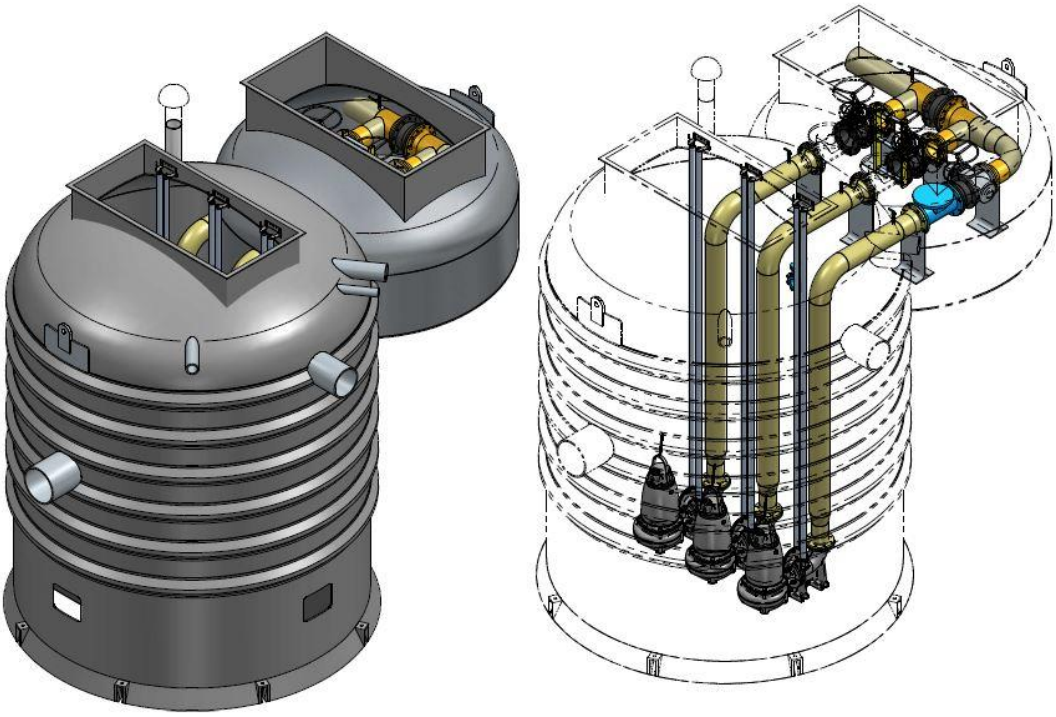

Figure 8: Isometric shop drawings of the Vernon Street GRP Pump Station (provided by Maskell Productions Ltd).

7 CONCLUSIONS

The post-earthquake infrastructure rebuild in Christchurch is the most massive engineering programme of works ever undertaken in NZ. Whilst a good level of resilience has been shown to have been in place prior to the earthquakes, when critical assets fail – sometimes apparently insignificant ones – entire systems can be rendered inoperative. A key lesson has been that, in terms of resilience, infrastructure assets must be considered as a system, not just individual elements.

The example projects referenced in this paper demonstrate the benefits of close working relationships between clients, consultants and contractors in achieving synergistic outcomes. In response to such a disruptive change to the business-as-usual paradigm, innovative solutions, incorporating safety, value and resilience have been developed, despite their seemingly mutual incompatibility. Right from innovative asset assessment methodologies, such as PDAT and the NPV-based rebuild optioneering tools developed at SCIRT, through to the consideration of operational aspects of the rebuilt assets, safety, value and resilience are evident in all of the referenced examples in this paper. Re-location, re-configuration, re-design and replacement have been demonstrated to be worthy options in the rebuild.

All the examples highlight that the greatest safety, value and resilience benefits are achieved at the concept design stage, when multi-disciplinary teams, including construction contractors and clients are engaged and working collaboratively together. As noted by Hunt & Hutchison (2015), this approach assists in identifying critical vulnerabilities which, in turn, allows the design to focus on an appropriate level of resilience. Moreover, incorporating resilience does not need to be expensive: with appropriate detailing, step changes in resilience can be achieved. Indeed, at the early planning stages, improvements in resilience can be achieved for little or no cost. For example, inclusion of easily-accessible and easily-repairable fuse points provides cost-effective resilience, compared to designing an earthquake-proof asset. Conversely, by the detailed design stage, the ability to improve resilience is limited and can increase the cost of the project substantially. This is relationship is neatly summarised in the schematic graph in Fig. 9, taken from Gibson & Newby (2015).

Site and/or route selection for infrastructure assets is a key decision in the design process that can have a major bearing on cost and future resilience; warranting due consideration. The next highest priority is foundation design, with a range of resilience options being available depending on the type, criticality and configuration of the asset. On this point, the Christchurch experience highlights the critical nature of the wastewater sewer network; with no back-up or bypass facility, short-term response costs to maintain service in the damaged system and protect public health were enormous. In hindsight, there is a strong argument for sewers to be designed with the same geotechnical rigour as pumping and treatment facilities.

Equally, pre-emptive inclusion of resilient features into routine upgrades of infrastructure assets has been shown to provide significant cost-benefit in the event of a natural disaster, even if the (apparently) additional costs can be difficult to justify at the time. Moreover, as demonstrated in the Vernon Street Pump Station example, even with different underlying project drivers, resilience and safety can be incorporated, providing capital cost savings, in the business-as-usual context.

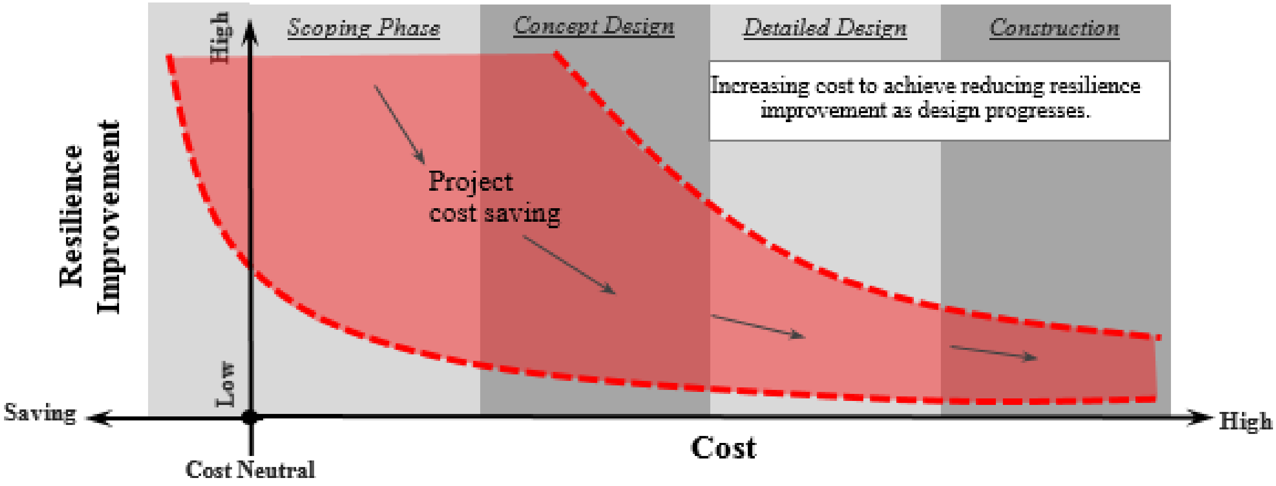

Figure 9: Schematic graph indicating the diminishing returns and increasing cost to achieve resilience improvement as a project progresses from scoping through to construction (from Gibson & Newby, 2015).

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Table 1: Generic resilience prioritisation for pump station foundation design (from Gibson et al., 2013).

Priority	Description	Typical mitigation incorporated into foundation design
1	**Improve slope stability and mitigate lateral spreading** to limit the translation and rotation of the structures**.**	• **Consider alternative sites** for pump station; increase distance from the free face • **Install ground improvement or large diameter piles** to limit lateral displacements or resist lateral loads exerted on the structure.
2	**Limit differential settlement** of the wet well structure and associated rotation, to reduce damage to connecting infrastructure and reduce the cost of post-earthquake repair or replacement.	• **Install ground improvement or piles** beneath the pump station, to limit differential settlement across pump station • **Install ground improvement** surrounding the pump station to support the sides and resist the potential for differential settlement • **Provide consistency in foundation depth and performance** for structures and connecting infrastructure to reduce the potential for structure rotation, differential settlement and damage to pipe connections.
3	**Limit buoyancy uplift** of the pump station structure under both hydrostatic and seismic conditions.	• **Relieve excess pore water pressures** through the use of permeable backfill or base drains • **Install tension piles or anchors** to resist uplift forces • **Add weight to the structure or utilise an extended base** to resist the uplift force.
4	**Provide compatibility between total settlement of the wet well structure and connecting infrastructure** to limit damage, and reduce potential differential settlement across the structure.	• **Appropriate ground improvement design** beneath and surrounding the pump station, to limit differential settlement across the wet well • **Piling of the pump station** to limit differential settlement across wet well, with flexible connections to accommodate differential settlement between the pump station and connecting infrastructure • **Design slightly deeper wet wells and over steepen inlet gravity pipes** to accommodate potential differential seismic settlement between the catchment and wet well, considering multiple future earthquakes • **Extend and transition ground improvement depth beneath critical pipe connections** to control in the rate of differential settlement and reduce the risk of damage from shearing • **Use flexible PE pipes, flexible pipe connections, and provide slack in service connections** to accommodate anticipated future differential settlement.
5	**Design of pump station layout for straightforward post-earthquake repairs.**	• **Layout components of the pump station within the site to ensure that access is available,** to allow repair of earthquake damage without temporary relocation of components or complicated and costly temporary works.
6	**Design of pump station structure to accommodate post-earthquake re-levelling**	• **Consider future re-levelling in the structural design of foundations**, especially where shallow foundations are utilised for ancillary buildings.