EARTHQUAKE REPAIRS AT CHRISTCHURCH WWTP – CLARIFYING THE SITUATION

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ABSTRACT

Christchurch Wastewater Treatment Plant has four large secondary clarifiers that separate solids from the mixed liquor in the final stage of treatment. The 6.3M earthquake on 22nd of February 2011 caused major damage at the site and rendered all four clarifiers unserviceable. Without clarifiers in operation the plant was forced to discharge biotrickling filter-treated sewage to the oxidation ponds for an extended period.

This paper outlines the investigations of earthquake damage, the strategy for "quick fix" repairs to restore plant function, and decisions on permanent repair priorities and methods.

Without the clarifiers in operation the City of Christchurch was exposed to environmental and health risks from the discharge. This created urgency to implement temporary repair on at least 2 clarifiers. The paper describes how a temporary "quick fix" was successfully implemented within 4 months to restore basic plant function.

More difficult and complex issues were faced with the permanent repairs. The paper describes the varying levels of damage discovered, the method for selecting repair options, and the relative performance of each option. The paper also describes some technical highlights including the success and failure of various diagnostic tools, and the use of very large bore (1.8M diameter) CIPP liners for pipe repairs.

KEYWORDS

Secondary Clarifiers, Earthquake Repairs, Resilience, CIPP Liners

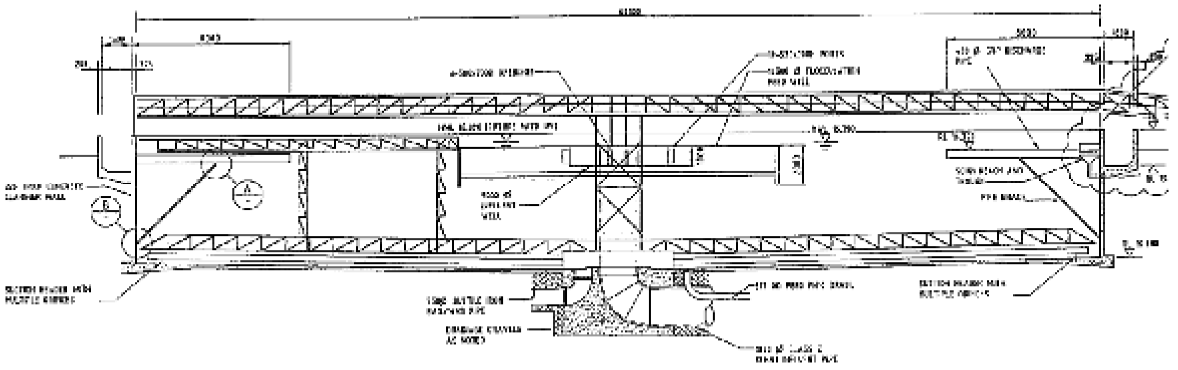
1 INTRODUCTION

The Christchurch Wastewater Treatment Plant comprises primary sedimentation, trickling filters solids contact process, secondary clarification and 225 hectares of oxidation ponds for disinfection prior to discharge through an ocean outfall. The secondary clarifiers were built in two stages in 2001 and 2004, and consist of 4 x 48m diameter circular concrete clarifiers with interconnecting supply and return channel structure. Each clarifier is fitted with a mechanical sludge scraper system that collects the settled sludge on the clarifier floor and pumps it back to the solids contact solids process. Clarified wastewater overflows via radial discharge pipes into the launder channel running around the perimeter of each clarifier. A photo of Clarifier 2 showing the central bridge that supports the mechanical scraper mechanism is provided in Figure 1.

Figure 1: Clarifier 2 at Christchurch Wastewater Treatment Plant

A cross sectional drawing of the clarifier is provided in Figure 2 below.

Figure 2: Clarifier cross section with scraper mechanism



The clarifiers were built with a 100 year design life incorporating 225mm thick precast, post tensioned, concrete walls and 160mm thick post-tensioned concrete floors. The floors have a 1:50 fall from the walls to the centre. Each clarifier is fitted with a rotating mechanical sludge scraper system that collects the settled sludge on the clarifier floor and pumps it back to the solids contact solids process.

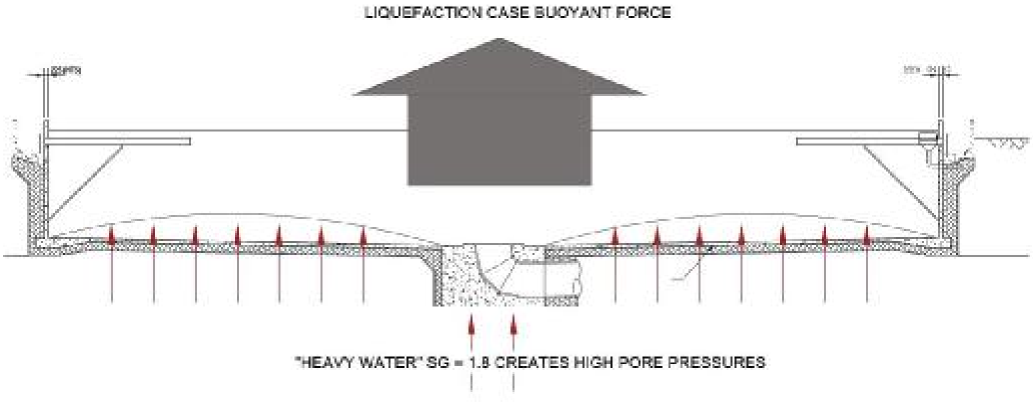
Stone columns to 5m depth were used to improve the ground under all four clarifiers when built. As the clarifiers are built in permeable sands with high natural groundwater (typical 2m below the ground surface), they are potentially buoyant and are installed with Pressure Relief Valves (PRVs) in the floor slabs to prevent flotation. In order to empty and dry out the clarifiers it is necessary to lower the groundwater to a point where the ground water is lower than the PRVs, and in the case of the damaged clarifiers below the fractures and cracks in the floor slab.

2 EARTHQUAKE DAMAGE

The major earthquake on the 22nd of February 2011 (magnitude 6.3M, intensity MM IX, epicentre 6km from plant and 5km deep), and associated liquefaction of soils at the site, caused major damage and rendered all four clarifiers non-functional. The full extent of the damage was not immediately apparent as the clarifiers remained full of wastewater and could not be immediately emptied without lowering of the water table. It was clear that some differential settlement had occurred and the bridges that run across the clarifiers were raised in the centre of Clarifiers 1 and 3 suggesting that either the centre foundation had risen or the external walls had settled.

Damage was caused by ground shaking as well as liquefaction effects. As the soil liquefied the clarifier bases were subjected to liquefaction induced uplift forces: static buoyancy force due to hydrostatic pressure, dynamic uplift force due to excess pore pressure and a seepage force resulting from uplift pressures acting on the soil block below. Figure 3 shows how the uplift pressures imposed forces on the clarifier structures, causing deformation of the floors and causing the entire structure to try to float out of the ground.

Figure 3: Liquefaction Effects on Clarifier



Lack of operational clarifiers created an immediate problem that biomass created in the trickling filters and propagated in the solids contact process could not be recovered and recycled. Treatment plant operators had no choice but to shut down the solids contact process and discharge the trickling filter wastewater including solids directly to the oxidation ponds.

The discharge of partially treated wastewater and solids to the oxidation ponds caused the dissolved oxygen levels in the ponds to drop to low levels. A temporary peroxide dosing system was set up to boost oxygen and mitigates the risk of severe odour emissions from the ponds. The dosing system continued in operation at the rate of 1000 l/day of peroxide until two clarifiers were back in service.

At the same time a project team was set up at the plant to work on a strategy to investigate and repair the damage to plant focusing primarily on the clarifiers and oxidation ponds.

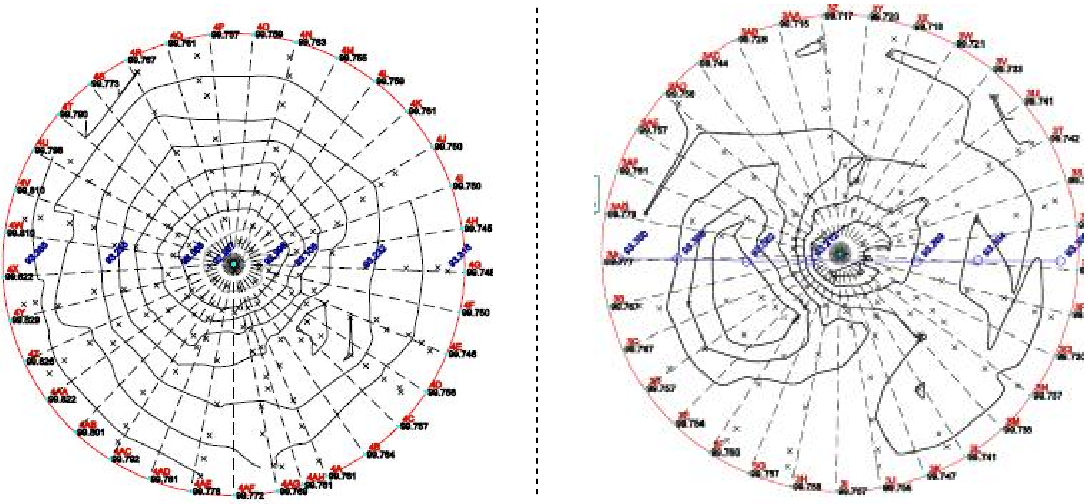
The clarifier repair strategy was divided into two phases:

- Short term emergency repairs to mitigate environmental and health risks
- Long term permanent repairs to fully restore the plant before the Earthquake condition

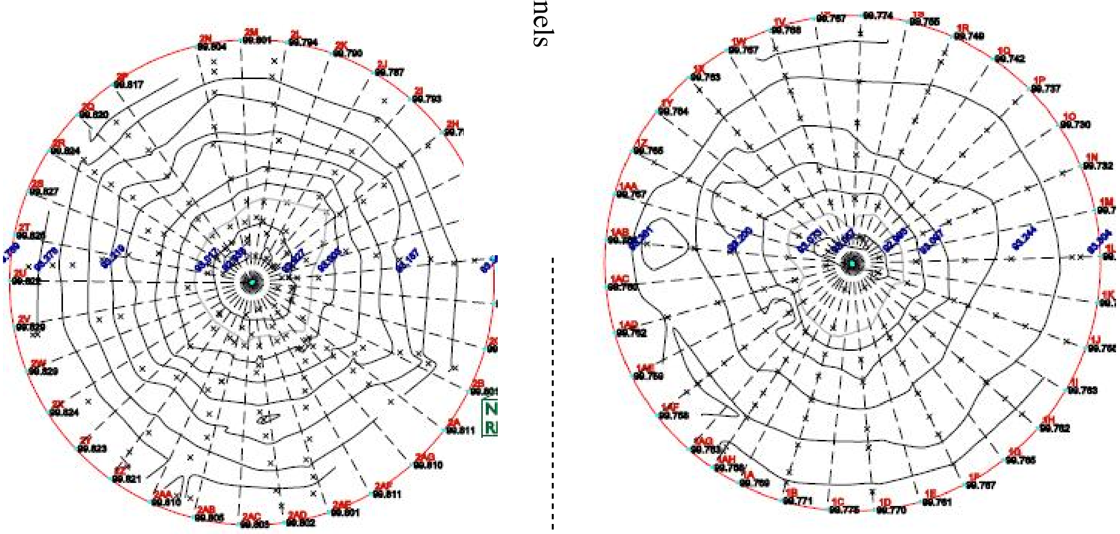
3 SHORT TERM REPAIRS

Initial visual inspection suggested varying levels of damage across the four clarifiers including differential settlement and bent bridges suggesting floor damage and deformation on Clarifiers 1 and 3. As described above, it was not possible to empty the water from any clarifier without first lowering the groundwater surrounding the clarifiers. To short cut the delays involved in installing and running the well pointing system, a bathymetric survey of the four clarifiers was conducted from a small dinghy to assess the state of the clarifier floors. The results of this survey are shown in Figure 4 below.

Figure 4: Bathymetric Survey of Clarifier Floors



Clarifier 4 **Clarifier 3**



Clarifier 2 **Clarifier 1**

The bathymetric survey showed that the floors of Clarifiers 2 and 4 appear to be relatively less damaged, with the original floor falls remaining largely intact. The floors on Clarifiers 1 and 3 showed significant deformation, with Clarifier 3 clearly the worst case. This was consistent with observations of the bridge across the centre of the Clarifiers 1 and 3. Based on these results the decision was taken to select Clarifiers 2 and 4 as the first units to be repaired with the objective that they would be fixed and brought back online fairly quickly.

Well pointing was installed on Clarifiers 2 and 4 and operated for the 6 weeks necessary to lower the groundwater to a level where the clarifiers could be pumped out. Water and residual sludge was then removed from Clarifier 2 and the internals inspected. Final clean out of clarifier 2 is shown in Figure 5.

Figure 5: Clean Out of Clarifier 2

A map of floor cracks down to 0.2mm in width was prepared – refer to Figure 6 overleaf. The floor of Clarifier 2 exhibited only minor cracking and no significant floor deformations – this finding was consistent with inferences made from the initial bathymetric work. At this point it was considered that Clarifier 2 could be repaired quickly and brought back on line. Repairs proceeded over the following 6 weeks involving epoxy injection of floor cracks and removal and reinstatement of the scraper mechanism, which had shifted out-of-vertical as a result of rotation of the central foundation.

By the end of June 2011 Clarifier 2 was ready to go back into service. But there was a problem – for the solids contact process to be recommissioned a minimum of two clarifiers were required in operation. By this stage Clarifier 4 had been emptied and cleaned and it was apparent that the damage to the floor slab was more extensive than indicated by the bathymetric survey and that a short term repair was not an option. The only viable option was to try to "jury rig" Clarifier 1 to get it running.

The dewatering around Clarifiers 2 and 4 had created a groundwater depression zone that extended out across the other two clarifiers. With some local piezo bore measurements to hand the water was carefully pumped out of Clarifier 1 until the top of the scraper support frame was exposed. Inspection of Clarifier 2 mechanicals had identified that the scraper was held up off the floor using simple U-bolts around two pieces of 40mm pipe (as shown in Figure 6).

Figure 6:U-bolt scraper support

During the earthquake the pipes slipped through the U-bolts until the scrapers hit the floor. It was speculated that the same thing had probably happened on Clarifier 1. If the scraper arm itself could be attached to a chain hoist and jacked off the floor then Clarifier 2 might be able to run. Two maintenance hands in a dinghy performed this task working up to their armpits in wastewater. The scraper arms were jacked well clear of the floor and the clarifier was able to be restarted (albeit with reduced performance).

With both Clarifiers 1 and 2 back in operation and with polymer dosing set up to compensate for 100% of the flow being directed through only half of the clarifier units, the solids contact process was able to be recommissioned in July 2011. The Council then set about developing a plan for permanent repairs.

4 PERMANENT REPAIRS

Using the strategy of shifting the well pointing progressively around the clarifiers “two at a time”, Clarifiers 4, 3 and 1 were able to emptied, inspected and repaired one at a time.

4.1 PHYSICAL INVESTIGATIONS

Physical investigations involved the following:

- Dewatering, empty and clean
- Removal of the rotating mechanism
- Detailed survey of central foundation, floors and walls
- Crack mapping
- Ground penetrating radar of floors to search for voids and weaknesses
- Floor cores, void measurements and Scala Penetrometer Tests (SPT)

A summary of survey results for the clarifiers is provided in Table 1 below.

Table 1: Clarifier Floor and Wall Deformations

Parameter	**Clarifier 1**	**Clarifier 2**	**Clarifier 3**	**Clarifier 4**
Maximum tilt (across top of clarifier wall)	73	45	70	110
Central foundation tilt (across foundation)	18	20	20	30
Central foundation uplift (relative to walls)	80	20	300	100
Maximum slab uplift	90	60	600	200

Survey of the four clarifiers showed considerable variation in the movement and deformation between the individual units.

Clarifier 1 survey indicated that the floor suffered uplift of about 90mm and the central foundation had risen about 80mm relative to the walls. The uplift of the slab was distributed reasonably evenly in a circumferential annulus around the mid-point of the slab, with the upward deflection causing a series of circumferential cracks of up to 2mm width at the surface of the post tensioned slab, with minor radial cracking in the outer third attributable to differential settlement around the perimeter.

Clarifier 2 surveys showed no significant floor deformations.

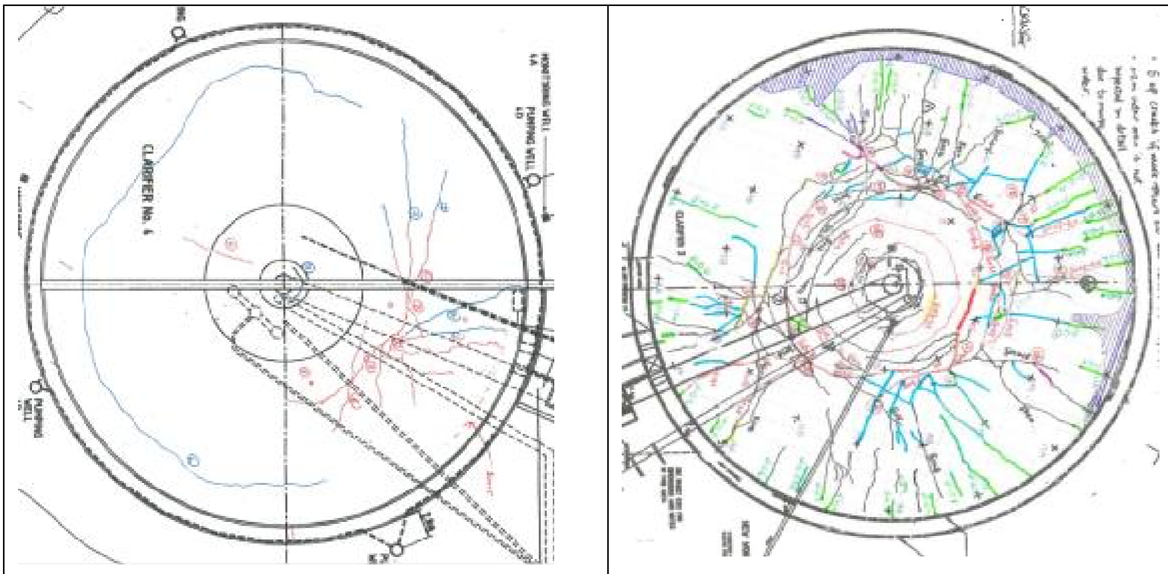
Clarifier 3 floor suffered considerable damage with a maximum uplift of about 600mm and widespread circumferential cracking of the floor slab – many of the cracks being several millimetres in width. The maximum uplift was also over the influent pipe. The central foundation also rose significantly – in the order of 300mm relative to the walls.

Clarifier 4 floor was subjected to uplift of up to 200mm and the central foundation rose about 100mm relative to the walls. The uplift of the slab was mostly confined to the area above the influent pipes where a pronounced local vertical deflection or “bulge” of approximately 100mm was observed. The upward deflection caused a series of cracks of up to 2.5mm width at the surface of the post tensioned slab, radiating outward from the point of maximum deflection.

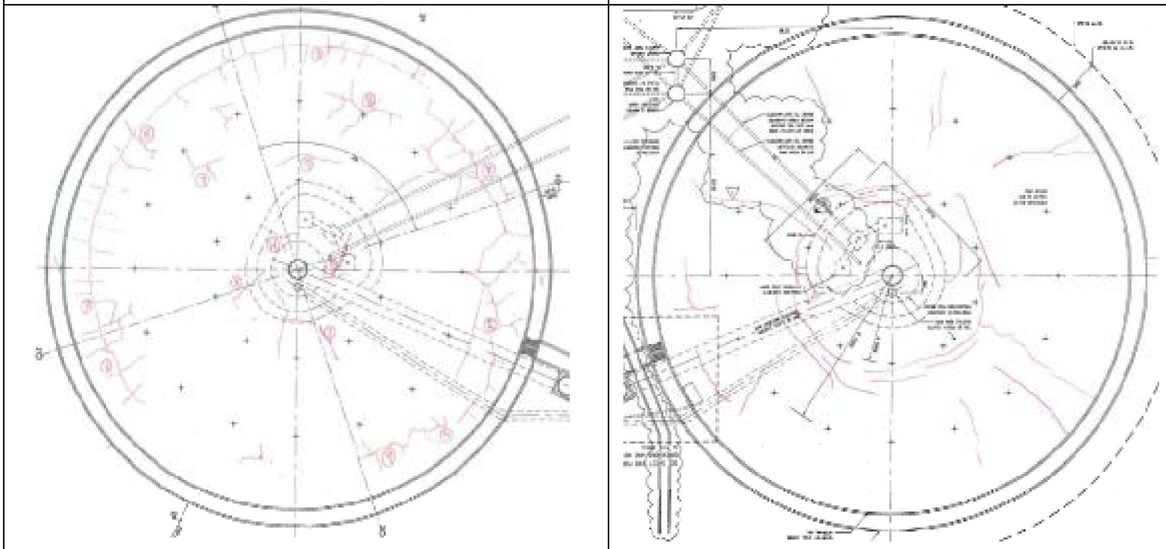
Crack Maps

Crack maps for Clarifiers 1, 2 3, 4 are shown in Figure 7 overleaf.

Figure 7 Clarifier Crack Maps



Clarifier 4 Crack Map **Clarifier 3 Crack Map**



Clarifier 2 Crack Map **Clarifier 1 Crack Map**

Crack mapping also showed wide variation in the response of each clarifier to earthquake –imposed loads. There is no obvious rational explanation for the wide disparity in floor cracking and deformation observed. The design of all clarifiers is the same and the foundations of all four clarifiers involved use of the same ground improvement in the form of stone columns to a standard set out and depth. Hypotheses for explaining the differences in behaviour include the following:

- There are subtle differences in the design of the drainage layer beneath clarifiers 1 & 2, and Clarifier 3 & 4 respectively. This may have influenced the extent to which the floors were exposed to the high pore pressures developed in liquefied ground (ie better drainage translates to higher risk)
- Natural variation in ground conditions at the site may have led to differences in pore pressures and ground movements around each clarifier

GPR, Floor coring and Scala Penetrometer Tests

Field investigations including GPR scans, coring and Scala penetrometer testing indicated some gaps immediately beneath the floors and some limited areas of less dense material, generally inside or immediately adjacent to the central foundation, and near the influent pipe. For Clarifier 3 loose material over the central 20m zone was observed. However this was significantly re-compacted in the 23 December 2011 Earthquake.

The GPR results could not be correlated with the more specific coring and Scala tests. The GPR tests were discontinued after the Clarifier 3 investigation as the results were of little value in assessing below-floor ground conditions.

4.2 PERMANENT REPAIR OPTIONS

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

- Two clarifiers are needed to provide sufficient residency (with polymer dosing) for activated sludge to be separated out of the wastewater and hence to enable the solids contact process to operate to provide effective secondary treatment. The repair sequence needed to allow for continued operation of two clarifiers at all times.
- Initially Clarifiers 1 and 2 were brought online. These two clarifiers were left online until Clarifiers 3 and 4 were both repaired. Clarifier 1 would then be taken off line for repairs

A summary of the options investigated are provided in Table 2.

Table 2: Summary of Clarifier Repair Options

Option	**Description**	**Cost ($NZ each)**
Repair existing slab	Repair the visible cracks in the slab with epoxy injection to reinstate durability, and provide a levelling screed. Not viable for Clarifier 3.	0.25M
Reconstruct existing slab	Cut out the bulging concrete in areas where the floor had deflected upwards, make good and compact subgrade, and cast new concrete to existing profile. Also not suitable for Clarifier 3.	0.35M
Overlay slab	Water blast floor and cast a minimum 225mm thick (over bulge) and up to 450mm thick in Clarifier 4, and up to 700mm in Clarifier 3, reinforced concrete slab overlaid to falls. Reinforce the overlay slab and provide tie bars over whole slab to provide composite action.	0.6 M
Thick overlay	Water blast floor and cast a minimum 1200 maximum thickness overlay slab. This option removes all constraints for maintenance dewatering and virtually eliminates the risk of damage to the floor slab from future seismic events.	2.0 M
Replace entire floor	Remove existing floor, improve the material to a significant depth beneath the clarifier to “eliminate” the existing potential liquefaction and provide new 225 thick reinforced concrete slab. Retain the existing “ring beam” part of the floor slab beneath the wall. Existing sand and stone columns below the slab would be removed and replaced with compacted new material not subject to liquefaction even under extreme shaking (e.g. cement stabilised sand).	2.2M
Replace clarifier	Replace clarifier with a fully piled structure constructed adjacent to the four existing clarifiers and connecting into existing gravity supply and return flow channels. The geometry of the clarifier and design of the mechanical internals would also match existing. Alternatively provide a “pumped” clarifier at grade.	12.6M

4.2.1 OPTION 1 – REPAIR EXISTING SLAB

Option 1 was based on repairing the visible cracks in the slab with epoxy injection to reinstate durability, and was only considered suitable for clarifiers with relatively narrow cracks including clarifiers 4, 1 and 2. This option was not considered suitable for Clarifier 3 due to the width of the cracks, extent of damage and failure of the centre foundation floor connection. A new levelling screed would be applied at a minimum of 30mm thick over the top of “the bulge”, or highest point on the damaged floor. In the case of Clarifier 4 this would provide a maximum screed thickness of 130mm.

Repairing the existing slab would not reinstate the existing floor slab back to its original strength. Cracks in the underside of the slab could not be injected and would therefore detract from overall integrity and durability. The risk of damage from potential future events similar or worse to that which caused the current damage was unchanged, and there was no improvement in maintenance dewatering constraints (in other words the clarifier would still be bouyant when emptied based on natural groundwater levels).

The estimated cost and timing of this option was $250,000 and 5 weeks duration.

4.2.2 OPTION 2 – RECONSTRUCT EXISTING SLAB

This option involved cutting out the bulging concrete in areas where the floor had deflected upwards, make good and compact subgrade, and cast new concrete to existing profile. The use of an expansive agent in new concrete would help to mitigate shrinkage and loss of prestress. The remaining slab cracking would be epoxy injected to reinstate durability.

This option would reinstate durability but not the full strength of the existing floor slab. The damage from potential future earthquakes remains similar and a potentially a little worse to that which caused the recent damage, and there was no improvement in maintenance dewatering constraints. Due to the extent of damage this option was not considered suitable for Clarifier 3 as the slab would be compromised.

The estimated cost and timing of this option was $350,000 and 6 weeks duration.

The cost assumed that the well pointing installation would lower the ground water enough for this repair to be undertaken. Observations during the repair works were that the ground water would not have been lowered sufficiently for this repair without sheetpiling around the clarifiers. This was not identified as a cost during the evaluation.

4.2.3 OPTION 3 – OVERLAY SLAB

The overlay slab repair involves water blasting the existing slab, epoxy injecting visible cracks, and casting a minimum 225mm thick (over bulge) concrete overlay over the entire floor of the clarifier. The thickness of the overlay would vary depending on the amount of deflection of the tank floor; up to 450mm thick in Clarifier 4, and 700mm in Clarifier 3. Clarifier 2 slab thickness would be 500mm. The overlay slab would be heavily reinforced and provided with drilled in hold down bars around perimeter, and over the whole slab to provide composite action.

A performance check on the 225mm overlay option found it had a minor impact on the overall hydraulic residence time in the clarifier and was not likely to result in any significant reduction in the solids settling performance.

This option had sufficient strength to sustain an assumed local upward pressure loading which can potentially cause a floor bulge. Durability of the new overlay slab is as for the original slab. The central column and rotating arm mechanism would need to be significantly modified and the operating volume would be reduced slightly. The risk of damage from potential future events similar to the February 2011 event is significantly reduced. The estimated cost and timing of this option was $650,000 - $800,000 and 12 weeks duration (the higher cost being for Clarifier 3).

4.2.4 OPTION 4 – PILED OVERLAY SLAB

Similar to Option 3 with the addition of piles under the slab to support the full weight of the slab and Clarifier. The piles extend to non-liquefiable material and reduce the risk of differential movements to a very low level. This also allows dewatering of the Clarifier at any time without the need for well pointing. The estimated cost of this option was $1,800,000 and 26 weeks duration.

The cost assumed that the well pointing installation would lower the ground water sufficiently for this repair to be undertaken. Observations during the repair works were that the groundwater would not have been lowered sufficiently for this repair without sheetpiling around the clarifiers. This was not identified as a cost during the evaluation.

4.2.5 OPTION 5 – THICK OVERLAY

As for Option 3 except with a 1200 maximum thickness of overlay slab. This option removes all constraints for maintenance dewatering and "eliminates" the risk of damage to the floor slab from future seismic events. However, because the floor is not held down there is still the risk of some (relatively small) upward movement of the clarifier in a seismic event large enough to cause widespread liquefaction of the site. The central column and rotating arm mechanism need to be substantially modified and the operating volume of the clarifier is considerably reduced. This option poses some risks relating to process performance as the depth and residence time in the clarifier will be significantly reduced. The estimated cost and timing of this option was $1,000,000 - $1,500,000 and 16 weeks duration.

4.2.6 OPTION 6 – REPLACE ENTIRE FLOOR

Remove all of existing floor, improve the material to a significant depth beneath the clarifier to "eliminate" the existing potential liquefaction and replace the floor slab with a 225 thick reinforced concrete slab similar to option 3. The existing "ring beam" part of the floor slab beneath the wall would be retained and the tendon strands would be lapped with new un-tensioned reinforcement.

The existing sand and stone columns below the slab would be removed and replaced with compacted new material not subject to liquefaction even under extreme shaking (e.g. cement stabilised sand). This would reduce the amount of earthquake induced settlements, although the new 225mm thick RC floor would need to be anchored down to the cement stabilised sand to resist any uplift from the liquefied sands that may occur outside the treated zone. This option eliminates the process risk issue identified for Option 4 as the clarifier hydraulics are unaffected.

The estimate cost and timing of this option is $2,200,000 and 26 weeks duration.

The cost assumed that the well pointing installation would lower the ground water low enough for this repair to be undertaken. Observations during the repair works were that the ground water would not have been lowered sufficiently for this repair without sheetpiling around the clarifiers. This was not identified as a cost during the evaluation.

4.2.7 OPTION 7 – NEW CLARIFIER

Two replacement clarifier options were also developed and costed to a conceptual level; as follows:

New Clarifier to Replace Existing - This option was based on a fully piled structure constructed adjacent to the four existing clarifiers and connecting into existing gravity supply and return flow channels. The geometry of the clarifier and design of the mechanical internals would also match existing. A new clarifier would be more resilient that the existing clarifiers due to the piled foundations which offer improved seismic performance. The estimated timing and duration of this option is $12.6M and 18 months

New Clarifier at Grade - The "at grade" option involves constructing a new clarifier on an engineered fill foundation at ground level. This option has somewhat lower geotechnical risk and does not require piling. A new pump station would be constructed to pump the wastewater from the existing inlet channel to the clarifier inlet. The treated wastewater would overflow from the launder channel to the return channel. The estimated cost of this option is also $12.6M with an estimated timing of 12 to 14 months.

4.3 SELECTION OF PREFERRED OPTION

The evaluation of options is summarised in Table 3 below.

Table 3: Summary Evaluation of Options

Option	Evaluation	Cost $NZ (each)
Repair existing slab	Not acceptable to CCC as it did not reinstate the clarifiers to pre-earthquake seismic resistance condition. GNS advise there is heightened seismic risk particularly in the next 10-15 years and with a significant risk of several earthquakes capable of causing liquefaction of the site.	0.25M

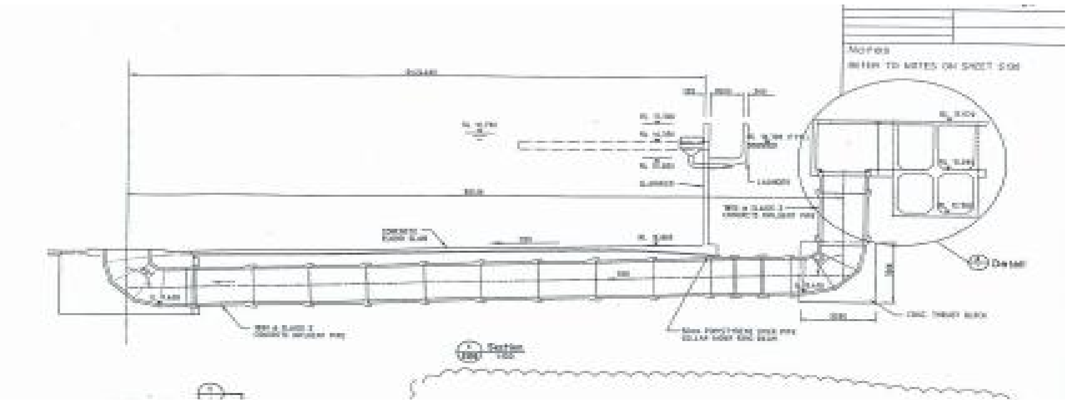
Reconstruct existing slab	Not acceptable to CCC due to the risk of similar damage in further similar earthquakes. GNS advise a heightened seismic risk with a significant risk of similar earthquakes capable of causing liquefaction of the site in the next 10 – 20 years. Also does not reinstate the clarifiers to pre-earthquake condition.	0.35M
Overlay slab	Preferred by CCC as a cost effective option that effectively reinstates the clarifiers to pre-earthquake condition. The overlay slab is designed to resist local liquefaction uplift pressures and buoyant liquefaction pressures from widespread liquefaction. Reduces the risk of damage from future earthquakes, albeit with some risk of further settlement	0.6 M
Thick overlay	Eliminates risk of floor slab damage from earthquakes. However not preferred by CCC as additional cost ($1.4M) and poses risks to process performance due to reduced hydraulic residence time.	2.0 M
Replace entire floor	Not preferred by CCC as risks during construction (from a seismic event) are considered significant, and at a cost premium over the overlay slab option.	2.2M
Replace clarifier	Not preferred by CCC due to high costs and low probability of cost recovery from insurance	12.6M

From the range of options investigated the overlay slab was identified as the preferred solution. This option provided cost-effective reinstatement of clarifier structural performance to pre-earthquake condition, as well as a net improvement in terms of resistance to liquefaction uplift pressures. Other options either did not reinstate the structural performance adequately or were extremely expensive and time consuming to implement.

4.4 PIPELINE REPAIRS

In addition to investigation of the clarifier structures, the 1800 Ø 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 8.

Figure 8: Influent Pipe Cross Section



Hydrostatic head testing of the influent pipes identified significant levels of leakage. A dive survey of the influent pipe on each clarifier was then conducted to ascertain joint movement and settlement. The dive surveys showed that the cumulative gap across all thirteen pipe joints had closed by as much as 120mm, with the cumulative gap along the bottom of the pipes typically less then across the top. The dive inspection also found evidence of spalling at the 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 – i.e. another 120mm, while retaining the integrity of the repair. Further minor shortening could take place to the point where all joints are closed, but equally, a future event could lead to extension of the pipe. This was an important consideration in the selection of the repair method.

4.4.1 PIPELINE REPAIR OPTIONS

A number of options were initially considered for the pipe repair. Physical excavation of the floor of the clarifier was considered high risk given the possibility of further earthquakes, and potentially very expensive, and this option was eliminated early on. The remaining repair methods were based on “trenchless” repairs involving a pipe liner or joint repair. The chosen option had to be able to be installed with the pipe full of water as, due to buoyancy risks, it was considered a risk to the structure to dewater the pipe. Options considered were as follows:

- Amex internal joint sealing system
- Use of a Cured-In-Place Pipe (CIPP) utilising a needle punched polyester fabric impregnated with thermo-setting resin inserted into the existing pipe.
- Ribline pipe lining
- Hobas GRP pipe insert

Both the Ribline pipe lining and Hobas GRP pipe insert were eliminated after discussions with the product suppliers confirmed that access was insufficient for their product to be installed. The Rib-line option is a formed in-situ, spiral wound pipe which requires clear access at both ends of any straight section of pipe for a pipe winding machine which forms the Rib-line pipe. It was considered unlikely the pipe winding machine would function under water or over the vertical section of pipe.

The Hobas GRP option required sufficient access to enable insertion of straight lengths of pipe which would have to be jointed in-situ at circumferential joints and along the crown where the pipe has to be cut and folded into itself to enable insertion to take place. Apart from access issues, it was considered unlikely this system could be installed with any water in the pipe.

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 the treatment plant after the September 2010 earthquake, and these had moved and become deformed in the February 2011 aftershock. The AMEX product supplier could also not 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 from considerations. The remaining, and really only, viable option with the capacity to meet the operating conditions as well as withstand seismic loads, was a Cured-In-Place Pipe (CIPP) pipe liner.

Preferred Pipe Repair Option

Having taken consideration of the above options it was concluded that the CIPP system installed with a vinyl ester resin binder offered the optimum solution to repair the leaking joints and provide resistance against future seismic events. The CIPP liner system results in what is effectively a new pipe formed 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 a scenario of all 120mm of pipe being transferred by frictional and interlocking forces to just one length of pipe between two joints at which the new liner is locked to the existing pipes. 120mm extension over one pipe length equates 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. Resins available fall into three categories; polyester, vinyl ester and epoxy resins each with different mechanical properties. In consultation with the CIPP liner supplier a vinyl ester resin (Derakane 8084) was specified that is capable of accommodating elongation up to 10% which gave 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.

One potential problem with a very thick CIPP liner is that it will not accommodate the sharp bends in the pipe if the liner is installed as a single length. The proposed approach to overcoming this problem on the inlet pipe involved installation of several liner sections including once section with custom made fitted CIPP bend piece. However during the construction phase it was found that a single straight liner was able to fit around the 90 Deg bend with a minimum amount of creasing and this was the finally adopted solution. Some creasing was identified on the straight section of the finished liner on Clarifier 4 and this occurred because the liner ID did not exactly match the pipe ID (refer to Figure 9.). This problem was corrected for the liners on Clarifiers 3 and 1.

Figure 9: Creasing of Liner on Clarifier 4 Influent Pipe

CIPP Liner Installation

The pipe repair works were let as a separate package and the contract was awarded to Pipeworks Ltd. The pipe repairs were timed to work in with the structural and mechanical repairs to the clarifiers. Pipeworks mobilised to site for each repair which was typically completed over a two week period. The 1800 diameter CIPP liners installed on the CWTP clarifiers are the largest CIPP liner installed to date in New Zealand. Figure 10 shows the contractor team unravelling the liner prior to installation.

Figure 10: CIPP Liner Prior to Installation

5 REPAIRS IMPLEMENTATION

The permanent repairs were implemented over a 2 year period between June 2011 and June 2013. The initial repair strategy was based on limited investigations being completed on Clarifiers 2 & 4. Once Clarifier 3 had been dewatered and the extent of damage to the floor was known, the structural engineers in consultation with the geotechnical engineers reassessed the loads which the clarifiers would be subjected to during a significant liquefaction event. As a result the floor overlay was redesigned and the amount of reinforcing steel substantially increased as a result, at a cost of $200K per clarifier.

Other changes in strategy which evolved during the implementation included:

- The original strategy of repairing Clarifier 1 & Clarifier 3 while operating on Clarifier 2 & Clarifier 4 was abandoned when it was discovered that the channel serving Clarifiers 2 & Clarifier 4 did not have the hydraulic capacity required. The plan was changed so that both the east and west channels were in use and this meant that Clarifier 1 was not decommissioned and repaired until Clarifier 3 was re-commissioned.
- Given the minimal damage observed on Clarifier 2, it was decided that cost of taking it out of service and reinforcing the floor with an overlay as for Clarifiers 1, 3 & 4 could not be justified by the reduction in risk to the process. Hence the temporary repairs became the permanent repairs.

Aspects of the repair works are shown in Figures 11 and 12 below.

Figure 11: Inverted floor cone on Clarifier 3

Figure 12: Clarifier 3 repairs showing reinforcing mats

Figure 13: Fully repaired Clarifier 4

6 DISCUSSION AND CONCLUSIONS

Secondary clarifiers at Christchurch Wastewater Treatment Plant were extensively damaged during the major aftershocks on 22nd of February 2011. Damage to the clarifiers rendered them unserviceable and this created major problems for plant operations.

Despite the extent of the damage short term repairs were able to be implemented to restore basic operation within 4 months. This provided some 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 an option chosen involving constructing concrete overlays in three out of four clarifiers. The concrete overlay repair provided a cost-effective solution that Christchurch City Council believes will be fully recovered from insurance. It also restored pre-earthquake function without impacting significantly on the process performance and improved the resilience of the clarifier to further seismic activity at minor additional cost.

In terms of optimizing design for resilience the question is, with the information to hand on how the clarifiers performed in the earthquakes, could they or should they have been designed differently?

The design of the clarifiers was structurally suitable for the load cases defined in the NZ Seismic Design Code. However the design was not as conservative as other assets at the site and 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 the treatment plant, both in terms of the total number of treatment steps, and in terms of the number of each treatment process provided.

Where one treatment step fails another step can work harder to reinstate some of the lost performance. Polymer dosing of the PSTs to reduce solids loads to the ponds with no clarifiers running is an example of this.

Furthermore, redundancy within each treatment step also played a key role in plant resilience. Despite mechanical damage to some of the PSTs, with 7 PSTs available there were always at least several on line.

The actual performance of the treatment plant during the February 2011 earthquake (which exceeded the seismic design basis by a considerable margin) bears this principle out; the layers of redundancy provided by the number of treatment steps and by the number of units for each step allowed the plant to continue operating and to effectively manage public health risks even though the clarifiers had failed completely. Furthermore, the damaged suffered by two of the clarifiers was relatively easy to repair. Given these circumstances it might be considered that the original clarifier design and construction was a reasonable balance in terms of cost and performance, taking into account the additional protection provided by other treatment processes within the plant.

One implication of this assessment is that the design of wastewater treatment plants needs to take an integrated and facility-wide approach to redundancy, not only to provide operational flexibility, but also to provide resilience. Where a plant has multiple treatment stages with opportunities to redirect the treatment load 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 must be highly resilient to natural hazards. Complete failure of a wastewater treatment plant for an extended period could have a major impact on the community it serves.

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REFERENCES

CH2M Beca Report “CWTP Clarifiers 3 and 4 - Design Report for Structural Damage Repairs due to the February and June 2011 Earthquakes” February 2012

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