WASTEWATER PUMP STATION 15 – A CASE STUDY IN ASSET REUSE AND RESILIENT DESIGN

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ABSTRACT

Pump Station 15 (PS15), commissioned in 1970, conveys wastewater from Woolston to the Christchurch Wastewater Treatment Plant for approximately 40,000 population equivalents. The 2011 Christchurch earthquakes resulted in significant damage to and prolonged wastewater overflow from PS15. The damage observed included reverse graded gravity pipes, shear failure of pressure pipe and service connections at structures and separation of the station superstructure due to different foundation conditions.

Ground improvement provided by a specialist contractor will reduce potential differential settlement between structures and pipes to acceptable levels minimising damage in future large earthquakes. The resilient design elements of the station repair coupled with the ability to reuse large components of an existing asset make this project somewhat unique to the Christchurch infrastructure rebuild.

Following damaging earthquake events, there is the potential to reuse existing assets by utilising modern construction techniques and by reconfiguring pipeline/system layouts. This requires that realistic designs are produced which quantify and qualify the risks from a construction perspective and involve key construction expertise. Where these risks can be eliminated, avoided or mitigated there is the potential for significant cost savings as part of the rebuild of infrastructure networks.

KEYWORDS

Wastewater, Pumping Station, Resilience, Asset Reuse, Christchurch Earthquake, SCIRT

1 INTRODUCTION

The 2010 and 2011 earthquakes had a huge impact on Christchurch's lifeline civil infrastructure. Large wastewater pump stations located in the east of the city were highly represented in this data set due to the geology of the area and the location of the Christchurch Wastewater Treatment Plant. One of these critical infrastructure assets is Wastewater Pump Station 15 (PS15).

Christchurch's PS15, commissioned in 1970, conveys wastewater from Woolston, 3.6 km to the Christchurch Wastewater Treatment Plant at Bromley as depicted in Figure 1. This terminal pump station has a contributing catchment spans from Taylors Mistake in the south east to Hillsborough to the west and Bromley in the north. The catchment is made up of 11,250 residential households and 3,700 household equivalents of commercial/industrial zoned land with multiple high water users.

PS15 is comprised of a single 900 mm inlet gravity main discharging to dual wet well suction chambers contained within a 10 m diameter, 8 m deep caisson structure. The caisson is further divided into the dry well housing three 380 mm dry mounted pumps, each with 120 kW motors, and 450 mm swing check and gate valves. A single 700 mm cast iron pressure main exits the caisson and where it separates into twin 600 mm cast iron pressure mains before passing through the concrete valve chamber. This is a separate buried structure housing further swing check valves, gate valves and pressure main scour lines which drain to one of the suction wells. Flow from the station can be passed down either or both of the 600 mm pressure mains using the electrically actuated gate valves in the valve chamber The generator room and gantry crane load out/service area was part of the station superstructure but was designed to be supported by a separate pad foundation. This configuration is summarized in the 1970’s For Construction Schematic depicted in Figure 2.

Pump Station 15 is located in the suburb of Woolston approximately 1 km from the Avon/Heathcote Estuary. Geology of the site is generally bedded silty fine sands and muds overlying mostly loose to medium dense sands down to 15 m below ground level with groundwater approximately 0.5 m below ground level. The surrounding residential area is zoned Technical Category 2 (TC2) as per the Department of Building and Housing (DBH) residential housing foundation technical categories. This indicates that minor to moderate future land damage is likely in significant earthquakes. The suburb of Brookhaven 200 m to the east is zoned as TC3 which indicates that moderate to significant land damage from liquefaction is possible in future significant earthquakes.

The February and June 2011 earthquakes resulted in widespread liquefaction to the area surrounding the station and substantial differential settlement between the caisson, the surrounding ground and the valve chamber. This caused brittle failure of the station connecting pipework and separation of the building superstructure at the caisson/pad foundation join (refer Photographs 1 and 2). This also caused shearing through of water service pipes and power supply cables. This resulted in prolonged wastewater overflows to the Heathcote River and receiving Avon/Heathcote Estuary.

Following the February 2011 Earthquake, the immediate focus of the city wide recovery works was to restore the wastewater network to a reasonable operating level. At stations like PS15, this required quick, but by no means simple, repairs to the gravity and pressure pipe work, make safe works to the superstructure including some demolition and installation of a temporary covering for the backup generator. The pressure pipework between the caisson and valve chamber failed again in the June 2011 earthquakes and the repair methods and materials were modified as a result. The materials available at the time and fixing details were field engineered to return the station to service with some added resilience. The station came through any further aftershock sequences unscathed, testament to the belt and braces nature of the repairs.

Condition assessments of PS15 carried out by IRMO (Infrastructure Recovery Management Office) engineering consultants and by SCIRT during the project scoping phase included site visits and reviewing photographs taken during the recovery phase. This highlighted the extent of damage to the station pipework and superstructure and the temporary nature of the emergency repairs. From these initial assessments it seemed pertinent to rebuild PS15. Further detailed condition assessments, carried out as part of the SCIRT concept design process highlighted the ability to reuse elements of the existing structure.

This paper highlights the methods, materials and philosophies behind the reuse of the existing structure including the large scale modifications required to allow sufficient staging of the reinstatement works. Although the ground improvement design and physical works forms a critical element of the resilient design of the station reinstatement, this paper focuses on the civil design aspects associated with the gravity and pressure pipework and connection details between this pipework and the station structures.

2 DISCUSSION

2.1 CONDITION ASSESSMENT

2.1.1 DIFFERENTIAL SETTLEMENT

Level survey of the pump station structure and the local gravity trunk mains indicate the substructure and superstructure lifted by approximately 620 mm. Some of the uplift is regional, but 300 to 400 mm of differential movement (flotation of the structure and/or settlement of the adjacent land) occurred between the pump station and the incoming gravity reticulation. This can be seen from the site photographs taken after the earthquake (refer Photograph 1). Damage to PS15 primarily resulted from the effects of this differential settlement and was observed in damage to the superstructure, including the adjoining generator service/area, and the pipework connections to the caisson and valve chamber.

The differential settlement resulted in the inlet gravity pipe being reverse graded by approximately 285 mm over the 31 m length. The reverse graded pipe and upstream pipes will collect sediment in dry weather flows and may compromise capacity if sufficient bed shear isn’t developed in wet weather flows. This created design challenges for the station repair as discussed in Section 3.2.

PS15 includes a biofilter at the rear of the site (depicted in Photograph 2) for treatment of foul air drawn from the trunk mains by a 4 kW fan. This also provides protection against corrosion for the reinforced concrete wastewater trunk mains. The reverse graded gravity main has resulted in submerging the network under most flow conditions which reduces the ability of the biofilter suction fan to draw clean air into and foul air out of the trunk mains.

The differential settlement between the caisson and the valve chamber and between the valve chamber and the pressure mains has also likely compromised the flow of air within the pressure mains, with implications on head loss and system capacity. This presented further challenges for the station repair design as discussed in Section 3.2.

2.1.2 PIPE CONDITION AND FAILURE MODES

The materials used in the original station construction were typically brittle in nature with unrestrained connections for the gravity pipework (reinforced concrete rubber ring jointed) and pressure pipe work (asbestos cement). Flanged cast iron to BS2035:1966 was used for the restrained pressure pipework both internally and between the caisson and valve chamber.

The differential settlement caused the inlet gravity pipe to be reverse graded and resulted in the pipe caisson connection pulling out by approximately 50 mm (refer Photograph 3). Repair works after the February event included casting a concrete corbel at this location to prevent groundwater infiltration drawing soil fines into pipe and the wet wells.

The pressure pipe connection from the caisson consisted of a short spigot of cast iron and an unrestrained mechanical coupler. Mechanical couplers (or spigot socket joints) are often used in pairs to form a rocker pipe connection for pipe to structure connections. This can allow for some differential settlement in the short term due to construction loads or in the long term slow settlement of unconsolidated soils. In this case, the scale of the differential settlement (250-300 mm) as seen in Photograph 4 easily exceeded the allowable deflection of the coupler and the joint sheared clean through.

The movement of the valve chamber during the shaking of the June event was witnessed by Council Engineers and IRMO Engineering consultants. This was described as similar to a very wild boat ride suggesting the combination of liquefaction and continued shaking meant the structure had significant freedom of movement.

The brittleness of cast iron pipe and the large movements of the valve chamber structure during the earthquakes caused fracturing of the cast iron flanges outside of the valve chamber and to the puddle flanges cast in the valve chamber walls (Refer Photograph 5). Further damage was evident in the pressure mains discharging from the valve chamber which consisted of an adapted coupler between cast iron and asbestos cement pipes as seen in Photograph 6. This was repaired by recasting concrete corbels at this location. The uplift of the valve chamber caused the Supertite asbestos cement joints collars nearest to the structure to fail by over extension as shown in Photograph 7.

Pressure pipe repair works following the February event consisted of replacing failed cast iron pipe sections with galvanised mild steel pipe fittings as depicted in Photograph 8. Although these restored service to the station, they were not able to withstand the ongoing sequence of aftershocks. It is evident from the damage in the June event that the use of these fittings combined with the unsupported pressure main upstream of the valve chamber caused the sections of cast iron cast into the valve chamber to fail. The bends were then reinstated with welded polyethylene (PE) mitre bends fabricated from large diameter water pipe as shown in Photograph 9.

The difference in level of the pressure mains at the caisson connection was temporarily resolved by using a fabricated steel flat-down-flat 3 piece mitre adjustment fitting with a mechanical coupler to the existing cast iron stub. Again this coupler looked to have failed in the June event due the freedom of movement of the pressure pipe exceeding the allowance of the mechanical coupler. Repairs to this section following the June event again used galvanised mild steel pipe but this time steel tie rods and an additional flange bolting ring allowed some axial restraint back into the caisson. Although the added strength of this modification was not likely quantified, and would likely fail in another significant earthquake, the addition would have provided some restraint in a moderate earthquake and reduces the risk at a relatively low cost. Refer Photograph 10.

As part of the station repair works the condition of the existing 2.1 km long section of AC pressure mains was assessed to determine an approximate allowable operating pressure. A sample of AC pipe taken from the Earthquake repair works was assessed for concrete deterioration by phenolphthalein testing and the ultimate strength was assessed by a crushing test. This found the ultimate strength to be 134% of the minimum for Class B pipe to the NZS 285:1959 standard. The rate of deterioration indicated literature values for typical asset life of the AC pipe was suitable when assessing remaining asset life. Furthermore, there was no observable deterioration or perishing of a rubber ring also recovered during repairs to the pressure main.

2.1.3 WET WELL CONCRETE DETERIORATION

The detailed structural assessments included concrete deterioration tests of the caisson wet wells, dry well, and valve chamber. Concrete core samples were taken from various locations and the depth of concrete carbonation was tested using phenolphthalein. This highlighted the excellent quality of the concrete used in the original construction as well as the effectiveness of the concrete protection installed in the wet wells. Based on the observed rates of carbonation and depth to reinforcing, and considering the proposed concrete protection work in the wet well, the caisson structure was assessed as having a residual service life of at least 58 years with probable residual life closer to 100 years.

2.1.4 TRUNK MAIN ASSESSMENTS

As part of the wider catchment rebuild project the condition and failure modes of the large diameter reinforced concrete wastewater pipes has been assessed. These trunk mains are installed at depths ranging from 3.0 to 4.5m deep with little pipe foundations. The rigidity of the large sized pipes meant that failure mechanisms were generally concentrated locally at pipe joints or circumferential cracks with little longitudinal cracking. This is to be expected as reinforced concrete pipes are not designed as beams. Defects tended to occur more commonly at manhole connections and were typically crushing of joints and circumferential cracking. It is thought this that greater freedom of movement of the large manholes, combined with differential settlement causes shear failures at circumferential cracks and compression failures of joints. More research is needed in this area.

2.2 DESIGN

2.2.1 STANDARDS OF REINSTATEMENT

There are risks associated with utilising an existing piece of civil infrastructure which has already suffered damage from seismic events. There are four key elements of the design of a repaired station required to ensure that it meets the necessary standards of full replacement:

1. The ground improvement or piling methodology needs to be adaptable for an existing structure and should deliver seismic performance acceptable for the pipeline materials and structural connections. This shall include ground improvement to prevent liquefaction and/or piling of structures to prevent liquefaction floatation.
2. The repairs or rebuild of the superstructure or other buildings structures shall be to the appropriate seismic structural standard (NZS 1170.5:2004).
3. The design of pipelines and pipe to structure connections, and the operability of the asset shall be equivalent to that of a rebuilt station and shall not be compromised by the existing structure.
4. The design shall allow for the staging of the repair works to maintain service i.e. it is not acceptable for the design of the repairs to expect overflows as part of construction staging.

In terms of “can it actually be done”, a large and potentially option-killing aspect of the project was how the repairs could be carried out whilst not compromising service. This was very much dependent on the existing configuration of the station. This was assessed early on in the concept design phase in discussions with construction delivery team. A detailed step by step process was put together and revealed which elements of the design required modifications/additions.

2.2.2 LEVELS RESOLUTION

The settlement of the caisson relative to the surrounding ground poses interesting challenges for the replacement of the inlet gravity pipes and outgoing pressure pipes.

The gravity pipes require relaying at a steeper grade to return the level of service of the trunk mains to the pre earthquake condition, in terms of air flow for odour management, dry weather self-cleansing velocities and wet weather capacity. It is also beneficial to allow for further settlement of the trunk main network in future earthquakes. The height of the existing bifurcation chamber between the wet wells currently allows for a free discharge to each wet well (refer Figure 3). A free discharge is not necessary for an even flow split to the wet wells and so there is some level available to relay new gravity main inlets. In this case the flow split could be provided separate to the station in a bifurcation chamber in the street with new gravity mains laid to new inlet chambers attached to caisson. Isolation penstocks in each of the inlet chambers allows for isolation of the wet wells. Discussions with the SCIRT Construction Delivery Team highlighted the benefits of locating the bifurcation chamber further from the existing terminal manhole. This will reduce the risk of damage to the existing inlet pipe during the repairs and allow for adequate space for over-pumping arrangements.

Uplift of the caisson structure compromised the ability of the pressure mains to clean out air trapped at the soffit of the pump discharge manifold and pressure mains. Additionally the uplift of the valve chamber reduced the effectiveness of the pressure main scour drain lines. These two challenges were resolved by lifting the valve chamber to the same level as the pump discharge manifold and installing air release valves. New pressure main drain valve chambers with flow meters installed have been designed at the low point on the pressure mains. This ensures maintenance on the pressure mains isn't compromised and allows for flow monitoring. These pressure main drain/flow meter valve chambers also served as inline thrust blocks to resist the Poisson's effect of the PE 100 pressure pipes and the thrust force from the long radius 90 degree bends. Poisson's effect occurs where elastic pipe materials under pressure expand radially and contract in the axial direction. This tension force needs anchoring to prevent transfer of axial loads to unrestrained pipe joints.

To protect the asbestos cement and reinforced concrete pressure pipes from surge events, Hytran modelling of the pumping system highlighted the need to install double acting air release/intake valves with a bias towards letting air into the pipeline

2.2.3 CONSTRUCTION STAGING DIFFICULTIES

The repair of the station will require special construction staging to reduce the risk of overflows and damage to the existing equipment. Through detailed planning with the Construction Delivery Team, design features necessary for these works to be undertaken were carefully considered. Some of these design elements and the necessary staging works are discussed below.

Gravity Inlet Repairs

The installation of the new bifurcation chamber in the street will require temporary installation of high level bypass piping. A significantly damaged manhole in the street adjacent to the station requires replacement which will include a blanked connection. This can then be used as part of the temporary works for the bypass piping connection.

The new bifurcation manhole will be installed offline of the existing gravity wastewater inlet pipe. Once installed, the bifurcation chamber will allow the new gravity main inlet pipes to be installed sequentially. One of the inlet gravity pipes then can be installed offline, pressure tested and put into service. The existing inlet can then be decommissioned allowing for installation of the second wastewater inlet.

Pressure Pipe Repairs

To enable repairs to the pressure mains, the concept design highlighted the need to isolate the pump discharge manifold at the midpoint between Pump No. 2 and No. 3 (refer Figure 2). This will be done by installing an electrically actuated knife gate valve during a series of controlled station shut downs. This valve installation will enable PS15 to remain in operation while a second caisson pressure pipe outlet is installed. This additional outlet will allow for replacement of the existing temporarily repaired pressure main outlet, replacement of the damaged valve chamber and connection to the existing pressure mains.

2.2.4 RESILIENT DESIGN

The key to of resilient earthquake design for civil water/wastewater infrastructure rests with designing ground improvement or piling systems, to control settlement in a design earthquake. Settlement needs to be limited to the amounts broadly acceptable to the pipe materials and connection types. Where differential settlement cannot be prevented such as the edge of the ground improvement zone at the boundary of a site this can be allowed for in the following ways:

- Designing for differential settlement of soils by laying gravity inlet pipes at steeper grades
- Using pipe materials with inherent elastic and flexible properties, such as polyethylene (PE) pipe, which may yield in a design event, but much like seismic building design, will not fail catastrophically and which can be replaced/repaired during the recovery phase

The design elements employed for PS15 utilised large diameter cast in ductile iron spools flanged to solid wall polyethylene pressure pipe using galvanized mild steel backing rings and PE stub flanges. Although there is no readily available published performance data for these pipeline systems it can be expected to perform better than other pipeline materials in seismic events. This based on well-documented material properties and evidence from earthquake damage across the Christchurch water and wastewater networks. These pipes can be fully restrained with respect to pressure thrust forces and axial "pull-out" type movements in earthquakes. Ductile iron offers good resistance to brittle failure (compared to cast iron) due to nodular graphite inclusions and so is suitable for cast in place pipelines where stresses can be concentrated.

The above outlet system has also been specified for the gravity main inlets as significant ground settlement is expected across the border of the ground improvement zone and so in this instance there is the potential for unrestrained pipe connections to fail by joints pulling out.

The connections to the existing asbestos cement pressure mains were taken well beyond the edge of the ground improvement zone; this means that differential settlement expected across the boundary of the ground improvement zone would be absorbed in the flexible PE pipe. This will not transfer loads onto the more fragile asbestos cement pressure pipelines due to the anchoring of the pressure main drain/flow meter chambers.

The feature of dual wet wells allows for new inlet pipes to be installed and repairs/concrete protection works to the wet well walls to proceed without station shutdown. This is a more commonly adopted approach for large wastewater pump stations due to the difficulty to take them offline and has benefits for cleaning sediment from wet wells of sediment, especially following seismic events, as well as future renewals works to mechanical equipment or concrete protection. This can be achieved for large modern wastewater pump stations by using with wet well dividing walls with an isolating penstock between.

Designing resilient infrastructure in terms of earthquake or natural disaster damage also presents the opportunity to design a station which is resilient in terms of operational flexibility. This includes the ability to carry out maintenance on key valves, air valves or even pumps.

2.2.5 COST IMPLICATIONS

Where the condition of existing assets is suitable for repair and where it is feasible to carry out complex modification works, reusing existing infrastructure assets can result in significant cost savings on large rebuild projects. The decision to progress with an option which reuses a large proportion of an existing damaged or compromised asset should be made in consideration of potential increases in design and lifecycle costs. For the Pump station 15 project it is estimated that the option to repair the existing station with ground improvements will result in cost savings of $1-2 M, however this is slightly offset by a small increase in design costs due to the added complexity of working around existing equipment. This is common to "brown field" developments in many construction disciplines. It is estimated that life cycle costs of the reinstatement options showed little differences in operations and maintenance costs.

3 CONCLUSIONS

It is useful to gain an understanding of what features of large wastewater pump stations are conducive to efficient repair methodologies following damaging earthquakes. This is particularly applicable to areas with high risk of liquefaction and differential settlement.

Evidence from the Christchurch earthquakes and the damage to Pump Station 15 has demonstrated the risks associated with inlet gravity pipelines which are installed without additional fall to account for future differential settlement. The extent of damage to unrestrained and or brittle pipelines, commonly used historically, was significant with extended loss of service and overflow to the environment. It is observed that designing for operational flexibility of critical infrastructure can also provide for resilient infrastructure in terms of likelihood of failure but also the ease with which repairs can be undertaken.

Where damage occurs to civil infrastructure, there is the potential to reuse existing assets by utilizing modern construction techniques involving ground improvement methods and by reconfiguring pipeline/system layouts. This requires that detailed concept designs are produced which quantify and/or qualify the risks from a construction perspective and involve key construction expertise. Where these risks can be eliminated, avoided or mitigated there is the potential for significant cost savings as part of the rebuild of infrastructure networks. This philosophy and approach can also be applied to upgraded existing undamaged infrastructure located in geologically vulnerable areas to provide for greater resilience in earthquakes and other natural disasters. The ability to reuse structures and components of these systems and to limit future damage by implementing resilient designs enables local and central governments to limit the social, environmental and financial impacts of natural disasters.

Figure 1: *Pump Station 15 Location and Contributing Catchment*

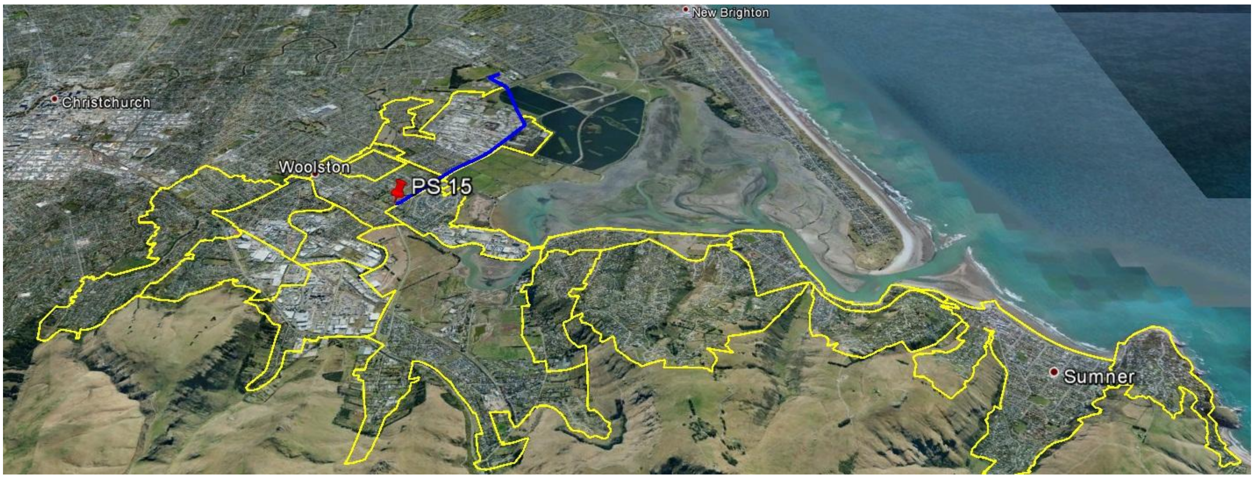


Figure 2: *Pump Station 15 1967 For Construction Perspective Plan*

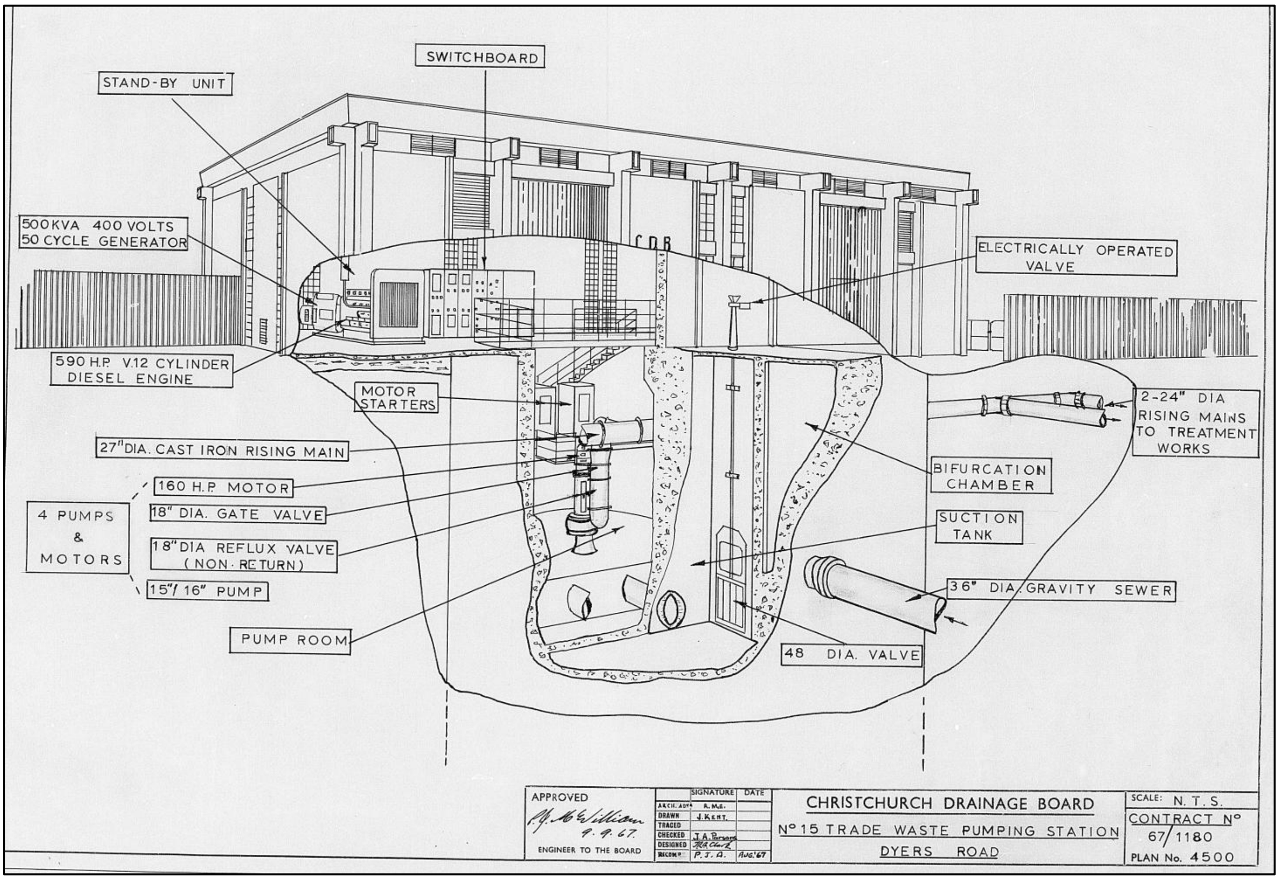
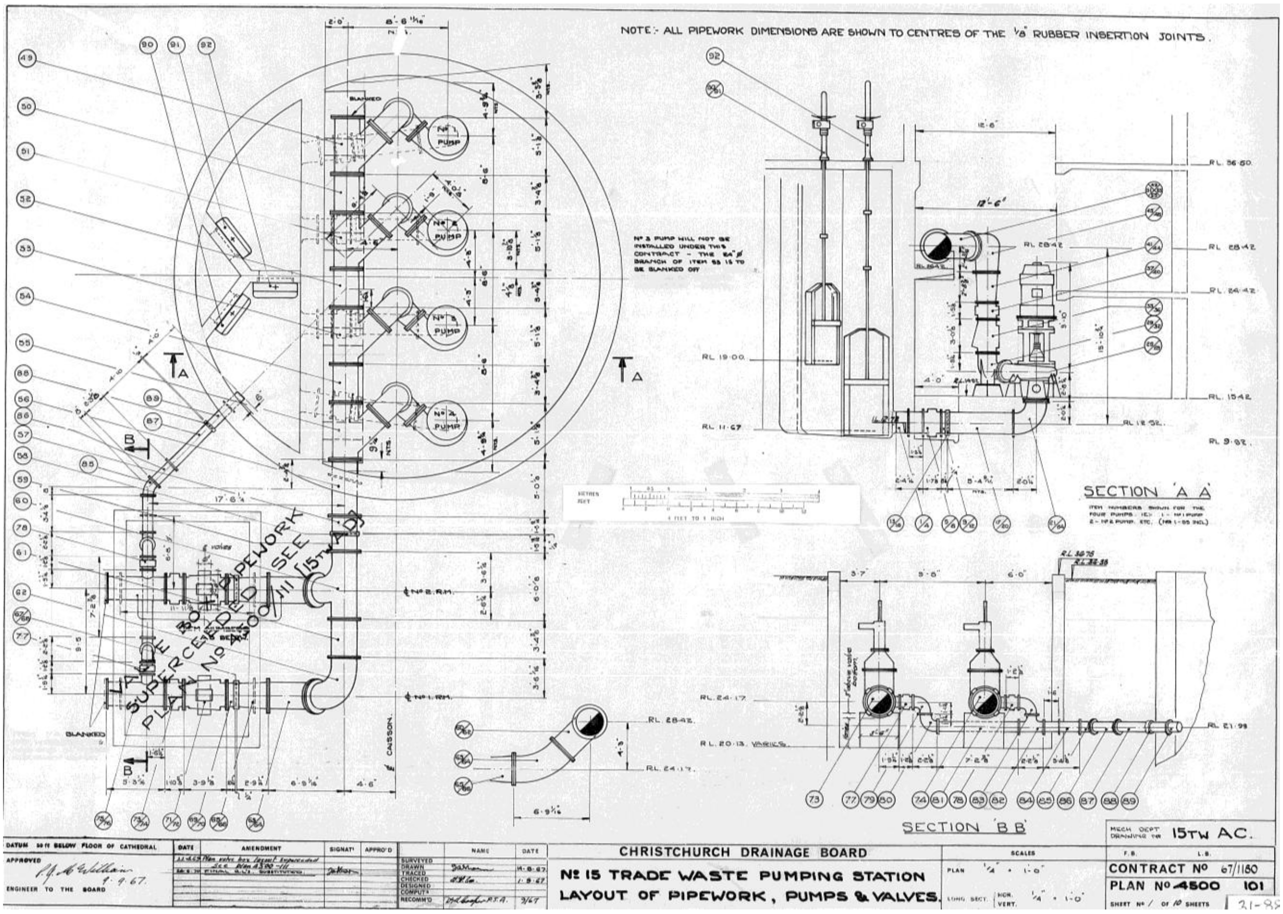


Figure 3: Pump Station 15 1967 For Construction Mechanical General Arrangement



Photograph 1: Relative displacement of Caisson to ground level.

Photograph 2: Damage to PS15 generator and service area due to differential settlement/uplift of caisson and pad foundation.

Photograph 3: Damage to caisson gravity pipe inlet (900 mm) showing pull out at connection to structure.

Photograph 4: Damage to caisson pressure pipe outlet (DN 27" or 685 mm) showing failure of first rocker joint.

Photograph 5: Shear failure of buried cast iron pressure pipe mains at connection to valve chamber. Circumferential crack to cast iron with seeping

Photograph 6: Damage to asbestos cement pressure main at connection to cast iron exit from valve chamber.

Photograph 7: Damage to asbestos cement pressure main Supertite Joint.

Photograph 8: Post-February 2011 Repairs to Pressure pipe Outlet.

Photograph 9: Post-June 2011 Repairs to Pressure pipe outlet.

Photograph 10: Post-June 2011 Repairs to Pressure pipe Outlet depicting use of flange modification and steel tie back rods..

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