Earthquake Repairs at Christchurch WWTP – Lessons for Resilience

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SUMMARY

The Christchurch Wastewater Treatment Plant (CWTP) was seriously damaged during the 2010-2011 Canterbury Earthquake Sequence. This paper describes the earthquake sequence and the damage it caused. It also outlines the strategy for managing short-term risks to the community during the immediate post-earthquake period, and the repair strategies for plant assets that were implemented over time. Finally it discusses themes for resilience for large infrastructure assets that emerged during the work.

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1. INTRODUCTION

Christchurch was subject to a major earthquake sequence during 2010 and 2011. The sequence was initiated by a Richter magnitude (M) 7.1 earthquake centred 30km west of Christchurch on 4 September 2010 (refer to Figure 1).

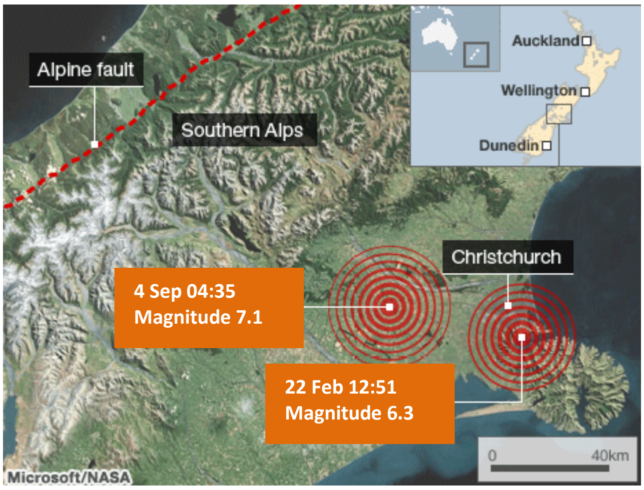

Figure 1: Canterbury Earthquakes 2010 - 2010

While over 12,000 aftershocks occurred in the region following the initial earthquake, it was the M6.3 aftershock on 22 February centred 5km directly below Christchurch that caused the most severe damage to the city and the CWTP. It generated ground accelerations that well exceeded design conditions (PGA vertical of 1.8g and PGA horizontal of 0.7g as measured at the nearby Pages Road seismograph). A further M6.1 aftershock occurred on 9 June 2011 and caused further damage. Shortly afterwards, the CWTP owner, Christchurch City Council (CCC), instructed CH2M Beca Ltd (Beca) to commence damage assessment and earthquake repairs. A project team made up of CCC and Beca personnel was established at the site to direct and prioritise the work. The priorities set for this group were to:

- Work alongside the operations team, to provide short-term repairs of critical assets to restore basic plant function as quickly as possible
- Conduct damage assessments for assets to inform the repairs and provide information to insurers and CCC
- Develop and implement robust and cost- effective permanent repair solutions, with the approval of CCC.

Through collaborative work with the CCC operations team, basic plant function was restored in four months. This reinstated the treated wastewater quality close to pre-earthquake standards and addressed immediate risks. More difficult and complex issues were faced with the permanent repairs.

2. DESCRIPTION OF TREATMENT PLANT

CWTP comprises screening, grit removal, primary sedimentation, trickling filters, a solids contact process with secondary clarifiers, 225ha of oxidation ponds prior to discharge through an ocean outfall. A site layout plan is shown in Figure 12 at the rear of this paper.

3. POST-EARTHQUAKE OPERATIONS

The CWTP site is located in an area of liquefiable sands with shallow groundwater, typically at 1.5m – 2.5m depth. Ground shaking and coincident soil liquefaction during the 22 February 2011 aftershock caused varying levels of damage to a range of unit processes at CWTP as shown in Figure 13 at the read of this paper.

In the initial two weeks after 22 February, very little flow was received at CWTP for two reasons: power to many pumping stations was limited, and the rising main network that serves the plant was seriously damaged. As early repairs proceeded at pace, the plant inflows were quickly restored. Accompanying these flows, massive quantities of sand were pumped to CWTP through ingress of liquefied material to the damaged sewerage network. The sand locked The grit traps and primary sedimentation tanks (PSTs), causing major on-going operational constraints. The contact tank process and secondary clarifiers were also completely inoperational due to structural damage.

Nevertheless, the CWTP was brought back to a level of basic functionality within one month. A big factor in this was the redundancy provided in the primary stages of treatment. With five grit traps and seven PSTs available, damaged or sand-inundated tanks were able to be taken off-line and spare tanks brought into service; the installed level of plant redundancy supported the resilience of the plant.

The out-of-service clarifiers prevented the contact tank process from being operated. The treatment duty normally performed by this section of the process was redistributed to the PSTs and the oxidation ponds. Whilst not ideal, with polymer dosing of the PSTs and peroxide dosing of the oxidation ponds in place, the process provided a level of treatment that adequately reduced the risk of a major odour event at the oxidation ponds.

A further important factor was the ocean outfall. Robustly designed as a critical infrastructural asset, it was able to continue functioning; discharging partially-treated wastewater 3km offshore throughout the earthquake sequence.

4. DAMAGE TO CIVIL STRUCTURES

With short-term risks addressed through a range of measures, attention turned to assessing damage and implementing repairs. Damage to the site's civil structures was widespread; including concrete cracking and deformation, loss of structural capacity, loss of water retention capacity, and differential settlement. The extent of damage varied depending on the type of structure and the depth below ground.

Structures built to a depth of 2.5m below ground or deeper were subject to very high external buoyancy forces associated with liquefied soils, as well as the effects of severe ground shaking. Consequently, deeply buried structures were the most severely damaged. Shallower and above-ground structures suffered much less damage by comparison.

4.1 Primary Sedimentation and Grit Tanks

The PSTs (7 no.) and grit tanks (5 no.) comprise a series of interconnected 4m-deep in-ground reinforced concrete tanks, built in the 1960s. The PSTs and grit tanks are close-coupled. The 70m-long rectangular PSTs suffered extensive cracking due to forces and deformations induced by the seismic actions in February and June events. Longitudinal surveys of the PSTs over their length (see Figure 2) indicated the floors had suffered differential vertical displacements up to 70mm due to liquefaction forces, causing cracking of the walls and top beams.

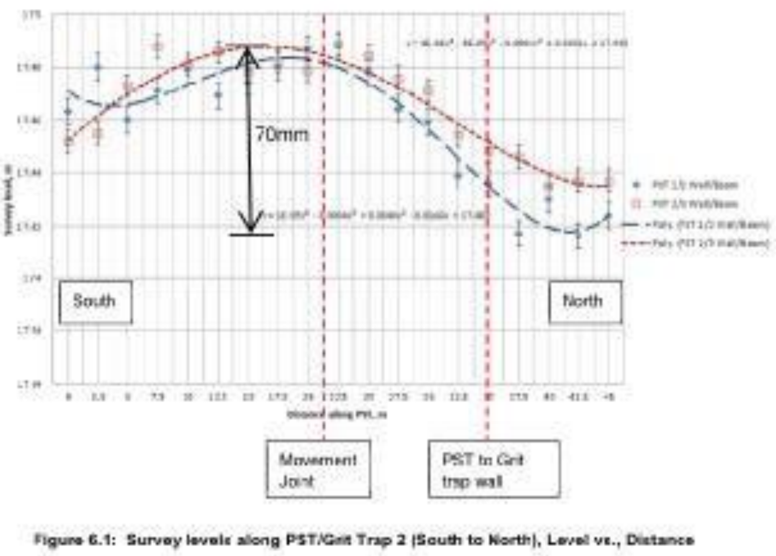

Figure 2: Longitudinal floor survey of PST

The liquefied sand from the network accumulated rapidly in the grit tanks at the front end of a series of PST tanks, with excess material carried over into the PSTs. This quickly overloaded the PSTs, breaking scaper flights, breaking chains and, in some cases, pulling sprockets off the tank walls. Keeping the process operating with ever-fewer tanks was an unpleasant and difficult task for CCC staff and contractors. Tanks had to be regularly dug-out or sucked-out using jetter/vacuum trucks. Few of these trucks were available immediately post-earthquake events as clearing major sewer lines in the network took priority. This meant staff and contractors had to hand dig the PSTs; very time consuming and hard work. The original design of the plant did not allow a grit tank to be de-coupled from its paired PST. This meant that a blocked grit tank necessitated the related PST to also be taken offline.

As well as repairs to PST and grit tank cracks using epoxy injection, as part of post-earthquake resilience measures a project to de-couple the grit tanks from the PSTs is currently underway. This project will improve the flexibility of plant operations so that, in the event of a grit trap becoming blocked or otherwise unserviceable, all of the PSTs will remain available.

4.2 Trickling Filters

The two trickling filters are 50m diameter shallow-founded concrete tanks containing plastic media (see Figure 3). Damage to these concrete structures has been assessed as relatively light, although internal inspections have only recently been conducted as these units operate continuously and are rarely taken offline. Trickling filter damage comprises vertical cracks at the joints between post-tensioned vertical wall panels and possible internal floor damage. Both trickling filters remained operational throughout the earthquake sequence, playing an important role in maintaining treatment function while downstream solids contact tanks were out of service.

Figure 3: Trickling filter at CWTP

4.3 Clarifiers

The secondary clarifiers consist of 4 no. 48m-diameter circular concrete clarifiers with an interconnecting supply and return channel structure. The clarifiers are fitted with a mechanical sludge scraper system that collects the settled sludge on the floor, pumping it back to the solids contact solids process. Clarified wastewater overflows into the peripheral launder channel around each clarifier. A photo of Clarifier 2 showing the central bridge that supports the scraper mechanism is provided in Figure 4.

The clarifiers were built in 2002 incorporating 225mm-thick post-tensioned concrete walls and 160mm-thick post-tensioned concrete floors.

Figure 4: CWTP Clarifiers

Damage to the clarifiers was caused by ground shaking and liquefaction effects. As the soil liquefied, the clarifier bases were subjected to liquefaction-induced uplift forces as well as static buoyancy force due to hydrostatic pressure. Figure 5 shows how the uplift pressures imposed forces on the clarifier structures, causing flotation effects on the entire structure and deforming the floors.

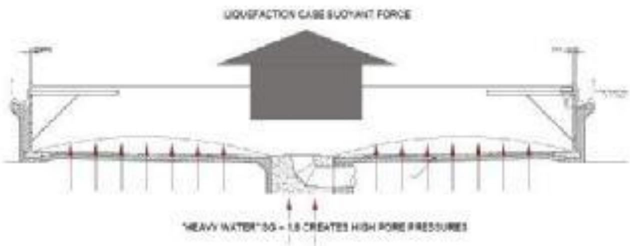

Figure 5: Liquefaction effects on clarifier

A number of operational requirements were addressed in developing a plan for permanent repairs to the clarifiers, including:

- Two clarifiers are needed to provide sufficient residency (with polymer dosing) for sludge separation, enabling the solids contact process to operate. The repair sequence needed to allow for continued operation of two clarifiers at all times.
- Initially Clarifiers 1 and 2 (the least damaged) were brought on-line using temporary repairs. These two clarifiers were left on-line until the more damaged Clarifiers 3 and 4 were both repaired.
- The repair team then went back to provide a permanent fix to Clarifiers 1 and 2.

4.4 Clarifier Repairs

Initial visual inspection suggested varying levels of damage across the four clarifiers including differential settlement and floor damage and deformation. Physical investigations of clarifier damage involved the following:

- Dewatering, empty and clean – involving external well pointing to lower groundwater
- Removal of the sludge removal mechanism
- Survey of central foundation, floors and walls
- Crack mapping
- Ground Penetrating Radar (GPR), floor cores, void measurements and Scala Penetrometer Tests (SPT)

A summary of clarifier damage is shown in Table 1.

Table 1: Clarifier Damage Summary

Parameter (mm)	**Clarifier 1**	**Clarifier 2**	**Clarifier 3**	**Clarifier 4**
Overall tilt	73	45	70	110
Central foundation uplift	80	20	300	100
Floor deformation	90	60	600	200

Investigations found a range of issues; Clarifiers 1 and 2 were relatively less damaged, while clarifiers 3 and 4 had major structural damage, necessitating major repairs.

Various options for clarifier repairs were evaluated as set out in Table 2. Of these, the concrete floor overlay slab was preferred. It provided cost-effective reinstatement of clarifier structural performance to pre-earthquake condition, as well as a net improvement in resistance to liquefaction uplift. Other options either did not reinstate the structural performance or were expensive and time-consuming to implement. Photos in Figures 6, 7 and 8 show the damage and repairs to clarifiers.

Table 2: Clarifier Repair Options

Option	**Cost ($NZ)**	**Evaluation**
Repair existing slab	1.0M	Not acceptable to CCC. Does not reinstate the clarifiers to pre-earthquake seismic resistance condition.

Concrete floor overlay slab	2.5M	Preferred by CCC as a cost- effective option. Reinstates the clarifiers to pre-earthquake condition. Reduces the risk of damage from future earthquakes.
Replace entire floor	9.0M	Not preferred by CCC. Risks during construction (from a seismic event).
Replace clarifier	50M	Not preferred by CCC. High costs and low probability of cost recovery from insurance.

Figure 6: Inverted floor cone on Clarifier 3

Figure 7: Clarifier 3 floor overlay showing reinforcing mats

Figure 8: Fully repaired Clarifier 4

4.5 Clarifier Inlet Pipes

In addition to investigating the clarifier structures, the 1800Ø concrete influent pipes which supply wastewater to the central distribution plenum were also checked. A schematic diagram of the influent pipe is shown in Figure 9.

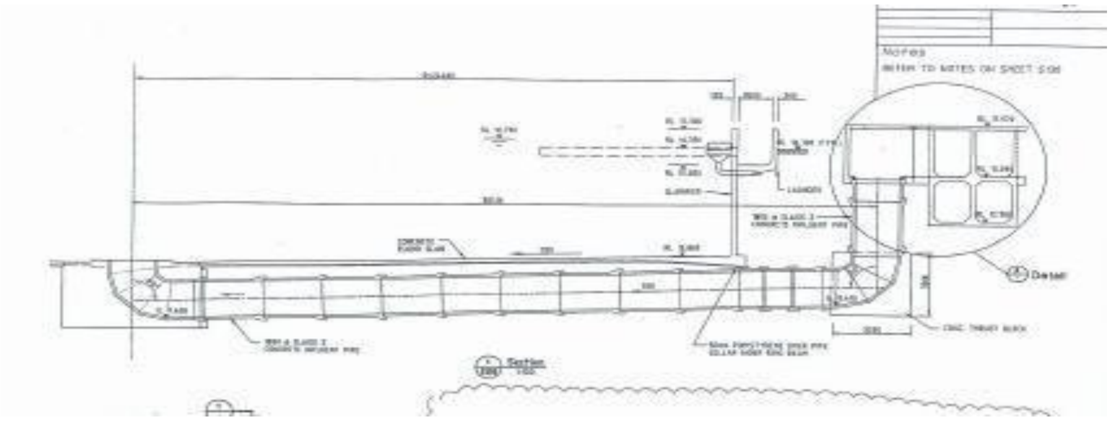

Figure 9: Influent pipe cross section

Hydrostatic head testing of the influent pipes identified significant levels of leakage. A dive survey found pipe movement and spalling at pipe joints indicating impact damage between the pipe sections.

This simple analysis indicated likely ground movement around the pipe, causing shortening, with the attendant risk that subsequent seismic events could cause further movement and damage. Any repair solution needed to be capable of accommodating a similar amount of movement – whilst retaining the integrity of the repair.

A number of options were initially considered for the pipe repair. Physical excavation of the floor of the clarifier was seen as high-risk, given the possibility of further earthquakes, as well as potentially very expensive; it was quickly eliminated. The remaining repair methods were based on "trenchless" repairs involving a pipe liner or joint repair. The chosen option needed to be installed with the pipe full of water as, due to buoyancy risks, it was considered too risky for the structure to dewater the pipe. Options considered were as follows:

- "Amex" internal joint sealing system
- Use of a Cured-In-Place Pipe (CIPP)
- "Ribline" pipe lining
- GRP pipe insert

Both the Ribline pipe lining and GRP pipe insert were eliminated after discussions with product suppliers confirmed that access was insufficient for their product to be installed.

The "AMEX" seal option, which consists of a reinforced rubber sealing ring held in place across the inside of the pipe joint by steel banding, was also eliminated. Several AMEX seals had been installed on concrete pipes elsewhere at CWTP after the September 2010 earthquake; subequently moving and become deformed in the February 2011 aftershock. The AMEX supplier was not able to verify the mechanical capacity of the seals to withstand axial loads and negative hydraulic pressures that might arise during an earthquake. For this reason, the AMEX seal was also eliminated. The only remaining viable option with the capacity to meet the operating conditions, as well as withstand seismic loads, was a Cured-In- Place Pipe (CIPP) liner.

4.6 CIPP Pipeline Repair

The CIPP liner system effectively forms a new pipe inside the existing pipe by using a polyester fabric impregnated with thermo-setting resin, inflated against the existing pipe and cured with hot water or steam. The thickness of the newly formed pipe was designed to suit loading conditions.

The permissible liner elongation is almost entirely dependent on the resin used in the liner given that the polyester fabric into which the resin is impregnated has a very low stiffness and thus does not contribute significantly to the mechanical properties of the composite material. A worst case design condition was set, based on axial movement of 120mm during an earthquake being transferred to just one length of concrete pipe; equating to approximately 5% extension. Uniformly spread over the length of the horizontal section of pipe the elongation is approximately 0.5%. The design approach was to use this range (0.5% to 5%) as one of the criteria for selecting a suitable resin. In consultation with the CIPP liner supplier, a vinyl ester resin was specified, capable of accommodating elongation up to 10%; giving a superior margin over the calculated 5% requirement.

The CIPP liner system was also designed to resist the worst case external pressures arising during a liquefaction event. This resulted in a liner with a wall thickness of 50mm taking into account the reduced mechanical strength (but increased ductility) of the specified vinyl ester resin.

Some creasing was identified on the straight section of the finished liner on Clarifier 4. This can occur with a thick liner because the final internal layer of polyester tends to bunch-up to a minor degree (refer to Figure 10).

Figure 10: Creasing of liner on clarifier 4

The 1800Ø CIPP liners installed on the CWTP clarifiers by Pipeworks Ltd are the largest CIPP liners installed to date in New Zealand. Figure 11 shows the contractor unravelling the liner prior to installation.

Figure 11: CIPP liner prior to installation

4.7 Sludge Digesters

The solids handling process at CWTP incorporates six anaerobic digesters and a thermal biosolids drying plant. Following the 21 February aftershock, the sand influx to the PSTs meant that heavy, inert material was being carried through the rest of the solids process. It accumulated in the digesters, particularly affecting the linked heat exchangers which were difficult and time consuming to clean. Hydraulic retention time was being lost in the digesters due to the sand build-up, while the quantity of volatile material reaching the digesters also dropped due to the PSTs and grit tanks being dug out and organic material being removed from the process. This reduced biogas production and increased reliance on diesel fuel (to heat digesters and improve combustion in the cogeneration engines) and the network for imported fuel.

4.8 Biosolids Drying Plant

A new thermal biosolids drying plant was being commissioned at the time of the September 2010 earthquake. It suffered little damage from this event and only minor damage from the February 2011 aftershock; remaining operable throughout. Advantages of the installed belt drying technology are its ability to handle varying sludge characteristics (as occurred post-earthquake) and to dry and pass a significant amount of abrasive silt and sand out of the solids process without undue wear. These were considerations when CCC was evaluating this technology against drum drying options, prior to purchasing. The belt dryer process proved very resilient throughout the earthquake sequence and was available to process biosolids as they were produced.

In the period after the February earthquake, zinc and copper concentrations increased in the biosolids by over 100% on pre-earthquake levels. CCC was initially concerned there may be large-scale dumping occurring in the network, as local industries cleaned up and brought process plants back into operation. Further analysis showed that the increased metal concentrations were likely to be a result of the large amount of pipe jetting carried out across the eastern side of the city, related to sewer clearing and then CCTV operations.

4.9 Ocean Outfall

Other aspects of resilience are not so obvious. CCC has a resource consent to discharge treated wastewater 3km offshore in Pegasus Bay. This pipeline and pump station suffered only cosmetic damage, allowing partially treated wasterwater to be discharged in a mixing zone well away from the shoreline. The public health risk posed by the natural disaster was from the failures in the upstream wastewater network, rather than failures at the CWTP itself. The availability of the outfall asset meant that the priority was to get wastewater to the CWTP as soon as possible, even if it could only be partially treated. This determined resource allocation to repair sites (i.e. sewer pressure mains were a very high priority).

4.10 Plant Services

Asset review sessions held in the year prior to the earthquake sequence (as part of the roll-out of a new asset management system) helped identify which critical assets had to be protected and repaired as a priority. CCC had embarked on a multi-year project to improve the site's power supply to an N-1 status. This involved completion of a 11kV loop on site, installation of a second 11kV HV feed from the local network company and installation of a 1MVA diesel generator. These earlier resilience projects greatly aided restoration of power after major aftershocks.

The criticality of the process water system on a number of plant operations had been underestimated in previous asset management renewal planning. For example, the biogas engines, which generate on-site power, cannot operate without cooling water. After the February 2011 event, the old galvanised iron water mains suffered multiple and on-going failures. This made it very difficult to bring any of the process streams back on-line, and keep them on-line. The entire system was replaced with HDPE mains, which proved very resilient in the June 2011 event and all major aftershocks. This one initiative made operation of a damaged plant much easier for the shift crew.

Fuel supply and network power were tenuous in the region around the CWTP following the February earthquake. The site had 30,000 litres of diesel stored; this was invaluable in providing energy immediately after the earthquake for heating digesters and powering emergency generators.

4.11 People Resilience

Often during resilience planning, the operational work force is forgotten; especially at the supervisory and management level. The long and intense duration of the Canterbury earthquakes meant CCC had to find ways to relieve senior operations staff so that they could spend time with families and rest. This was particularly important given that most staff at CWTP suffered damage to their homes. For maintenance and operating staff, the shift cycle (6- man rosters on 24/7 cycle) allowed staff their normal time off. However for the Plant Manager, Process Engineer and Network Operations Manager, relief options were not so obvious. CCC engaged with other water authorities seeking staff could relieve CCC's key personnel. This was supported by Beca providing additional process engineering support for the plant. Bringing in external staff was also beneficial for the home organisations as they gained first-hand operational experience in crisis management.

The establishment of strong relationships through industry networks, and contractor and consultant agreements, was essential to providing this type of support. A continuing services agreement between CCC and Beca, established prior to the earthquakes, enabled rapid mobilisation of staff to the site within 24 hours of the February 2011 aftershock. The project team established had the benefit of four years' prior working knowledge of CWTP, as well as access to a wide range of expertise. Through this arrangement, rapid progress was made on damage assessment, condition investigations and repairs, with certainty for CCC on costs based on the fee mechanisms set out in the services agreement.

5. CONCLUSIONS

Assets at CWTP were extensively damaged during the major aftershock on 22 February 2011. Despite the extent of the damage, short-term repairs and contingency measures were able to be implemented, restoring basic operation within one month. This provided security while permanent repairs were developed and implemented.

A variety of diagnostic tools were used to analyse the damage and form a view about the damage mechanisms. Permanent repair options were evaluated and cost-effective options implemented with the aim of restoring pre-earthquake performance, whilst improving resilience on critical assets. After two years of repair work, the critical functions of CWTP were restored and resilience to further aftershocks has improved.

An important learning from the earthquake repair work at CWTP is that resilience should be assessed as a function of whole-of-plant performance, and the interaction between assets, as well as in terms of individual asset performance. Key factors in such an assessment are:

- Defining critical assets and prioritising their performance
- Assessing plant flexibility in terms of ability to transfer load from one process step to another
- Assessing the level of redundancy needed within each stage of the process
- Contingency planning measures

A simple analysis of the criticality and performance of key assets at CWTP is provided in Table 3.

Table 3: Asset Performance at CWTP

Asset	**Critical Asset?**	**How asset performed**	**Comments**
PSTs & grit tanks	Yes – core treatment process	partial failure	High level of redundancy provided
Trickling filters	No – plant functions without	no failure	Robust design
Contact tanks / clarifiers	No – plant functions without	total failure	Load transferred to other process units
Oxidation ponds	Yes – convey wastewater to outfall	partial failure	Earth bunds strengthened in repairs
Ocean outfall	Yes – disposal of wastewater	no failure	Robust design
Plant services	Yes	partial failure	Importance not fully recognised prior to earthquake

Where a plant has multiple treatment stages, with opportunities to re-direct wastewater if the plant is partially compromised, then the overall risks are lower. If the plant is highly reliant on specific treatment assets to provide the most basic function, without alternatives, then these assets need to be highly resilient to natural hazards. Complete failure of a water or wastewater treatment plant for an extended period could have a major impact on the community it serves.

The design of the CWTP clarifiers included for structural seismic and liquefaction mitigation measures, in accordance with the NZ Seismic Design Code. However, the in-ground design was not as resilient as other assets at the site; hence the clarifiers were damaged to a greater extent. At the time when the clarifiers were first built, the designers made decisions that sought to optimally balance the seismic performance risk against the capital cost of the plant. An important factor in these decisions was the level of redundancy provided overall within CWTP, both in terms of the total number of treatment stages, and in terms of the number of each treatment process provided.

Where one treatment stage fails, another can work harder to replace some of the lost performance; an example being polymer dosing of the PSTs to reduce solids loads to the ponds, while the clarifiers were inoperational.

Furthermore, redundancy within each treatment stage played a key role in plant resilience. Despite mechanical damage to some of the PSTs, with a total of seven PSTs, there were always at least several on-line at any one time.

The actual performance of CWTP during the February 2011 aftershock (which exceeded the seismic design basis by a considerable margin) bears this principle out. The layers of redundancy provided by the number of treatment stages, and by the number of units for each stage, allowed the process to be maintained and to effectively manage public health risks, even though the clarifiers had failed completely.

The resilience of treatment facilities cannot be looked at in isolation. They are an integral and important part of the wastewater system, along with the main trunk sewers and terminal (large) pump stations. Much of the risk to public health in Christchurch existed because many pressure and gravity sewers, in liquefiable land, failed and filled with silt.

Decentralised wastewater treatment was suggested and investigated by CCC and its consultants very quickly after the February 2011 event. NPV costings illustrated that retention of the central plant was, in fact, by far the more resilient and cost-effective solution. However, it reinforced the point that the major sewers (particularly pressure sewers - as gravity trunks continue to function even when damaged) are key assets and must be designed with the same geotechnical rigour as the pump stations and treatment plants.

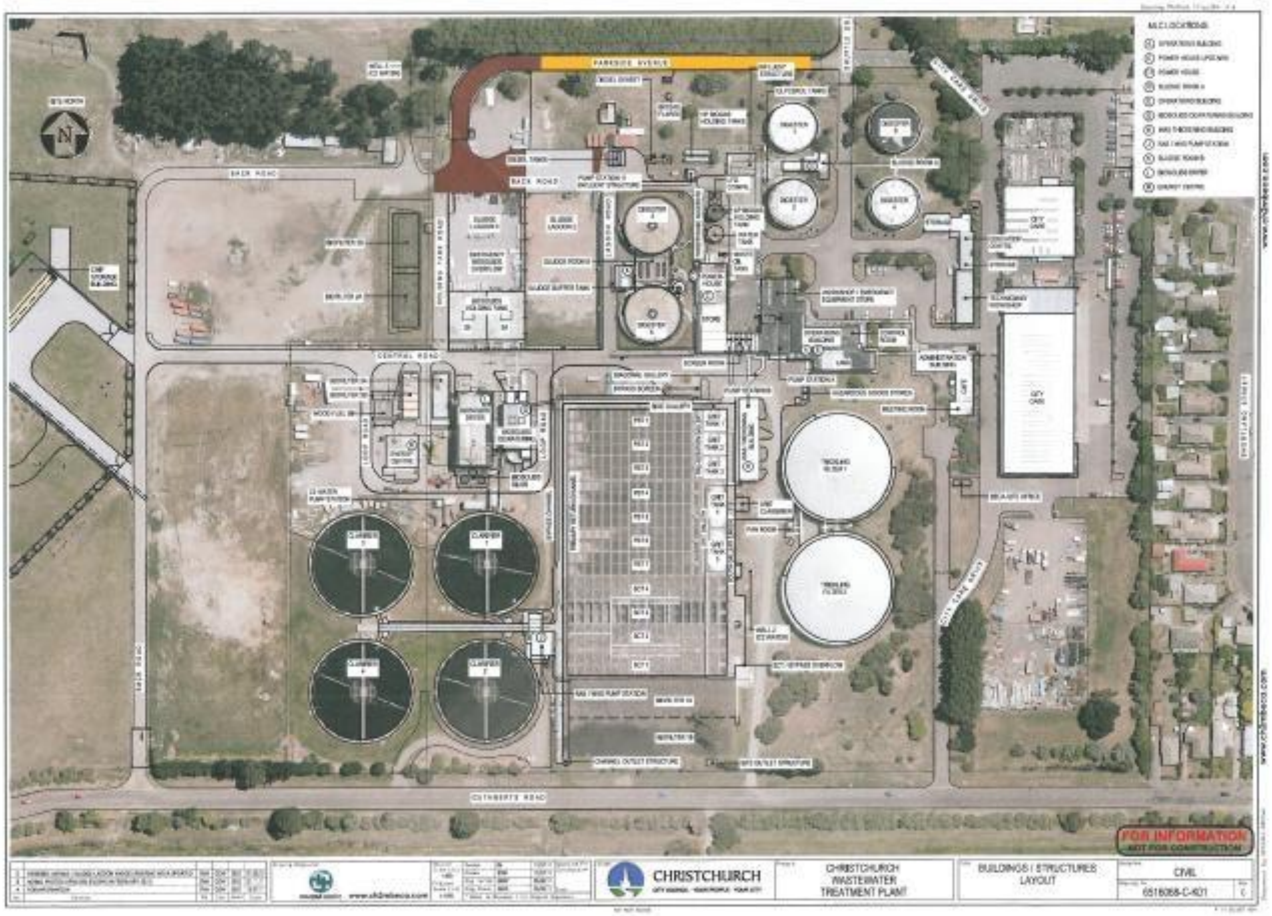

Figure 12: Christchurch Wastewater Treatment Plant Layout Plan

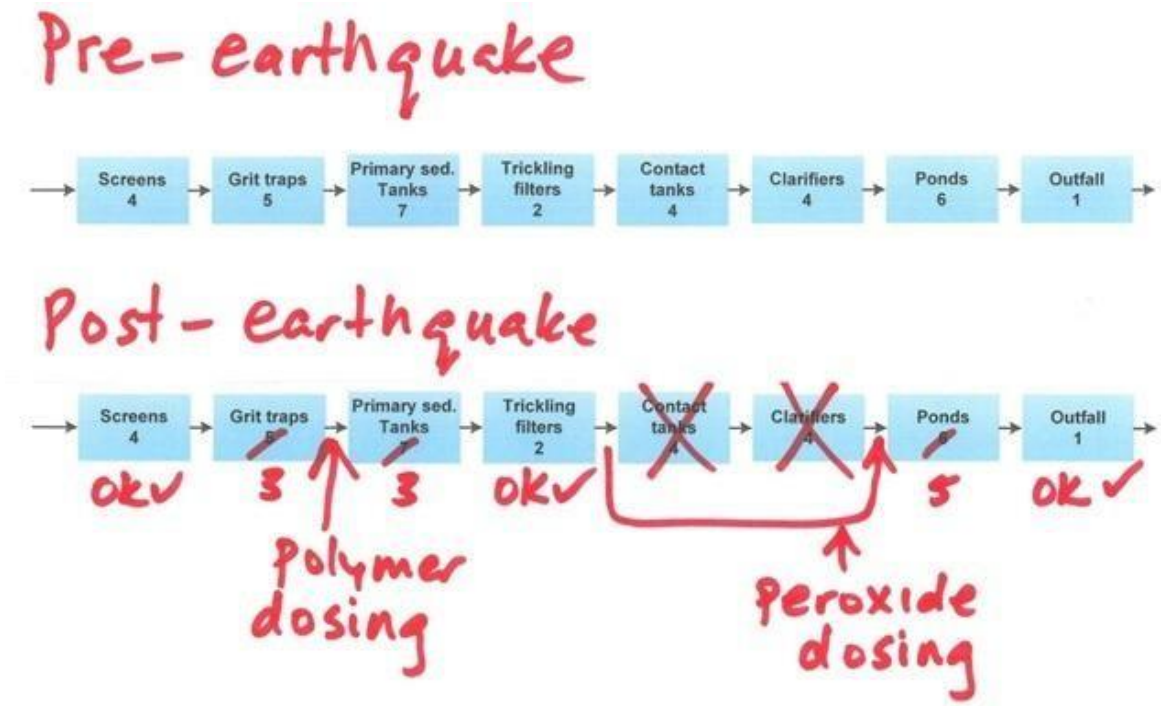

Figure 13: Short-Term Operations Post-Earthquake

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