SEISMIC PERFORMACE OF PLASTIC PIPE SYSTEMS IN 2010/11 CANTERBURY EARTHQUAKES

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ABSTRACT

The re-build of the damaged water and wastewater networks in Christchurch following the 2010/11 Canterbury earthquake series has almost exclusively been undertaken with modern Poly-vinyl Chloride (PVC) and Polyethylene pipe materials.

Assessments of the seismic performance of water and wastewater pipe networks to date have been dominated by initial repair records, but also include CCTV assessments, leakage and infiltration studies.

Polyethylene pipes performed exceptionally well, with only a handful of documented mains failures in the water and sewer networks. Polyethylene service connection pipes did not perform as well as larger diameter mains, with a number of pipe repairs required to restore service. Service connection failure issues associated with polyethylene pipe include historical material issues and fitting failures. Significant damage of PVC gravity pipe networks was limited to areas of high liquefaction and to older pipes. The majority of the damage and loss of service to PVC pipe networks occurred within pressurized pipe networks, with pipe joint damage/failure the predominant failure mechanism.

Assessment of damage which was not critical to the operation of the networks is on-going, as the effects become apparent in the operation of the networks. This in particularly evident in parts of the wastewater gravity network which have experienced increased infiltration rates, but is less evident in the pressurized water supply and wastewater networks.

KEYWORDS

PVC, Polyethylene, earthquakes, water supply, wastewater, pipe networks, infiltration

1 INTRODUCTION

Polyethylene and PVC pipes are being widely used in the rebuild of the Christchurch water supply and wastewater networks following the 2010/11 Canterbury earthquakes. This paper examines the performance of these pipe materials to demonstrate why their use has been so prevalent in the re-build.

Polyethylene pipe is widely recognized as having good seismically resilient properties, which is supported by its performance in the 2010/2011 Canterbury earthquakes and earthquakes around the world. Prior to the earthquakes, polyethylene pipe had been extensively used as a water supply sub-main material in the Christchurch water supply network, but had limited use as a mains pipe material in the water supply and wastewater networks. Polyethylene pipe has been used in the replacement pressure water supply and wastewater pipe networks including vacuum and pressure sewer systems.

PVC-U has been primarily used for the replacement gravity wastewater pipes. Polyvinyl Chloride pipes have been used in the water and wastewater industry in New Zealand since the early 1960's, with the earliest pipes installed in Christchurch in the mid 1960's. Ease of construction has been a major factor in selection of PVC pipe for replacement of damaged gravity wastewater networks.

The recovery of the damaged water and wastewater networks is occurring in three distinct stages;

a) Repair of critical defects to restoration service by the Councils maintenance contractor

b) Repair and rebuild of damaged pipe networks by the Stronger Christchurch Infrastructure Rebuild Team (SCIRT) to restore reliable operation and restore a reasonable asset life to the pipe networks

c) Ongoing repair and upgrading of "non-critical" damage causing ongoing operational and environmental effects.

While the plastic pipe networks in Christchurch sustained some initial damage, very limited repair and rebuild of the pre-earthquake plastic pipe networks has been undertaken to date by the SCIRT construction programme. The third level of recovery is longer term and can only be realised as non-critical defects (and in some cases unknown effects) are identified in the ongoing operational performance of the networks. Each level of recovery has differing performance measures to categorise the level of damage which requires a response. This paper examines some of performance measures used, and document what is currently known about the performance of plastic pipe systems following the 2010/2011 Canterbury Earthquakes.

2 PERFORMANCE FACTORS

2.1 MATERIAL PROPERTIES

Table 1 below lists the respective material properties for Polyethylene and PVC pipe.

Table 1: Comparison of Material Properties

	PVC	**Polyethylene**
Yield Strength	40-50 MPa	20-26MPa
Elongation at Yield	3%	10-20%
Elongation at Break	50-80%	300-500%
Joint Details	Spigot and Socket	20-26 MPa (fused)

PVC pipe has higher material strength but lower levels of ductility in comparison to polyethylene pipes. The pipe jointing has been included as a material property owing to the strength of fused connection, which is the predominant joint type associated with polyethylene pipe.

2.2 FAILURE MECHNISMS AND FIELD OBSERVATIONS

Initial observations indicated that a number of repairs were required to restore service to the polyethylene sub-mains in the water supply network around Christchurch. Typically, the damage was caused by failure of mechanical couplers, with some material failures. PVC mains failures also occurred throughout the network, with split pipes, pulled joints and socket damage common modes of failure.

Other than areas susceptible to heavy liquefaction and lateral spread (such as Brooklands, Spencerville, Bexley, Parklands & Brookhaven), initial observations indicated that the plastic wastewater pipe networks performed well and service was maintained with minimal repairs. Polyethylene was adopted by Christchurch City council (CCC) as material of choice for wastewater pumping main and water supply main replacements and repairs following the 2010 earthquakes. All of these replacements survived the 2011 earthquakes without a single pipe failure, thus demonstrating their effectiveness and seismic resilience. This included replacements across the Avon River in some of the most severely damaged areas. For many of the initial repairs in the wastewater, it was often impossible to fully inspect and identify the failure mechanism due to the presence of liquefaction in the pipe along with surcharged water levels. Often the pipe would be also damaged in excavating down to the failure.

The observations of joint separation and liquefaction material entering both wastewater and water supply pipes led to Christchurch City Council and University of Canterbury staff recommending wrapping of rubber ring joints with geotextile to limit sand ingress into pipes following joint displacement (Cubrinovski et al, 2011a).

2.3 LIQUEFACTION

Previous studies have identified strong correlations between repairs to damaged pipes and extent of the liquefaction experienced (Cubrinovski et al, 2014). The degree of liquefaction is considered the greatest factor affecting pipe performance in the Canterbury earthquakes. This is specific to both ground conditions and proximity to the earthquake epi-center for these earthquakes. University of Canterbury (Cubrinovski et al, 2011b) developed the Liquefaction Resistance Index (LRI), to compare the severity of the surface liquefaction observed after the February 2011 earthquake. Initially, this was solely based on visual observations of surface liquefaction, but later correlated to ground settlements and lateral movements and provides a measure of the severity of the liquefaction and ground settlement. This provides a means to correlate the degree of liquefaction or land damage against pipe damage.

2.4 NETWORK AGE

The long term performance of both PVC and polyethylene pipe materials are characterised by a decrease in material strength with age that needs to be accounted for in the pipe selection and design. Both PVC and polyethylene pipe materials have also developed significantly over the last thirty years. Pipework installation specifications also develop over time according to issues encountered by the asset owner and material developments. The following factors are considered relevant to PVC and polyethylene pipes in Christchurch.

2.4.1 POLYETHYLENE PIPE MATERIALS

Significant changes in polyethylene pipe resins occurred in the early 1990’s with the development of bi-modal resins with improved slow crack resistance. Historically, “HDPE” is recorded within the CCC GIS system as being used for the construction of sub-mains until the late 1990’s. After this date, the records suggest PE80 were used for sub-mains construction. GIS records suggest “MDPE” and PE80 were used from the early 1990’s for water supply mains followed by PE100 pipe material becoming more prevalent through the 2000’s.

The following periods were specifically investigated for differences in pipe performance: - Pre 1994, 1994-2003, 2004-2010.

2.4.2 PVC PIPE MATERIALS

Significant changes to PVC pipe materials led to the introduction of the current PVC manufacturing standard AS/NZS 1477 in 1997. This was a result of advancement in materials research and some variance in additives and performance of pipes between manufacturers leading up to this date. Therefore, periods of approximately 10 years were investigated either side of this date. The following periods were specifically investigated for differences in pipe performance: Pre-1986, 1986-1996, 1997-2006 and 2007-2010.

These dates also roughly coincide with recorded changes in PVC pipe material used in Christchurch. The CCC GIS data-base shows that PVC-M pipe was used between 1998 and 2009, and was the dominant water main material in Christchurch between 2000 and 2007. Some PVC-M was also used for sub-mains between 2004 and 2006. Pipe installed before and after these dates is recorded as “PVC” and “UPVC”.

2.4.3 PIPE BACKFILL SPECIFICATIONS

Christchurch City Council has historically devoted a lot of effort to development to their pipe backfill and surround specification requirements which are understood to have been related to the groundwater and soil conditions in Christchurch. Since the mid 2000’s, graded AP20 has been used as pipe bedding and surround to provide improved pipe support and limit trench settlement. This was adopted to provide a measureable compaction standard for pipe support, and limit risks of pipe and trench settlement with flat pipeline grades and high groundwater tables. This is intended to provide good support, through a cohesive pipe surround, that is reasonably resistant to migration of fines. Prior to the mid-2000’s; a more open graded sandy drainage metal, as well as native sandy materials, had been historically used.

2.5 NETWORK TYPES

The water supply and wastewater networks have different operational characteristics and seismic movements have different consequences on pipe operation. Therefore, the pipe performance is examined separately for gravity wastewater and pressure water supply and wastewater pipe networks. The construction of sub-mains and crossovers in the water supply network is considered a substantially different construction to the water mains (greater than 100mm diameter) due to the different jointing methods and shallower pipe depths employed during sub-main construction.

2.6 MEASURES OF PIPE NETWORK PERFORMANCE

2.6.1 REPAIR RATES

Repairs to the pipe network to restore service have been used in a number of studies to characterise pipe material performance. The studies to date mainly relate to the water supply networks, and are indicative of the critical repairs required to restore the network to an acceptable operational condition. They are not necessarily indicative of full damage to the entire pipe network. These studies generally do not account for pre-earthquake repair rates, and the underlying assumption has been that the pre–earthquake repair rates are low compared to the post-earthquake repair rates.

Repair rates are relatively easy and quick to assess to provide an early indication of the level of damage to the pipe network. These are considered a measure of the serviceability of the network, but represent different levels of performance for different services and different types of networks. Repair rates in pressure networks are considered more representative of the full extent of seismic damage than repair rates in gravity pipe networks.

Repairs were rapidly completed to the water supply network and wastewater pumping mains to restore network operation and service to residents and business after the earthquakes. Hence, repairs to the pressurized water network and wastewater pressure pipes generally achieved close to full restoration of service and are considered close to the full extent of the network damage known to date. Repairs to the gravity wastewater networks generally were delayed after the earthquakes owing to several factors. Initially, it was very difficult to locate the severity of the pipe damage due liquefaction blocking pipes. In many instances, pipes had to be cleaned three or more times as the pipes re-filled with liquefaction from the laterals prior to inspection and identification of breaks. Repairs to the wastewater network also often took many weeks (and some cases many months) to complete owing to the additional depth and difficult ground conditions, which is not reflected in the repair rates in the wastewater network.

Direct comparison of repair rates in gravity and pressure systems needs to account for the cost and difficulties of repairs undertaken deep gravity wastewater mains and on shallow small diameter pipes, along with the remaining work to restore full performance to the network. Gravity networks have a lot greater ability to operate to some level of effectiveness in a damaged condition, hence statistically, repair rates will be lower in gravity networks than pressure pipe networks.

In the initial response, to restore service to the gravity wastewater network, repairs were completed to prevent damage causing on-going blockages. For less critical damage, such as loss of pipe grade, this indicator will require the history of blockages to be monitored and a physical inspection to identify if they are likely to be related to pipe condition.

2.6.2 PIPE RENEWALS & REPLACEMENT

The next level of performance assessment involves the pipe renewals and replacements that have been undertaken by SCIRT to restore an acceptable level of service to the pipe networks.

To date, replacement of pressure pipe networks following the earthquakes have largely been based on on-going pipe failures, which are a reflection of the repairs undertaken, and there has been a considerably greater number of repairs to restore service than actual planned replacements completed.

Repair of the wastewater network has been undertaken based on criteria developed by CCC and Cera relating to the risk of pipe damage causing structural failure or loss of service in the future. The criterion for replacement of pipes has also changed as the extent of damage has been discovered and full costs and budgets realised. In some of the severely damaged areas, it has also been considered more economical to reconfigure entire wastewater catchments in order to achieve shallower construction and greater resilience for further earthquakes. Therefore, the repair rates of the wastewater network are more related to the restoration of critical serviceability of the network following the earthquakes rather than the overall seismic performance.

2.6.3 CCTV INVESTIGATIONS

CCTV inspection has been used extensively to identify damage to gravity pipe network and to locate many of the repairs undertaken to restore service to date. These risk based CCTV damage classifications, used to determine the criticality of the damage, have been developed internationally around brittle pipe materials such as earthenware and concrete pipes, and the criticality is weighted towards avoiding catastrophic structural failure of the pipe.

CCTV survey is time consuming, and expensive, to undertake over the entire network. Limited CCTV investigation has been undertaken in some of the most damaged areas of Christchurch, usually because time and costs had been focused on repairing and replacing damaged pipework to restore service rather than collecting data to fully assess the network damage. Therefore, while a very important tool for locating and assessing damage at all stages of the recovery, CCTV is not considered the most effective tool for assessing the performance of the entire network without a considerable amount of work and cost.

CCTV assessment does not necessarily provide the full network performance criteria for plastic pipes. It does not always address the performance of non-structural /service related defects such as dipped pipes, or provide positive identification of infiltration from displaced joints, or deformed pipes. The majority of structural damage to plastic pipes has not been readily identified from CCTV footage, either due to sand and weather ingress preventing inspection of the pipe or due to the nature of external damage to pipe sockets or fittings.

A number of the failures of plastic pipes have been attributed to loss of grade, which is not fully quantified by CCTV, and other tools have been required such as traditional survey or profileometer surveys. The limitations of CCTV to identify the performance of plastic pipe systems are considered a reflection of the good structural performance of plastic pipe materials in the 2010/2011 earthquakes.

2.7 OPERATION PERFORMANCE MEASURES

Operational performance measures, such as water leakage from water networks and infiltration into wastewater networks, are longer term performance measures that are being used as the recovery moves into the third response stage. These operational performance measures are more complex to assess and require a good understanding of the environmental variations affecting the operational variability of the networks. These factors include variations in population, rainfall and groundwater levels, as well as the structural condition of the network. Full understanding of such parameters can be a time consuming exercise and, in some cases, are expensive to collect and analyse. In some cases, these changes may remain indeterminate if data affecting other aspects of the network performance cannot be determined retrospectively.

2.7.1 LEAKAGE LEVELS – WATER SUPPLY NETWORKS

Initial leakage studies have been completed by SCIRT to assess service performance of the water supply network. These have generally indicated limited change to the leakage rates in the water supply pipe network. In completing such assessments, assumptions do need to be made in relation to populations and night time water- use. Population can be estimated from census data in 2006 and 2013 and properties developed from aerial photography. Night-time water use is also highly dependent on water use for garden irrigation in Christchurch, and this restricts such surveys to limited seasonal windows for accurate comparison or requires assumptions to correct surveys undertaken at different times of the year. Assessment of leakage levels in the water supply network is ongoing.

2.7.2 INFILTRATION – WASTEWATER NETWORKS

Dry-weather infiltration rates in Christchurch, across the whole wastewater network, have been estimated to be 40% higher than pre earthquake infiltration rates. Owing to the limited repairs and replacements that have been required to date on PVC and polyethylene pipe gravity wastewater networks, there has been limited focus on infiltration increases in the plastic pipe wastewater network, and this remains largely unquantified.

Infiltration may be assessed from flow monitoring surveys or changes to pump operation. There are no gravity sewer sub-catchments constructed entirely from polyethylene in Christchurch and only a few wastewater pump station catchments constructed entirely from PVC pipe networks. There are also limited suitable pre-earthquake wastewater flow monitoring surveys available to assess changes in gravity wastewater catchments, so changes in infiltration rates can only be assessed for a handful of pumped wastewater catchments that are constructed entirely from PVC pipe.

3 ASSESSMENT OF REPAIR RATES

3.1 PREAMBLE

The initial post-earthquake repair rates have been examined to investigate differences in the service related damage for the different gravity and pressure networks in relation to the severity of liquefaction and pipe age.

3.2 DATA

Pipe network and repair data was obtained from SCIRT to the middle of 2013. This matches the time frame assessed by Cubrinovski et al, (2014).

Lengths and repairs may vary slightly owing to the time period during which the data set was taken and the buffering process used in the GIS analysis. As highlighted by Cubrinovski et al (2014) there are also a number of anomalies in the database that are a result of historical recording practices and levels of accuracy. No attempt has been made to resolve these anomalies, as the data reflects the records of the time, and is only used to assess general trends in performance of the plastic pipe materials and to illustrate the issues arising assessing the performance of pipe networks following significant seismic events. Updating and correcting these historical anomalies is an ongoing task being undertaken by the Council and SCIRT.

Table 1: Christchurch Water mains at September 2010 (km pipe)

LRI [1]	PVC Water Mains	PVC Sub-mains	Polyethylene Watermains	Polyethylene Sub-mains
0	**11.1**		**1.0**	**48.8**
1	**39.2**	**4.0**	**1.6**	**170.3**
2	**58.1**	**4.9**	**2.6**	**227.5**
3	**82.4**	**8.0**	**2.9**	**346.7**
4	**298.6**	**62.3**	**8.6**	**629.0**
Total	**489.4**	**79.2**	**16.7**	**1422.4**

[1] LRI = liquefaction index

Table 2: Christchurch Wastewater pipes at September 2010 (km pipe)

LRI	PVC Gravity	PVC Pressure	Polyethylene Pressure	Polyethylene Gravity
0	**8.4**	0.0	0.10	0.1
1	**19.6**	2.8	0.39	2.0
2	**37.1**	3.5	0.00	1.6
3	**61.5**	7.3	0.01	4.4
4	**233.1**	64.9	2.92	11.3
Total	**359.7**	**78.6**	**3.42**	**19.5**

4 RESULTS

Figures 1 to 3 show the extent of the plastic pipe networks and repairs with the liquefaction resistance (LRI) zones.

4.1 WATER SUPPLY NETWORK

4.1.1 PVC PIPE

The following tables list recorded initial failure rates in PVC water supply mains and submains/cross overs according to when the pipes were installed and liquefaction resistance index (LRI) of their location.

Table 3: PVC Watermain failure rates (repairs/km)

LRI	Total	Pre 1986	1986-1996	1997-2006	2007-2010
0	**6.21**		7.38	4.49	7.23
1	**1.45**	12.20	1.41	1.79	0.00
2	**0.53**	0.51	0.74	0.40	0.54
3	**0.23**	3.56	0.31	0.18	0.00
4	**0.30**	1.10	0.40	0.21	0.17
All Zones	**0.54**	**1.14**	**0.76**	**0.41**	**0.12**

The highest failure rates occurred in LRI zones 0 &1 and in pipes installed before 1986.

Table 4: PVC water sub-mains/cross overs failure rates (repairs/km)

LRI	Total	Pre 1986	1986-1996	1997-2006	2007-2010
0					
1	**2.72**	1.51	3.53	15.38	
2	**1.43**	2.63		0.00	0.00
3	**1.51**	2.35	0.95	0.00	0.00
4	**0.91**	1.33	0.62	0.00	0.00
All Zones	**1.10**	**1.53**	**0.81**	**0.18**	**0.00**

The failure rates in sub-mains and cross overs show similar patterns to the failure rates in water supply mains with highest repair rates occurred in LRI zones 0 &1 and in pipes installed before 1986.

4.1.2 POLYETHYLENE PIPE

No failures were recorded in the 16 km of polyethylene water mains listed in the GIS records that were constructed prior to the September 2010 earthquake.

Polyethylene has been used extensively for sub-mains and cross over water supply pipes throughout Christchurch and the polyethylene sub-main and cross over failure rates were considerably higher than the PVC sub-main and cross overs failure rates, with higher failure rates observed in older pipes and in heavily liquefied areas.

Table 5: Polyethylene water supply sub-mains and cross over failure rates (repairs/km)

Zone	Total	Pre 1994	1994-2003	2004-2010
0	**3.65**	5.87	2.93	1.32
1	**2.72**	3.90	1.89	1.10
2	**2.11**	2.95	1.29	1.02
3	**2.00**	2.64	1.32	1.13
4	**1.15**	1.60	0.94	0.45
All Zones	**1.78**	**2.46**	**1.32**	**0.74**

Figure 1 Water Supply Mains Repairs

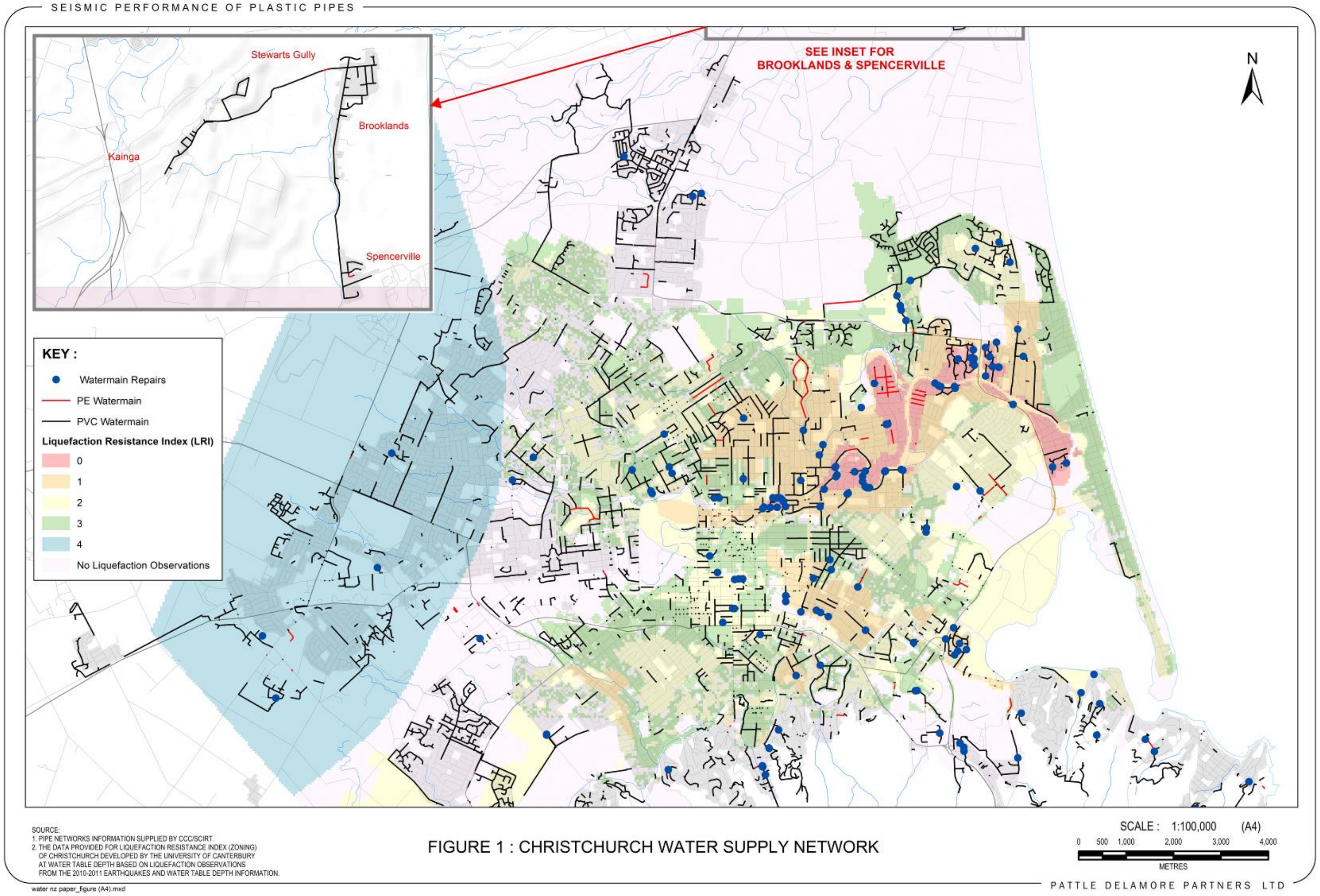


Figure 2 Water Supply Sub-mains and Cross Overs Repairs

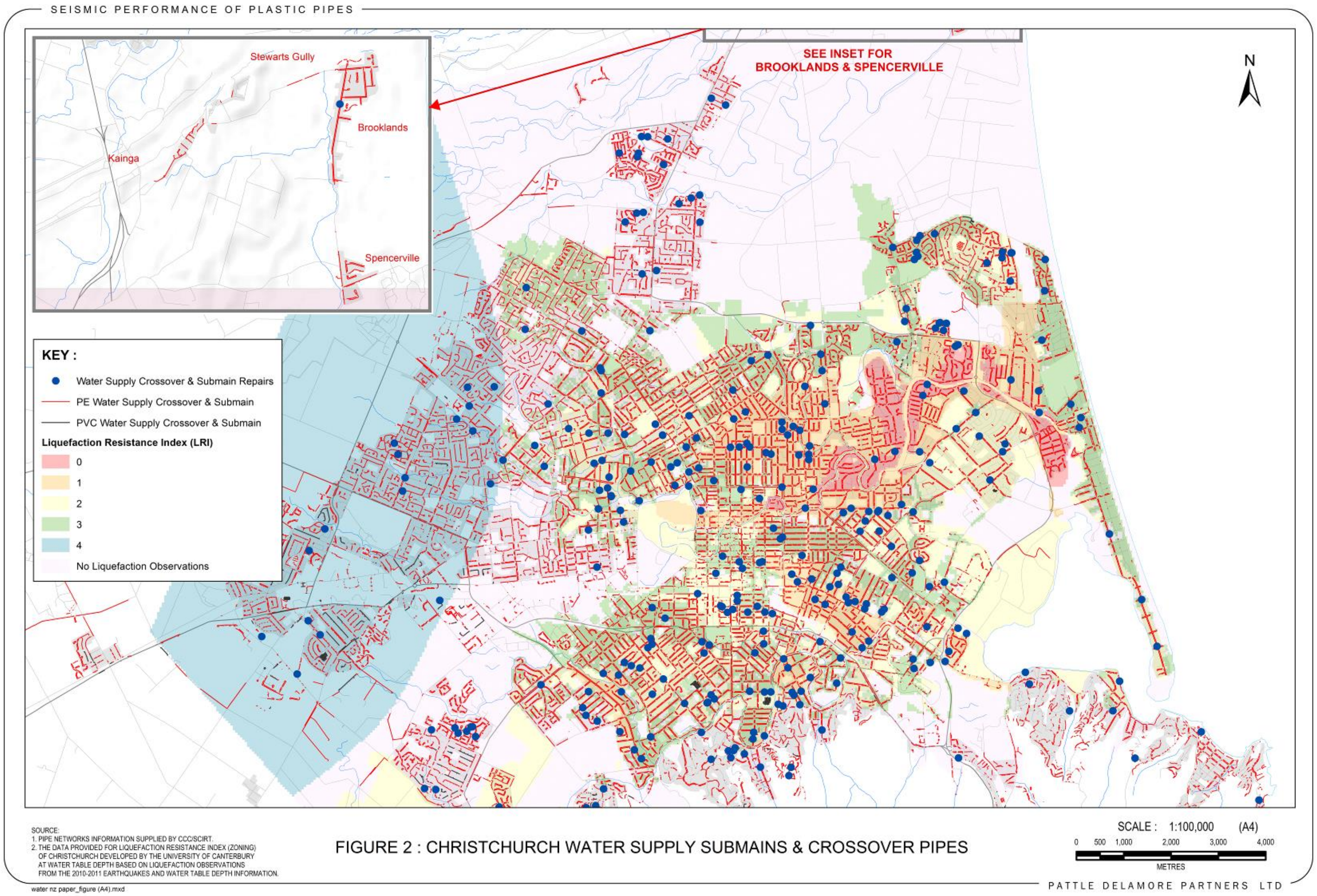
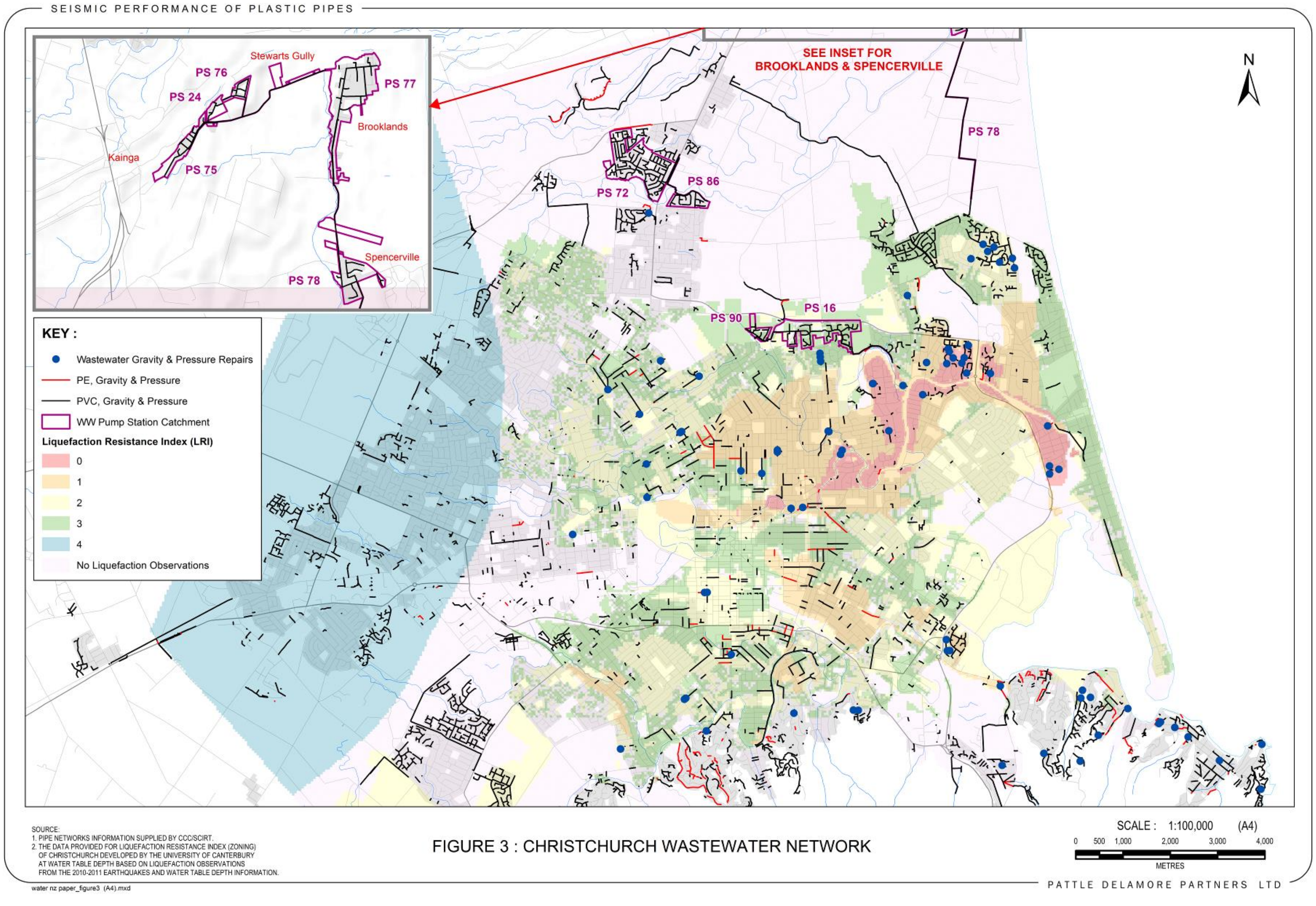


Figure 3 Wastewater Main Repairs



The failure rates in sub-mains and cross overs show similar patterns to the failure rates in PVC water supply mains and sub-mains. Highest repair rates occurred in LRI zones 0 &1 and in pipes installed before 1986. The repair rates for polyethylene sub-mains were significantly higher than PVC water supply mains and sub-main repair rates.

4.2 WASTEWATER NETWORK

4.2.1 PVC PIPE

Table 6 below shows the repairs on wastewater gravity sewers are much lower than the failure rates water supply mains as shown in Table 3.

Table 6: PVC wastewater Gravity sewer failure rates (repairs/ km)

LRI	Total	Pre-1986	1986-1996	1997-2006	2007-2010
0	**2.1**		1.2	3.6	0.0
1	**0.3**	1.8	0.2	0.2	0.0
2	**0.7**	5.8	0.5	0.4	0.0
3	**0.1**	1.9	0.0	0.0	0.0
4	**0.1**	0.6	0.2	0.0	0.0
All Zones	**0.2**	**1.8**	**0.3**	**0.1**	**0.0**

No repairs are recorded on the 78km of PVC wastewater pressure main installed prior to 2010. However, failures of PVC pressure mains are understood to have occurred in Brooklands and Spencerville following the September 2010 earthquake.

4.2.2 POLYETHYLENE PIPE

Table 7: Polyethylene Wastewater Pipes failure rates – (Repair/km (No. of Repairs))

Zone	PE Pumping [1]	PE Gravity
0	10 (1)	0.0
1	2.6 (1)	0.5 (1)
2	0	1.2 (2)
3	0	0.5 (2)
4	0	0.3 (3)
All Zones	**0.58 (2)**	**0.4 (8)**

[1] At least five km of polyethylene pumping main was installed in LRI zones 0 and 1 between September 2010 and June 2011. Most of these mains were installed in areas of severe liquefaction and lateral spread. No repairs were required on any of these pumping mains.

4.3 SUMMARY OF DIFFERENCES BETWEEN MATERIALS

There are significant performance differences between PVC and polyethylene pipes. Factors that affect performance of the two materials include location, pipe network age and type of network.

4.3.1 PVC PIPE PERFORMANCE

PRESSURE NETWORKS

Failures of PVC water supply pipes occurred throughout the pipe network, but were higher in older pipes and in highly liquefied areas. Previous studies by University of Canterbury (Cubrinovski,2014) show that over 50% of known failure mechanisms in PVC water supply pressure networks relate to some form of joint failures. Service lateral junctions are an identified weak point.

GRAVITY NETWORKS

Similar trends are observed in the wastewater gravity networks, compared to pressure pipe networks, with higher rates of repairs to restore service in areas of severe liquefaction and with older pipes. Lower rates of repairs are recorded compared than the pressure pipe repairs. This is considered indicative of the ability the gravity pipes to remain operative with a greater level of damage than pressure pipework. The lower repair rates for gravity networks are also possibly indicative of outstanding issues required to restore full operational performance of the pipe network after the initial restoration of service.

Field observations indicate loss of grade and joint failures to be significant modes of failure with disconnection of service laterals from the main. This is consistent with the more formal studies of the observed failure modes in pressure pipework. These failure modes would indicate that ground conditions and detailing issues are more prevalent than material deficiencies.

4.3.2 POLYEYTHLENE

PRESSURE NETWORKS

Polyethylene has been the dominant material used for small diameter crossover and sub-mains in Christchurch. The failure rates are significantly higher than for larger diameter PVC and polyethylene gravity and pressure mains. As with PVC pipes, higher rates of repairs were recorded in areas of high liquefaction and in older pipes installed prior to 1994. The higher failure rates in sub-mains and cross overs is largely attributed failure of fittings with some indication of material failures in the older HDPE sub-mains constructed prior to 1994.

Less than five recorded repairs were completed in polyethylene pressure networks of mains greater than 100mm diameter. This included replacement pipes, which were installed in areas of the most severe liquefaction and lateral spread following the September 2010 earthquake and which remained undamaged through the 2011 earthquakes.

GRAVITY NETWORKS

Less than ten recorded repairs were completed in polyethylene gravity pipes. Examination of these repairs indicated damage and blockages associated with junctions as well as weld beads catching debris and causing blockages in the mains.

5 OPERATIONAL PERFORMANCE MEASURES

5.1 PREAMBLE

To date there has been limited evidence of excess leakage from polyethylene or PVC water supply or wastewater pressure pipes, once the initial pipe failures have been repaired. Infiltration into the overall gravity wastewater network has been estimated to have increased by over 40% over the entire network at the city's treatment plant at Bromley. Infiltration rates are investigated for areas serviced solely by PVC and polyethylene pipes.

5.2 WASTEWATER CATCHMENTS INVESTIGATED

Four wastewater pumping station catchments in northern Christchurch constructed solely with PVC gravity wastewater pipes (as shown on Figure 3) were selected to examine changes in pump hours pre and post-earthquake in order to assess possible changes in infiltration rates due to the earthquakes. Unfortunately, there are no polyethylene wastewater sub-catchments to allow full comparison of the operational performance with catchments of PVC or other pipe materials. Pump station operational records were reviewed to confirm no changes occurred with the pumps.

5.3 PS72 - NORTHWOOD

PS72 wastewater network catchment was constructed in the early 2000's solely from PVC-U pipe. No repairs to the wastewater network were recorded as being completed in this catchment between 2011 and 2013, and no cleaning of liquefaction was required in 2011 to restore service to the wastewater network. Aerial Photographs indicate some development completed in the northern part of the catchment. The effect of this development is estimated to be less than 5% increase in catchment population.

Surface liquefaction was observed over at least 50% of PS72 catchment following the September 2010 earthquakes. The LRI is listed as having no liquefaction after the February 2011 earthquake. However, observations by the author and aerial photography indicate low levels of surface liquefaction after the February 2011 earthquakes. After the June earthquakes, minor to moderate liquefaction was recorded in Mounter Ave.

5.4 PS86 – REDWOOD NORTH

PS86 wastewater network catchment was constructed in the early 2000's solely from PVC-U pipe. No repairs to the wastewater network were recorded as being completed in this catchment between 2011 and 2013. Aerial Photographs do not indicate any infill development in this catchment between 2010 and 2014.

Liquefaction was recorded as observed in one street following the September 2010 earthquake. The LRI is listed as having no liquefaction after the February 2011 earthquake. However, aerial photography indicates low levels of surface liquefaction occurred at the end of Harry's Way occurred in the September 2010 earthquake. After the June earthquakes, no liquefaction was recorded in the catchment. Moderate levels of surface liquefaction were observed immediately to the south of this catchment following the February and June earthquakes.

5.5 PS90 MAREHAU NORTH

Construction of PS90 wastewater network catchment commenced in the mid 2000's solely from PVC-U pipe. No repairs within this wastewater network were recorded as being completed in this catchment between 2011 and 2013. Aerial photographs indicate a 40-50% increase in houses in this catchment between 2010 and 2014 and a significant sized retirement home was developed and serviced with pressure sewer drainage.

Liquefaction was not recorded within this catchment following the September 2010 earthquake. Small amounts of liquefaction were recorded following the February 2011 earthquake, with a LRI assessment of 2 and 3. No liquefaction was observed in this catchment following the June 2011 earthquake. Moderate levels of surface liquefaction were observed immediately to the south and north of this catchment following the February and June earthquakes.

5.6 PS16 SHIRLEY NORTH

PS90 catchment feeds into the PS16 catchment immediately to the east of PS90 catchment. Construction of the PS16 wastewater catchment commenced in the mid 1990's solely from PVC-U pipe. No repairs to the wastewater network were recorded as being completed in this catchment between 2011 and 2014. Aerial photographs indicate that this catchment was fully developed in 2010. Census records indicate a population increase of 74% between 2006 and 2013 occurred in this catchment.

Liquefaction was not recorded in the catchment area following the September 2010 earthquake. Small amounts of liquefaction were recorded following the February 2011 earthquake, with LRI assessments of 2 and 3. Liquefaction was observed in this catchment following the June 2011 earthquake but was limited to one street in the south west corner of the catchment. Moderate levels of surface liquefaction were observed immediately to the south and north of this catchment following the February and June earthquakes.

In summary, all four wastewater catchment examined suffered minor to moderate amounts of liquefaction during the 2010/2011 earthquakes with no repairs or cleaning of silt required to maintain service. Significant population increases occurred in PS90 catchment, but otherwise changes to the wastewater flows due to population or construction effects are expected to be limited.

5.7 INVESTIGATION PERIOD

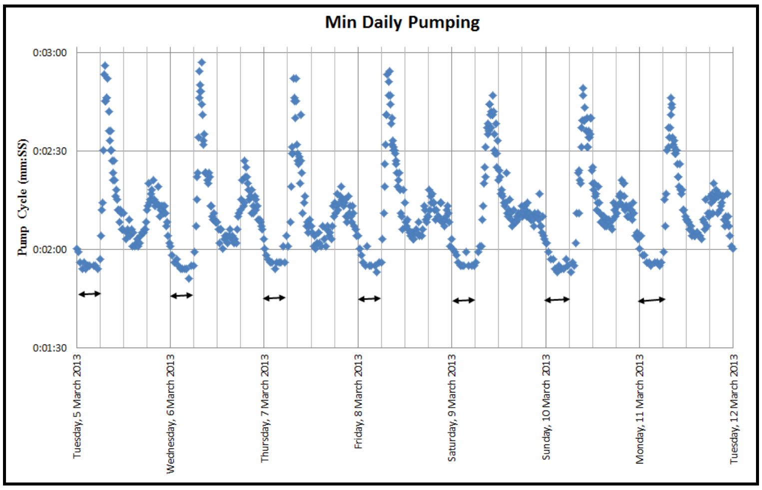
The pump hours from PS72, 86, 90 & 16 were assessed to investigate changes in pump station operation and wastewater flows pre-and post-earthquakes.

Periods selected for comparison were; March – August 2010, March – August 2013 & January –August 2014. The periods were selected to include roughly equal summer and winter periods in order to consider the range of groundwater levels and their effect on wastewater flows. The 2014 period was selected from the beginning of the year as this was an exceptionally wet autumn (March-June). The post-earthquake periods selected were 2013 and 2014, to coincide with the census and short term CCC flow surveys. The data for 2014 included an exceptionally wet autumn followed by a dryer than average winter. Population changes were assessed based on houses constructed between aerial photographs undertaken in 2010 and 2014.

5.8 INFILTRATION RATE ASSESSMENT

Changes in wastewater flows are assessed from 7-day average dry weather pump hours and nightly pumping hours assessed between midnight and 6:00 am as a measure of base infiltration. Dry weather days are defined as days with less than 0.5mm rainfall over the two preceding days. Figure 6 below demonstrates the records show consistent dinurnal pumping patterns that may be relied on to assess night time infiltration flows.

Figure 6 Nightly pump operation



Infiltration into wastewater systems is also often related to groundwater levels. Relevant groundwater data is limited in availability for the catchment area. The response of the PS72 wastewater flows to groundwater levels is shown in figure 7. This shows different relationships prior to and after the earthquakes between groundwater level and average dry weather night time pump operation.

Figures 8 and 9, show that the variation in nightly pump operation for 2010 and 2013 in PS72 catchment. Peak groundwater levels were similar for the two years, but there was approximately 20% more rainfall for the period investigated in 2013 compared with 2010. Figure 8 shows summer night time dry weather pumping times of between 10-15mins in 2010, which increased to between 20-25mins in 2013 in Figure 9. Winter dry weather night time pumping times were typically 15-20mins in 2010 as shown in figure 8, and these increased to approximately 25mins in figure 9.

Table 9 shows increases in pumping hours hours in excess of that expected for the different increased rainfall at PS72, PS16 and PS90 catchments.

Figure 7 ADWF fluctuations with Groundwater and rainfall

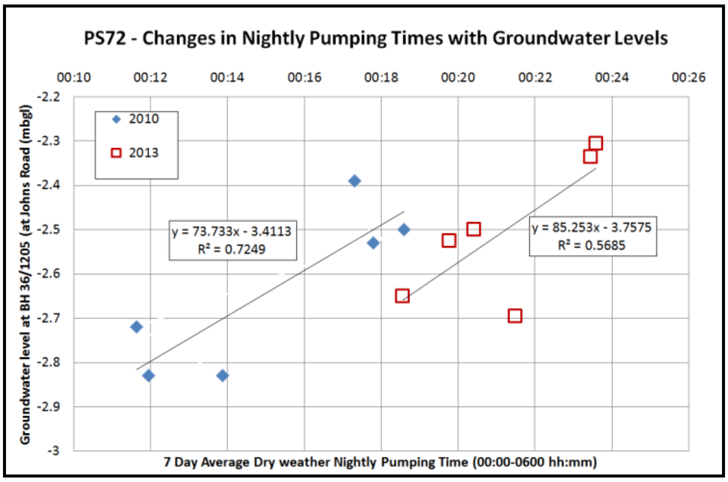


Figure 8: PS72, 2010 Operation

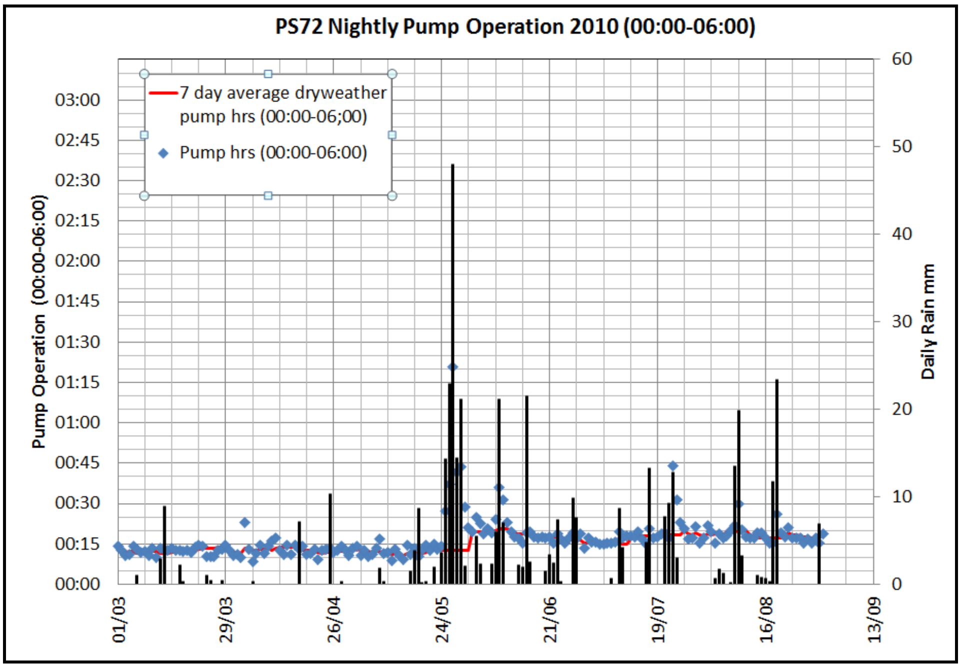
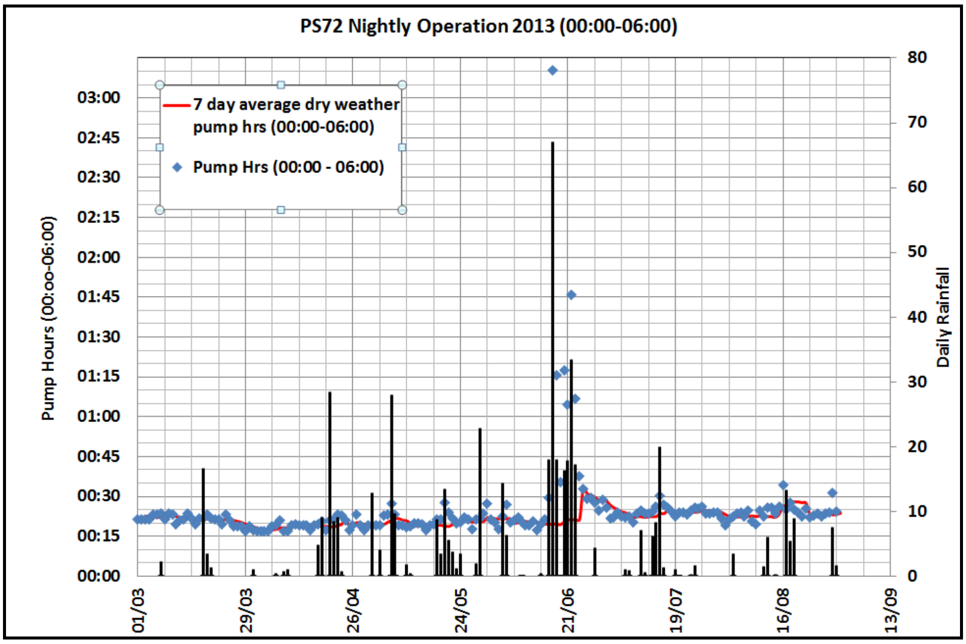


Figure 9: PS72, 2013 Operation



5.9 OTHER AREAS CONSTRUCTED SOLELY FROM PLASTIC PIPE NETWORKS

5.9.1 PS75, 24 & PS76 (KAINGA AND STEWARTS GULLY),

The wastewater network for these areas was constructed from PVC pipe in the late 1980's. This included three pumping stations pumping to a shared DN150, PN6 pumping mains to Brooklands. The water supply network was installed in the early 2000's from PVC-M pipe. No repairs to the water supply mains were recorded in these areas following the earthquakes.

SCIRT investigations showed limited evidence of changes in daily dry weather and minimum nightly pump station operational hours between 2010 and 2013 in these catchments. Limited liquefaction and ground settlement occurred in these areas, apart from small pockets of severe liquefaction adjacent to the Waimakariri stopbanks during the September 2010 earthquake. Two repairs to sewers were required completed in the PS24 catchment in 2012-2013. One of these repairs related to loss of grade, and the other related to a displaced rubber ring joint.

Table 9: Comparison of pre and post-earthquake pump station operation)

Station		ADW Pump hrs(hh:mm)	Nightly Min Pump (hh:mm)	Max PWWF (hh:mm)	ADW Pump Increase	Nightly Pump Increase	AWWP /ADWP	Comments
PS16	2010	2:43	0:13	4:29			1.65	5/3/14 rainfall event excluded all sites
PS16	2013	3:17	0:17	16:33	21%	35%	5.02	
PS16	2014	3:25	0:18	12:14	26%	40%	3.58	
PS72	2010	2:44	0:14	6:10			2.26	
PS72	2013	3:22	0:21	14:00	23%	49%	4.15	
PS72	2014	Data inconsistencies during Winter 2014						
PS72	2010- Summer	2:34	0:12					
PS72	2013 - Summer	3:19	0:19		29%	60%		
PS72	2014 - Summer	3:12	0:19	5:02	25%	58%	9.04	
PS86	2010	4:07	0:22	13:56			3.38	
PS86	2013	3:49	0:27	15:07	-7%	13%	10.22	
PS86	2014	4:26	0:33	2:38	8%	36%	5.99	
PS90	2010	0:50	0:06	2:11			2.60	
PS90	2013	2:23	0:15	18:43	182%	123%	7.84	Catchment under construction
PS90	2014	2:55	0:16	18:43	246%	145%	6.40	Catchment under construction
PS75/76		As per SCIRT project 11058 no change in daily pumping or min nightly pumping identified						
PS2		Min nightly pumping reduced to 1/3 pre EQ baseflows with new PVC pipe network.						

5.9.2 PS77 BROOKLANDS

Brooklands wastewater network was constructed from PVC pipe in the late 1980's. This included twin DN175, PN6 pumping mains to Spencerville. The water supply network was installed in the early 2000's from PVC-M pipe.

Brooklands wastewater system was severely damaged in the 2010 earthquakes with severe loss of grade, displaced joints and ongoing sand ingress. The sewers in Brooklands were constructed over four meters deep in cohesion-less beach sands that are highly susceptible to liquefaction. A siltier surface crust of approximately one metre depth exists which is less susceptible to liquefaction. Sections of the sewer main along the southern portion of Lower Styx Road were abandoned after the 2010 earthquake and by-pass pumps were installed to maintain service to the residents. These were subsequently replaced with a more reliable interim solution of individual pressure pumps, prior to red zoning of the entire area by the Canterbury Earthquake Recovery Authority (CERA).

Attempts to CCTV the remaining gravity network were abandoned in 2011 owing to difficulties controlling groundwater and sand ingress. The on-going loss of service to the remaining sections of gravity sewer throughout 2011 all involved blockages from sand ingress to lateral connections, with suspected joint displacement at the junction to the main. Severe infiltration occurred in this catchment following the earthquakes and the gravity network operated in a surcharged state to match the adjacent groundwater level with the wastewater pump station pumps operating 24 hours per day. This caused ongoing sand ingress and damage to the pumps and accumulation of sand in the downstream pumping mains and the Spencerville catchment.

Remarkably, apart from initial repairs reconnecting mains to the water supply and wastewater pump station structures, there are no recorded water main or wastewater pressure main failures in Brooklands. This is attributed to the shallow depth of the mains and less liquefaction around the pipe. The recorded damage to the water supply network was limited to sub-mains and cross overs.

5.9.3 SPENCERVILLE

Like Brooklands, the Spencerville area suffered extensive damage in the September 2010 earthquake. Severe ground settlement and liquefaction occurred in the center of the wastewater catchment with ground settlements estimated at over 0.5m.

The patterns of damage and repair that occurred in Spencerville area are similar to those that occurred in the Brooklands area, but to a lesser extent. The pressure main connecting Spencerville to the Christchurch network was extensively damaged following the 2010 earthquakes. Following initial repairs of the Spencerville gravity network in 2010, one severe failure occurred which resulted in collapse of the road at the end of Nautilus Place in 2011, but otherwise the network has remained largely in service despite some severely dipped pipes. The failure in Nautilus place was attributed to disconnection of two lateral junctions to the main in close proximity to each other. As with the Brooklands catchment, damage to the wastewater network was far greater than the damage to the water supply network.

5.10 DISCUSSION – INFILTRATION RATES

CCC design requirements permit infiltration rates just over 31% of the average dry weather flow based on water usage at 150 l/p/day and design wastewater allowances of 220 l/p/day,

Further analysis of the ratio of the average minimum nightly pumping rate to average daily dry weather pumping rate in Table 9, (and assuming 85% of the minimum nightly pumping rates consists of infiltration flows), shows the proportion of infiltration flows increasing above the design infiltration allowance for PS72 and PS86 following the earthquakes. As no net increase in average dry weather pump operation is observed in PS86, a decrease in wastewater flows is indicated.

For PS90 catchment, the proportion of infiltration flows is estimated to decrease from approximately 46% to 33% of average dry weather wastewater flows even though the absolute infiltration rate as assessed with nightly pump operation trebled with the increased development in the catchment. The proportion of infiltration flows has increased in PS16 despite net decreases in PS90 catchment upstream.

Therefore, increases in the proportion of infiltration to total dry weather flows are assessed in PS16, PS72 and PS86 catchments. Infiltration due to damaged pipes is also confirmed but unable to be quantified in PS77 (Brooklands) and PS78 Spencerville) wastewater catchments owing to difficulties in isolating flows from Brooklands. Infiltration increases are assessed as unlikely in PS24, 75, 76 & 90 catchments.

Table 10 Measures of post earthquake changes in infiultration rates

	Est. Post EQ Increases in ADWF (2013, 2014)	Est Post EQ Increases in ADW nightly pump hrs (2013, 2014)	Est, % Infiltration Pre EQ	Est, % Infiltration Post EQ (2013, 2014)	Est. post EQ % Increases Infiltration (2013,2014)
PS16 Catchment	21%,24%	35%,40%	27%	31%, 30%	12%,12%
PS72 Catchment	23%,25%*	49%,58%*	30%	36%, 35% *	31%, 26%*
PS86 Catchment	-7%,8%	13%,36%	31%	38%, 39%	22%, 26%
PS90 Catchment	182% ,146%	123%,145%	46%	37%, 33%	-21%,-29%

*2014 Summer period only

All catchments were operating at infiltration rates close to or above 30% of average dry weather flows prior to the earthquakes. The maximum wet weather pump hours have also been compared as an indication of the maximum response to rainfall. This includes a combination of direct inflows and rainfall induced infiltration. The maximum daily post-earthquake peak wet weather pumping time factor is shown in Table 9 as exceeding the standard wet weather design factor of five times the average dry weather flow at all four pumping stations in the post-earthquake records. The peak wet weather pumping operation is anticipated to be a combination of rainfall induced infiltration and direct inflows and is not exclusively associated with pipe damage, but it shows post-earthquake performance in excess of design allowances.

The observed increases in post-earthquake infiltration rates have yet to be positively identified as being caused by earthquake damage in all cases investigated as changes in infiltration in wastewater networks are a complex process that can also occur from other factors such as variations in rainfall, groundwater levels and catchment water use and population changes. The causes of this increased infiltration may be a difficult task to determine with any certainty, as CCTV of the PVC mains may not readily identify infiltration causing faults and may require inspection of the wastewater laterals. If the mains cannot be inspected while infiltration is occurring (ie after rainfall), there will be a period of time for before encrusted residue from the seepage to appear around the pipe joints to indicate a possible source of the observed infiltration. In the first instance the consequences of these levels of infiltration need to be identified and prioritised across the entire network.

There are no polyethylene water or wastewater sub-catchments where the operational performance can be assessed for full comparison with PVC or other pipe material systems.

6 IMPLICATIONS FOR DESIGN AND MANGEMENT OF PIPE NETWORKS

6.1.1 DESIGN AND CONSTRUCTION MEASURES

PRESSURE NETWORKS

The water supply network repair rates should be useful in assessing future performance and response requirements to seismic damage in pressured wastewater networks. Pressure sewer networks will require a greater number of repairs to be completed to restore service initially, but overall will experience quicker recovery times than a gravity wastewater option.

PVC pipes showed higher failure rates in areas of high liquefaction, and alternative jointing systems should be considered for such areas including improvement or avoidance of rubber ring jointing systems. Well-constructed polyethylene pipe in pressure networks showed high levels of performance even in highly liquefied areas.

The high number of failures observed in polyethylene sub-mains and cross overs indicate particular attention is required for polyethylene fitting selection and junction detailing of sub-mains and service connections. Reported experience, by some Delivery teams in SCIRT, was that where pressure testing was required on small diameter pressure sewer connections, electro-fusion welded fittings and jointing was preferred over mechanical couplers, as the pressure tests were a lot more successful.

A better understanding of the reasons for higher repair rates in older PVC pipes is required including assessing if the repair rates are significantly different from other older materials. This has been attributed by Cubrinovski et al (2014) as possibly due to improved pipe bedding and backfill requirements, but there are also a number of other factors that could cause the higher failure rates of older pipes.

GRAVITY NETWORKS

The increased infiltration rates observed in gravity wastewater networks require further investigation to prioritise the observed increases against other increases over the entire network and to determine the causes of the infiltration. Particular design, detailing and construction attention is required to minimise infiltration in new wastewater pipes (regardless of pipe material). This includes control of construction inflows, attention to pipe support, jointing and connections to ancillary manhole structures.

A better understanding of the reasons for higher repair rates in older PVC pipes is required to investigate if this is significantly different from other materials.

6.2 ASSET MANAGEMENT MEASURES

The ability to provide the pre-event performance standard or asset condition is a major limitation in being able to define the seismic performance of the pipe networks. This requires a good understanding of the both the pipework performance and surrounding environment such as groundwater levels, population changes prior to the event. Asset and environmental data is key to achieving this. However, there are limits to maintaining full knowledge of pipe condition and performance throughout the network on a continuous basis. Key indicators of the network performance include:

- Operational records (eg pump run hours, flow records from permanent flow metering)
- Pipe failure and repair records
- Groundwater levels
- Rainfall records
- Population changes
- Non domestic water use/metering (flow records)

Of these parameters, the variations in groundwater levels are usually the least understood and is also the most difficult to estimate retrospectively, but remains an important factor in understanding infiltration into wastewater networks.

6.3 ONGOING WORK

Assessment of the long term effects of the Canterbury Earthquakes on the water and wastewater pipe networks is ongoing. Recent focus has been directed by climatic events towards controlling the effects of inflows to the wastewater network and limiting overflows to the environment. Over time a fuller picture will be obtained from operational records of the networks. The ability to attribute these effects to the earthquakes will also depend on the level of understanding of other environmental factors affecting the operation of the networks.

7 CONCLUSIONS

Effective measures of pipe performance need to be simple to be undertaken and the limitations of the performance measures understood. Performance measures vary according to the level of criticality of damage that is being assessed. Assessment of full seismic performance, incorporating non-critical defects, will be on going as they become evident during operation of the network.

Repair rates have been widely used as an initial measure of damage to the water supply and wastewater pipe networks in Christchurch following the 2010/2011 earthquakes. They are a measure of the efforts to restore initial service and are largely based on the fundamental assumption that low levels of repairs were undertaken prior to the earthquakes. These show good performance of PVC and polyethylene pipes compared to other pipe materials. Consequently, PVC pipe has been used for reconstruction of gravity wastewater pipe networks and polyethylene pipe for the replacement of pressure pipe in the repair and reconstruction of the water and wastewater networks.

Moderate to extensive damage occurred in both pressure and gravity PVC pipe networks in areas of severe liquefaction, with damage also more prevalent in older pipe. Based on field observations and assessments of repairs completed to date, the majority of this damage is believed to be related to ground conditions and joint failures (either at the rubber ring socket or with mechanical couplers). Less than ten repairs were required to polyethylene wastewater or water-mains following the 2010/2011 earthquakes. This includes replacement water mains and wastewater pressure mains in some of the worst areas of lateral spread and liquefaction adjacent to the Avon River following the September 2010 earthquake which were undamaged in the 2011 earthquakes. Small diameter polyethylene sub-mains and cross overs experienced moderately high failure and repair rates. This suggests the need for improved future detailing and fitting selection for the construction of polyethylene sub-mains. Pressure testing quality controls prior to acceptance of newly constructed small diameter polyethylene pipe sub-mains and cross overs is also considered important to ensure resilient small diameter polyethylene pipework.

Gravity PVC pipe networks showed significantly lower repair rates than pressure pipe networks. Ongoing operational issues are evident in some wastewater catchments, with increased infiltration rates and blockages not attributable to other effects evident in three of the four catchments investigated for this paper. Pump operation records show increases in infiltration rates are evident in night-time flows, average dry weather flows and the proportion of infiltration in total wastewater flows has increased after the earthquakes. Records for PS72catchment show increased infiltration rates for a given groundwater level following the earthquakes.

Operational effects that are not critical to the regular service of the networks are more complex to assess and require assessment of other environmental factors affecting the performance of the networks. In some cases, these factors are not fully understood and improved understanding of these factors prior to seismic events will assist in assessing network performance. Collection and assessment of simple relevant asset management data (such as rainfall, pump operation, pipe repairs and groundwater levels) is key to achieve this.

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