# RESILIENT PUMP STATION DESIGN

## FEATURES OF THE NEW CHRISTCHURCH PUMP STATIONS

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### ABSTRACT

As a result of the significant land movement experienced in areas of Christchurch during the earthquakes, most of the wastewater and stormwater pumping stations sustained damage to some degree, ranging from minor cosmetic damage, through to complete operational failure and damage beyond repair.

The primary goal of the Stronger Christchurch Infrastructure Rebuild Team (SCIRT) alliance is "*creating resilient infrastructure that gives people security and confidence in the future of Christchurch*". The damage sustained and the spectre of increased seismic activity has led to much greater emphasis being placed on resilient design of new pump stations. The modern pump stations are designed to include features to better withstand seismic activity and to allow rapid recovery from damage.

This paper describes the features included to provide a more resilient infrastructure for the new SCIRT designed pump stations including:

- Description of failure mechanisms experienced at Christchurch pumping stations;
- Design of foundations and ground improvements to minimise potential future seismic damage;
- Design of pipe connections to accommodate differential settlement.

By drawing on examples from four new large pumping station designs, the paper provides information on the resilient design developments being championed by SCIRT and how the wider industry might benefit from this unprecedented post-disaster recovery.

### KEYWORDS

**Wastewater Pump Station, Stormwater Pump Station Resilient Design, Seismic Design,**

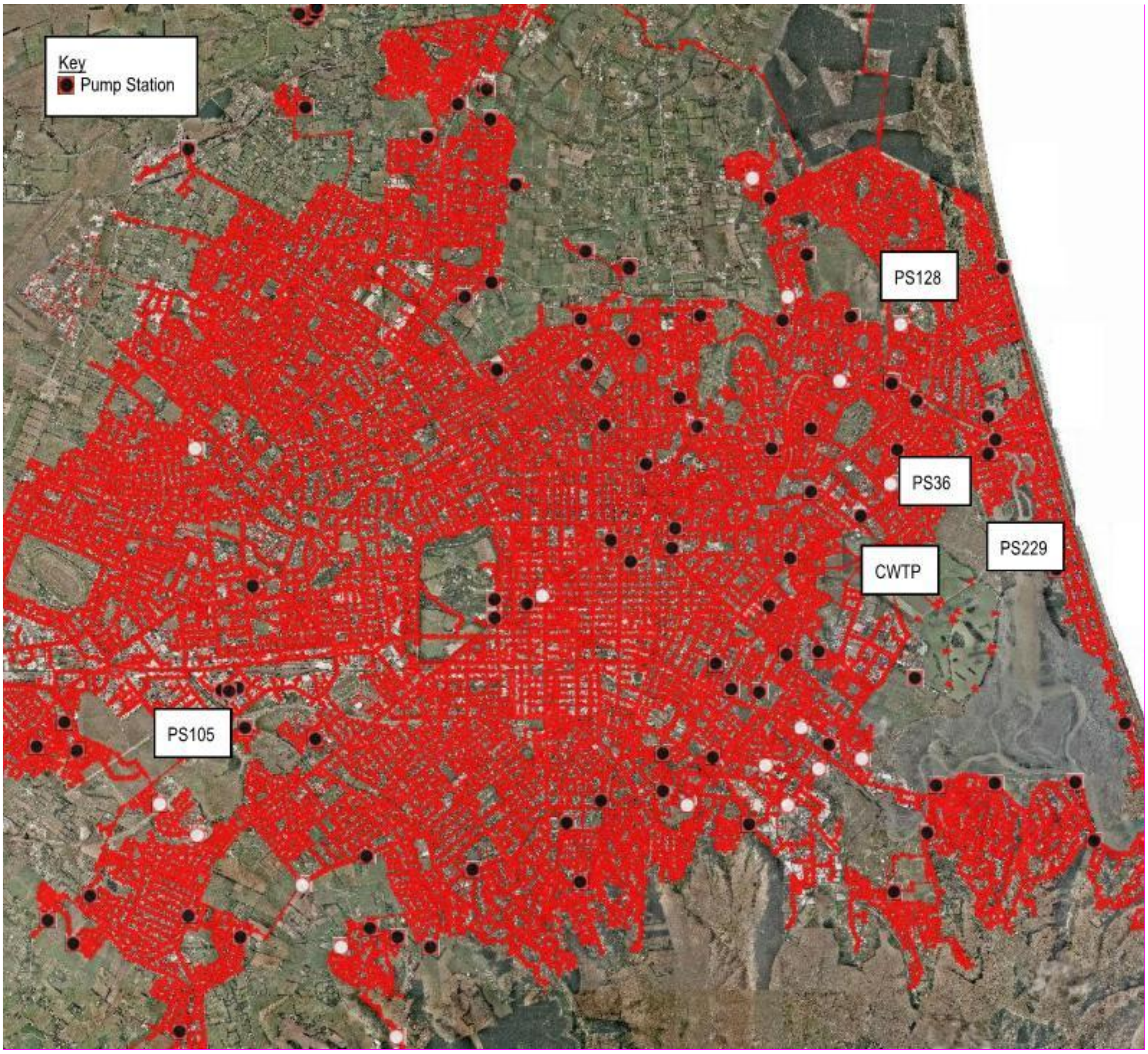
# 1 INTRODUCTION

Canterbury was struck by a series of major earthquakes in September 2010, February 2011 and June 2011 as well as numerous smaller earthquakes. In addition to a very high human toll, these earthquakes caused extensive damage to the city's infrastructure including the wastewater and stormwater infrastructure.

The majority of Christchurch city is located on flat land that has a fall of approximately 1 in 500 across the city. All wastewater is pumped at least once before reaching the Bromley wastewater treatment plant located in the eastern part of the city. In total, Christchurch has more than 100 wastewater pump stations, 4 of which have a capacity over 500 l/s. The city also has 19 stormwater pump stations ranging in capacity from a few litres per second to 13 m³/s.

Many of these pump stations suffered some form of damage. Land, property and infrastructure damage was most severe in the eastern suburbs and the pump stations in this area were no exception.

*Figure 1: Map of Christchurch City Council Pump Stations and Wastewater Network*




Peak ground accelerations during the magnitude $M_w$ 6.2 February 2011 earthquake exceeded that provided for in NZS1170. An accelerometer located at Pump Station 1 recorded ground accelerations as tabulated in Table 1. These were by no means the highest accelerations experienced during the Canterbury Earthquake Sequence (CES), but are representative of the forces experienced in the eastern suburbs.

*Table 1: Strong Ground Motion recorded at Pages Rd Pumping Station Seismograph*

| Earthquake | Magnitude ($M_w$) | Approx Duration (seconds) | Peak Horizontal Acceleration | Peak Vertical Acceleration |
|---|---|---|---|---|
| 4 September 2010 | 7.1 | 50 | 0.23g | 0.31g |
| 22 February 2011 | 6.2 | 13 | 0.72g | 1.63g |
| 13 June 2011 | 6.0 | 10 | 0.46g | 0.70g |

*Data sourced from www.geonet.org.nz*

This paper examines the damage that occurred to some of the large wastewater and stormwater pump stations and the design features that are incorporated into the new pump stations. The primary goal of the Stronger Christchurch Infrastructure Rebuild Team (SCIRT) alliance is "*creating resilient infrastructure that gives people security and confidence in the future of Christchurch*". The damage sustained and the increased likelihood of future seismic activity has led to much greater emphasis being placed on resilient design of new pump stations. The modern pump stations are designed to satisfy statutory requirements including features that enable the structures, mechanical plant and pipe connections to better withstand seismic activity and to allow rapid recovery from damage.

## 2 DAMAGE TO EXISTING PUMP STATIONS

The damage sustained by the wastewater and stormwater pump stations can be categorised as follows:

- Structural damage caused by temporary loss of foundation support due to liquefaction of the ground.
- Total settlement or buoyant uplift of structures.
- Differential settlement between structural elements and between structures and connecting pipes.
- Follow on operational problems such as increased inflow and infiltration (I/I), ingress of silt and sand, and accelerated wear.

Table 2 summarises the damage that occurred to the 5 largest CCC wastewater pump stations.

*Table 2: Summary of Earthquake Related Damage at Major CCC Wastewater Pump Stations*

| Pump Station | Damage | Repair Required |
|---|---|---|
| **PS36 – Terminal Pump Station**<br>▪ *PWWF = ~700 l/s*<br>▪ *Constructed 19XX*<br>▪ *6 m deep wetwell*<br>▪ *no ground improvements & asymmetric structure* | ▪ Flotation/rotation of wetwell<br>▪ 350 mm differential settlement and approximately 300 mm total settlement of the site and building.<br>▪ Breaks in twin AC pressure mains outside structure<br>▪ Flooding of drywell and damage to motor due to pressure main break.<br>▪ Rapid wear of impellors from sand in wastewater | **Complete Replacement** |
| **PS63**<br>▪ *PWWF = 470 l/s*<br>▪ *Constructed 1983*<br>▪ *Archimedes screw lift station* | ▪ Flotation and differential settlement of structure – tilting towards river (open face)<br>▪ Archimedes screw continued to operate but with increased maintenance requirements due to bearing lubrication system out of level. | **Complete Replacement** |

| | | |
|---|---|---|
| ▪ *6m deep wetwell* | | |
| **PS11 – Terminal Pump Station**<br>▪ *PWWF = 2700 l/s*<br>▪ *Constructed 2007* | ▪ Modern piled design, no significant settlement damage to structure.<br>▪ Break to discharge pipework immediately outside structure. | **Repairs required to pipe connections** |
| **PS15 – Terminal Pump Station**<br>▪ *PWWF = ~500 l/s*<br>▪ *Constructed 1970*<br>▪ *8 m deep caisson wetwell* | ▪ 400-500 mm differential settlement causing failure of the superstructure.<br>▪ Damage to inlet pipe with reverse grade.<br>▪ Shearing of cast iron discharge pipes at the connection to the structure and break of AC pressure main. | **Substantial Repair** |
| **PS1 – Terminal Pump Station**<br>▪ *PWWF = 2600 l/s*<br>▪ *Constructed 1955*<br>▪ *5 m deep wetwells* | ▪ Wetwell founded on dense sand which did not exhibit seismic settlement but part of superstructure on shallow foundations settled 115 mm.<br>▪ Structural damage due to differential settlement. | **Repairs Under design – Substantial Repair** |

**STORMWATER PUMP STATIONS**

Stormwater pump stations in Christchurch are generally located next to water bodies and suffered from the effects of liquefaction, lateral spread, seismic settlement and buoyant uplift. Examples of damage to this type of station are:

- PS205, an Archimedes screw lift station located on Horseshoe Lake sustained minor damage with limited differential settlement (approximately 50 mm) and overall settlement of 150mm compared to 400-600 mm in the surrounding land. This pump station is in an area of residential red zoned properties with severe land damage and the structure is founded on some 808 driven concrete piles (100×75 mm). This pump station being a lift station with no pipe connections, survived remarkably well.

- PS203 and 204, located on the banks of the Avon River in the red zoned Bexley both had their outlet pipes sheared off at the structure wall. Both of these pump stations settled some 400-600 mm with the surrounding land.

## 2.1 MECHANISM OF DAMAGE

The majority of seismic related damage to pump stations occurred as a result of ground settlement and in some cases coupled with flotation of the structures. Structures and mechanical equipment generally suffered little significant damage as a direct result of seismic shaking. Structural damage was typically a consequence of foundation failure. Damage to pipes occurred at several pump stations with the cause of this damage attributed to differential movement between the pipes and structures.

Elements of the pump station that are founded at different depths (for example deep wetwells and shallower valve chambers) can experience different amounts of seismic settlement that can stress and break connecting pipes, cause rotation across a structure or break foundations. Similarly, variation in ground conditions across the pump station site can result in different amounts of settlement between connected pipes or structures.

During a liquefaction inducing seismic event, elevated soil pore pressure and associated significant reduction in shear strength can exert increased buoyant forces on structures causing flotation and rotation of the structure.

Conversely, a reduction of soil bearing capacity during a liquefaction event can cause settlement and rotation of the structure.

Where a structure has deep piled foundations and suffered minimal settlement, such as the modern Pump Station 11, damage can still occur to the connecting pipes. In this case, the pressure main pipes immediately outside the main pump station structure sheared as a result of settlement of the ground surrounding the structure. At Pump Station 36, broken pressure mains caused further damage to structures and pipe work by scouring material away when the pumps were restarted.

During a strong earthquake the amount of ground settlement decreases with depth through the soil profile. This decrease in settlement with depth caused many pump stations in Christchurch to develop reduced or reverse grades in the gravity pipes entering the pump station. Typically, a pronounced reverse grade developed in the length of gravity pipe immediately outside the structure as a result of the wetwell being founded in deeper soils than the shallower gravity pipes. The loss of pipe grade exacerbated problems with blockages from silt and sand entering the pipes.

*Photograph 1: Settlement of Pump Station 36*


*Photograph A: PS36 showing differential settlement and 6° angle of building and wetwell*

*Photograph B: Settlement of ground at edge of PS36 wetwell*

As a consequence of the earthquakes, some normal wear and maintenance requirements occurred at a greatly accelerated rate. These operational problems that affected Christchurch wastewater pump stations included:

- Rapid and ongoing accumulation of liquefaction ejecta, silt, sand and gravel in the wetwell. This required frequent wetwell isolation and cleaning with vacuum truck and confined space entry. The need for cleaning was near daily immediately after an earthquake with diminishing frequency in the months that followed.

- Accelerated wear on pump impellors from the high quantities of sand that were being pumped. In the case of PS36, impellors were wearing within 6 months causing a reduction in the pumping capacity of the station.

- Greatly increased levels of inflow and infiltration as a result of damaged pipes, leading to longer pump run hours and overflows.

Careful design of the pump station can limit damage from seismic events and allow operational problems to be managed more easily following a major earthquake, allowing station operation to be returned to service more quickly and maintained in operation.

# 3 DESIGN CONSIDERATIONS FOR NEW PUMP STATIONS

The following priorities were identified to build resilience into the new pump station designs:

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

These priorities are discussed below using examples drawn from three new wastewater pump stations and one stormwater pump station designed and constructed by the SCIRT alliance. Details of these pump stations are summarised in Table 3.

*Table 3: Details of new SCIRT designed pump stations*

| Pump Station | Details |
|---|---|
| Pump Station 105 | ▪ A 'business as usual' pump station located in Wigram and designed to service new residential subdivision growth in western Christchurch.<br>▪ Design capacity of 560 l/s provided using two duty pumps and a standby in a 7.4 m deep wetwell. |
| Pump Station 128 | ▪ A new 625 l/s wastewater pump station to replace the damaged PS63.<br>▪ Operating with two duty pumps and one standby in a 7.7 m deep wetwell.<br>▪ Relocated to North New Brighton following changes to the catchment as residential properties were zoned red. |
| Pump Station 136 | ▪ A new 1000 l/s terminal wastewater pump station to replace the damaged PS36.<br>▪ Operating with two duty pumps and two standby pumps in a 8 m deep wetwell.<br>▪ Located in Aranui (eastern Christchurch) opposite the existing pump station. |

Each of the new wastewater pump stations is constructed with a building over the wetwell to provide for maintenance and with a standby generator for emergency power supply.

In addition to the wastewater pump stations, detailed design is underway on several large stormwater pump stations. These stations are required to mitigate the damage caused to the stormwater system by widespread land settlement in the eastern suburbs. The stormwater pump stations require a slightly different design approach due to their location near river banks - areas that are prone to further seismic settlement and lateral spread. The need to convey overland flow makes them more sensitive to differential settlement relative to the surrounding catchment than wastewater pump stations. However, the smaller structures, less frequent operation and shorter run hours allow for a simpler design than for wastewater pump stations of similar flow capacity.

An example of a new stormwater pump station, PS229, is offered for comparison to the wastewater pump stations. This station is located on the edge of a new stormwater retention basin in New Brighton and has a capacity of 1000 l/s discharging to the Avon River though a 90 m pressure main.

## 3.1 SITE SELECTION

Although requirements of the topography and existing catchment strongly dictate pump station location, site selection within these constraints was a key consideration for the new pump stations to provide resilient infrastructure. In the case of Christchurch critical factors affecting the seismic performance of a pump station include:

- Proximity to areas prone to lateral spread – typically this is areas close to open faces such as river banks.

- Local ground condition variations within a site – in the case of Christchurch, where the eastern suburbs are built on a series of historic sand dunes with swamp and water courses between them, the use of historic maps and ground investigations allowed minor adjustments within sites to avoid historic river beds which may be prone to liquefaction

- Crust formation – building the PS in areas that are above the groundwater table to avoid superficial damage to the site from liquefaction.

Other factors such as flood levels, constructability and impact on community were also considered.

## 3.2 SEISMIC DESIGN BASIS

Seismic design criteria for the new pump stations were governed by NZS 1170. The structures were deemed to have an Importance Level of 3 and a 100 year design working life. The ultimate limit state (ULS) event of 0.61g peak ground acceleration, Serviceability Limit State (SLS) of 0.11 g and a moment magnitude, $M_w$, of 7.5 was assessed to result in similar liquefaction effects to the 22 February 2011 earthquake.

### 3.2.1 BUOYANCY AND BEARING CAPACITY

The design of buried structures needs to implement measures to mitigate buoyancy for both static and seismic conditions. Where the ground liquefies beneath a structure the uplift is equivalent to being immersed in a dense fluid of unit weight in the order of 18kN/m$^3$. Even in strong seismic events that do not liquefy the ground, or where liquefaction mitigation is installed, earthquake shaking will still elevate pore-water pressures in the soil, inducing uplift pressure beneath buried structures. Even when structures are founded within ground improvements, the design needed to allow for increased buoyancy from the elevated pore water pressures occurring during a seismic event.

Buoyancy mitigation was provided in the design by incorporating additional weight to balance uplift or by piling the structure. This was achieved by extending the wet well base slab beyond the edges of the wet well and backfilling with engineered fill to create a non–liquefiable wedge adjacent to the structure.

The deep wetwells for the new wastewater pump stations allowed the structure to be founded in deeper, denser sands which have sufficient bearing capacity for static loading conditions. However, the founding dense sand layer beneath the wetwell could potentially liquefy under design ULS earthquake conditions. The ground improvement design mitigates liquefaction risk in this bearing layer for the pump station and the hardfill layer will limit buoyancy uplift effects.

## 3.3 FOUNDATION DESIGN

### 3.3.1 WASTEWATER PS128 AND 136 - CFA COLUMN GROUND IMPROVEMENTS

Much of the land in the eastern parts of Christchurch area is underlain by 30-40m depth of silt, sand, clay and peat deposits of the Christchurch Formation with between 3 - 20m of Riccarton Gravels beneath (Brown & Weeber, 1992). The groundwater table varies seasonally and with location but is typically from near to the surface to 3 m below ground level (bgl).

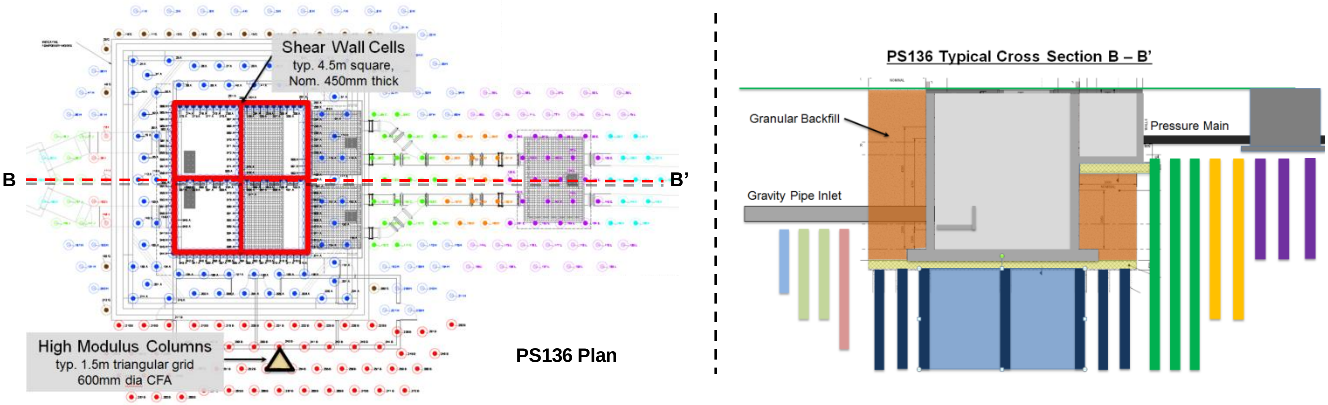
The ground conditions are similar for PS128 and 136 with the ground expected to liquefy to a depth of 10-20 m in a ULS event. During the CES, the land at these sites has settled 200-300 mm with a similar amount of settlement being expected during each future seismic event of similar strength. Ground improvements or piled foundations were required to limit displacements as required to meet NZS1170.

Ground improvement was chosen over a piled foundation because of the depth of liquefiable material at the site and due to the high cost of piling to the depths in excess of 30 m. A piled structure founded on gravels would largely eliminate all settlement but the surrounding catchment would settle, potentially leaving the pump station raised as much as 600 mm above the catchment after several events.

Ground improvements beneath and surrounding the structure are designed to mitigate the potential for liquefaction and effects of seismic settlement, reduced bearing capacity and buoyancy uplift associated with liquefied ground during SLS and ULS design earthquakes. Granular backfill surrounding the wetwell with ground improvements beyond the backfill is designed to provide lateral support to the structure and in combination with a flanged base, will help resist buoyant forces associated with increased pore pressure.

High modulus ground improvement was identified as the best value, technically feasible foundation design available in Christchurch at the time. The method of ground improvement chosen was Continuous Flight Auger (CFA) piles using 600 mm diameter columns of 20 MPa unreinforced concrete. This method offered low construction risk, high productivity and the ready availability of CFA piling rigs in Canterbury at the time.

*Figure 2: Ground Improvements at PS136*




The ground improvements form rectangular lattice structures of contiguous CFA columns directly under the wetwells which is surrounded by a grid of individual columns. The contiguous piles under the wetwell form shear walls that limit the shear strain on the soils contained within the lattice, preventing liquefaction.

Individual CFA columns are arranged in a triangular grid at 1.5 m centres, extending approximately 10 m around the wetwell structure. These columns provide lateral support to the wetwell and building to limit rotation and differential seismic settlement as well as controlling differential settlement between valve chambers and connecting pipe work.

One of the key resilient design features of these two stations is the use of tapered ground improvements along the route of the inlet and discharge pipes. The columns beneath the wetwell are 6 m long, extending 14 m below ground level, with depth of columns reducing to 6 m bgl towards the periphery of the ground improved area. By tapering the depth of ground improvement surrounding and under the pipes as they move away from the structure, the seismic settlement will occur over an extended length of pipe allowing the pipe to bend more gradually rather than imparting a shearing action at the point of connection to the structure.

As an example, with the ground improvements at PS136, it is expected that 50 mm of differential settlement will occur between the main structure and the deep inlet pipe in a ULS seismic event, and 100 mm at the shallower discharge pipes. This settlement will occur across the 6-10 m taper in ground improvements.

*Photograph 2: CFA Piles at base of PS136*

The ground improvements are designed to mitigate liquefaction within the improved area. In a very large seismic event, the soil beneath the ground improvements may liquefy, causing the structure to settle along with the surrounding land, albeit to a lesser degree.

### 3.3.2 WASTEWATER PS105 - PILED FOUNDATIONS

The ‘Geology of the Christchurch Urban Area’ (Brown & Weeber, 1992) geological map indicates that the proposed site is underlain by alluvial gravel, sand, and silt of historic river flood channels of the Springston Formation which is underlain at a depth by the Riccarton Gravels. The Riccarton Gravels commence at a depth of 15-20m and vary in thickness from a few meters to 20m.

The PS105 site offer better ground conditions than PS128 and PS136 and is less susceptible to liquefaction than eastern Christchurch. It is expected that settlement of 100-200 mm will occur at this site in a ULS earthquake and less than 50 mm under a Serviceability Limit State (SLS) event. To meet the requirements of NZS1170, foundation treatment was required at this site.

The shallower depth to stable gravels and the reduced amount of differential settlement that is expected to occur between the deep founded pump station and surrounding catchment allowed the use of a piled foundation. For this design, use of 250UC steel H piles, bearing within the Riccarton Gravels was identified as the most appropriate foundation, with a total of 44 piles being required for the structure.

This foundation design provides a robust foundation design resistant to settlement. However, the potential for 50-200 mm of differential seismic settlement between the structure and connecting pipes required specific treatment of the connection points.

### 3.3.3 STORMWATER PUMP STATION FOUNDATION DESIGN

Stormwater pump station 229 has its intake located in the bank of a new stormwater retention basin which allows for a relatively shallow structure of only 2.5 m deep. A raft foundation of reinforced imported fill is proposed as a cost effective solution for this site to limit differential settlement while allowing the structure to settle at a similar, albeit slightly smaller rate, to the surrounding catchment in a large earthquake. Settling with the catchment will allow the continued operation of overland flow paths to the pump station and minimal adjustment to the operating levels of the retention pond.

Following a large earthquake, the static head that the pumps operate at may need to be modified to allow continued discharge to sea level, but this can be accommodated relatively easily with changes to the pump impellor.

As with the wastewater pump stations, the structure layout is symmetrical with consideration to providing a centralised centre of mass to minimise tendency for differential settlement.

## 3.4 PIPE CONNECTIONS

The connection of the inlet and discharge pipes to the pump station is a significant point of vulnerability in a large earthquake. Differential ground movement between the pump station and surrounding ground can result in shearing of the pipes at the structure or introduction of reverse grades in the final length of gravity pipe entering the station. The efforts made in foundation design to limit settlement of the structure are likely to magnify the difference in behaviour of the surrounding ground relative to the structure.

Differential movement between the structure and pipes caused damage to many Christchurch pump stations during the Canterbury Earthquake Sequence and this movement should be considered in design of new stations.

### 3.4.1 INLET PIPES

For pump stations 105,128 and 136, the foundation design will limit the amount of settlement of the main structure, but differential settlement is expected between the structure and pipes outside the ground improved area in the order of 50-200 mm per event where soil liquefaction occurs.

To mitigate this differential settlement, which would flatten or reverse the grades of incoming gravity pipes, the gravity pipes between the last manhole outside of any ground improved area and the pump station were designed at a steepened grade. The amount of over-steepening is site specific and is dependent on the estimated differential settlement between the catchment and the ground improved structure. Typically, for the Christchurch pump stations, an additional 500-1000 mm additional fall was provided over the minimum grade provided by the CCC Infrastructure Design Standard (IDS).

As an example, PS128 was designed with a DN900 PE pipe at an initial grade of 1:250 to allow for settlement from future earthquakes whilst still maintaining the minimum required design grade of 1:500.

A balance needs to be achieved between providing for repeated future seismic settlement and the increased cost and operational implications of a deeper wetwell structure. The SCIRT design basis for large pump stations was to allow for a further two ULS seismic events.

Where the pump stations were designed with tapered ground improvement surrounding the structure, the risk of damage to pipes at the point of connection to the structure is reduced. However selection of pipe materials and connections needed to consider the effects of differential settlement between the structure and improved ground. It is expected that settlement in the order of <50mm will occur. Restrained pipes such as welded PE were selected over socket and spigot jointed pipes where the expected ground movement exceeded the allowable rotation per joint.

**HYDRAULIC CONSIDERATIONS**

Over-steepening of gravity pipes can cause hydraulic problems at the entrance to the pump station. Introducing a very steep grade can result in supercritical fluid velocities causing hydraulic jumps with the attendant problems of significant noise, corrosion and odour release. For the SCIRT-designed large pump stations, the conflicting requirements of steep inlet pipes and good hydraulic design have been managed by controlling the operating level of the pump station to hold the hydraulic grade line above the inlet pipe - effectively 'drowning' the inlet pipe.

Nightly flushing cycles are included in the pump control to remove floatable material from the gravity pipe. Should seismic settlement occur, the operating levels can be adjusted to provide an appropriate hydraulic grade into the pump station.

### 3.4.2 PS136 – RESILIENT DESIGN FOR TRENCHLESS INSTALLATION OF A LARGE DIAMETER PIPE

PS136 required connection to the existing 1075 mm diameter RCRRJ gravity pipe located on the opposite side of the road. Pages Road, where the existing and new pump station are located, is a major route for buried and overhead services, with the new connecting pipe needing to cross multiple telecommunications, high voltage power, water, stormwater as well as the pressure mains for the existing pump station. With so many services to protect and pipe depth of 5-6 m, it was apparent that open trench installation would be very difficult and expensive.

Settlement of 200-300 mm has occurred in Pages Rd during the earthquake sequence to date, with similar settlement expected to occur with each future ULS earthquake. Differential settlement in this order of magnitude will need to be accommodated along the 40 m length of pipe between the wetwell and Pages Road. The design criteria requires the pipe to remain intact (no joint separation) during settlement and to minimise the load transferred to the manholes at each end.

With close co-ordination between the SCIRT Delivery Team, their specialist sub-contractor and the design team, a novel trenchless solution was developed that meets the needs of health and safety during construction, constructability and seismic performance.

The solution developed used a 1600 mm diameter steel pipe with 25 mm a thick wall that was hammered beneath the road. The steel pipe acts as a sleeve for a 1200 mm outside diameter polyethylene pipe (PE100 SDR11) that will carry the wastewater. An oversized sleeve pipe was used to accommodate the accuracy limitations inherent with driving a pipe this distance. Once the PE pipe is in place, the annulus was filled with a low strength grout to prevent voids forming above the pipe.

To retain flexibility in the sleeved pipe and prevent it acting as a rigid beam during settlement, circumferential cuts have been made in the steel sleeve at 2 m intervals after it was installed. These cuts allow the sleeve to break and deform as the ground settles.

Pipe connections to the manholes are secured with puddle flanges cast into corbels. Slip joints for PE pipe that allow the pipe to pull out of, or insert into, the manhole are available, but were not considered necessary in this location.

To provide a future options in case the pipe does require repair, sufficient space has been provided in the bifurcation chamber immediately outside the wetwell to allow a future large diameter pipe to be installed while the current pipe remains live.

### 3.4.3 MANHOLES

As discussed in section 3.2.1, buoyancy forces exerted on buried structures during seismic events can exceed the static buoyancy from groundwater. The PS136 bifurcation chamber immediately before the wetwell is constructed in ground with a high liquefaction potential and has been designed with permeable backfill and underfloor drains to assist the release of excess pore water pressure and reduce the buoyant forces.

The underfloor drains consist of perforated drainage pipes in a filter sock buried in the backfill under the structure, and non-perforated pipe leading to the surface. They are a low cost addition to further reduce buoyant forces in a large earthquake by venting some of the elevated pore water pressure. Proprietary seismic pressure release valves are also available which serve a similar purpose.

### 3.4.4 DISCHARGE PIPES

Damage to pressure mains near the point of connection to the main wetwell/valve chamber structure occurred at several wastewater and stormwater pump stations. The damage was attributed to differential settlement between the pipes and the structures. At some pump stations, further damage occurred from material being scoured away from pipes and structures when the pumps restarted.

The new pump stations have incorporated several design features to minimise the potential for damage at this point with the following features included:

- Use of flexible, restrained pipe materials such as PE between the pump station and remote valve chambers to accommodate movement without the pipe pulling apart or shearing.

- Containing the manifold pipe inside the valve chamber to provide a single point of exit from the structure and reduce the number of potential points of failure. This results in a larger structure than if an external manifold were used, but can reduce the cost of treating the pipes to avoid shearing due to settlement. In the case of PS136 which has a more complex pipe arrangement with 4 pumps and 3 pressure mains, the manifolding of pipes occurs outside the main pump station structure, but is within the area of ground improvement.

- Use of flanged bases or corbels above the pipe connections to reduce the abrupt ground movement at the wall of the structure.

- Pump stations 105 and 128 incorporate a proprietary pipe connection on the discharge pipes, and on PS105, on the gravity inlet pipe as well. The 'Flextend' joint is proprietary extendable pipe connection incorporating ball joints at each end that can accommodate up to 15° deflection at each end and 150 mm of elongation.

*Figure 3: 'Flextend' flexible seismic expansion joint*

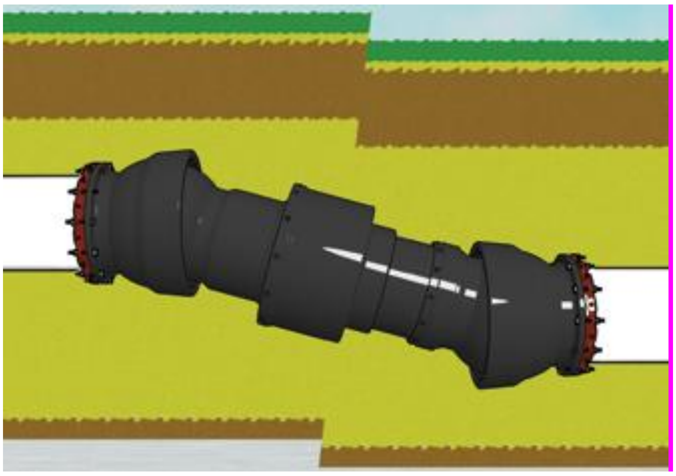


*Image courtesy: EBBA Iron Inc.*

### 3.4.5 PIPE CONNECTIONS AT STORMWATER PUMP STATIONS

The shallower depth of the pump station structure and 'excavate and replace' raft foundation will reduce the differential settlement between the pipes and the structure in a seismic event. Flexible expansion joints have been provided at the point of connection to the structure to accommodate this movement.

Both discharge and inlet pipes in stormwater are often large diameter and in the case of eastern Christchurch, it is desirable for them to be shallow to minimise cost and allow penetration of the stopbanks at an elevation that provides for maintenance access to non-return valves. The shallow depth and consequent small weight of cover, coupled with the large diameter of the pipes and likelihood that the pipes will be empty most of the time means that they are subject to greater buoyant forces during ground liquefying events (compared to wastewater pipes that are typically running at least 1/3 full which provides useful ballast to resist buoyant forces during liquefaction events). The design of these pipes uses geotextile wrapping of the pipe backfill to restrain the pipe against buoyant forces.

Pipes that pass through the stopbank are subject to lateral spread forces that could open socket and spigot joints and risk damage or failure of the stopbank. Restrained pipe materials such as welded PE, or concrete pipe with seismic restraints are used at these points.

## 3.5 GENERATOR FOUNDATION DESIGN

As is common with essential infrastructure, the large SCIRT wastewater pump stations are provided with prime rated emergency generators. Following significant earthquakes in Christchurch these proved their worth as network electricity supplies were disrupted for extended periods (from several days to weeks in some places).

In the case of PS105 and PS128, the generators are containerised sets in an acoustic enclosure providing an inherently resilient solution. The generators can simply be lifted onto a new concrete slab should the site be damaged. The larger generator required for PS136 is housed in a substantial reinforced concrete structure (approximately 6 m wide by 15 m long) that is needed to contain the acoustic treatment needed to meet the site noise limits.

A foundation of reinforced gravel raft was determined to be a lower cost method of controlling differential settlement than extending the ground improvement columns out to the generator building. The structural design of the building is designed to allow re-leveling should differential settlement occur.

Generator cables are direct buried but pass through a concrete chamber at the transition between ground improvement types. The cable within the chamber has sufficient additional length to allow differential movement between the generator building foundation and pump station ground improvements.

## 3.6 OTHER DESIGN FEATURES

Other design features that have been included in the new SCIRT designed pump stations to improve resilience include:

- Isolatable wetwell chambers to allow maintenance such as the removal of silt while the pump station continues to operate. In the case of PS105 and 128 which both have three pumps (operating on a duty/assist/standby basis) stoplogs can be inserted to isolate each pump bay. PS136 has four pumps (duty/assist and two standby pumps) contained in a wetwell divided into two chambers that can be isolated with penstocks.

- Tanker discharge couplings on the pressure mains serving PS128 and PS105 to allow by-pass pumping or direct truck discharge in the event of catastrophic failure of the station.

- A gravity by-pass around the station from the gravity inlet to the pressure main on PS128 and PS105. This is possible due to the flat nature of Christchurch where the pressure main discharge is at a lower elevation than the pump station.

- Electrical equipment is divided into two rooms to provide redundancy in event of fire. SCADA is not duplicated as the pump station could operate as an island without SCADA – the benefit provided by duplicating SCADA does not outweigh added cost and complexity.

# 4 CONCLUSIONS

The Canterbury earthquake sequence caused much damage but also provided opportunity to learn from the failure modes to make new infrastructure resilient to future seismic events.

Several existing pump stations were damaged beyond economic or practical repair and require replacement. The new pump stations have been designed with greater consideration of future earthquake damage to provide communities with confidence in their infrastructure. These design features included:

- Specific design of foundations and ground improvement to minimise damage from differential settlement.

- Design of pipe connections to accommodate differential settlement between the main PS structure and the surrounding catchment. Including over steepening of gravity pipes to allow future settlement, inclusion of pipe products to specifically allow settlement and use of tapered ground improvements to allow settlement over a longer length.

- Incorporation of low cost details or modification to provide additional resilience, such as additional slack in cables, use or flanged bases or corbels to provide a less abrupt transition from the structure wall to the ground at pipe connections.

## NOMENCLATURE

| | |
|---|---|
| Bgl | Below ground level |
| CES | Canterbury Earthquake Sequence |
| CFA | Continuous Flight Auger |
| I/I | Inflow and Infiltration |
| PE | Polyethylene |
| PWWF | Peak Wet Weather Flow |
| RCRRJ | Reinforced Concrete, Rubber Ring Joint |
| SLS | Serviceability Limit State |
| ULS | Ultimate Limit State |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