Technical Note 7 – Kaiapoi Wastewater Damage

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Technical Note 7 – Kaiapoi Wastewater Damage

1 Executive Summary

In September 2010 the Darfield earthquake caused extensive damage to wastewater reticulation system in parts of Kaiapoi and ProjectMax Ltd completed damage assessments in 2010. This report discusses the evaluation of these to determine damage trends and the frequency of damage.

The findings from this report can be used by asset managers to assess the vulnerability of wastewater and stormwater networks to seismic events.

Works to repair damage have been categorised as follows:

- Restoration – works required on damage that stopped the wastewater system from functioning and was required to be repaired to restore service;
- Reinstatement – works requiring further damage, on top of damage repaired to restore service, that was required to reinstate the system to its pre-earthquake condition.

1.1 Restoration Works

The earthquake caused sections of the wastewater system in Kaiapoi to be damaged and service to be lost.

After the earthquake liquefied material entered the system through gully traps, pre-existing faults and earthquake related damage in both the private and public sections of the wastewater network. The liquefied material blocked the system and stopped service. In some cases, service was lost for up to 22 days.

The liquefied material had to be flushed from the pipelines and damaged sections repaired. Flushing and damage repair often had to be undertaken several times before service could be restored.

Restoration works involved repairing pipes by spot excavation or by the installation of CIPP (Cured in Place Pipe) patches. These works were primarily undertaken to limit the amount of liquefied material entering into the system and to reduce the likelihood of further blockages occurring.

The performance of the wastewater system was influenced significantly by the behaviour of the ground and varied depending on pipe material.

- In areas that did not liquefy service generally continued without interruption. There was only a small amount of damage that required repair;
- In areas affected by liquefaction or lateral spread the wastewater system was generally unable to function until the pipes had been repaired and unblocked;
- About two to three times more breaks occurred in areas of lateral spread than in areas of liquefaction;

- The majority of damage occurred at pipe joints. Damage within the pipe barrel tended to be limited to earthenware and asbestos cement pipes. Damage was observed at lateral connections in only three cases. No faults were specifically recorded at manholes, although some of these faults may have been recorded as pipe faults;

- Asbestos cement and earthenware pipes sustained about three times more damage than concrete pipes. Concrete pipes sustained three times more damage than PVC pipes.

1.2 Reinstatement Works

Additional assessments were undertaken after service had been restored to identify works needed to return the network to a condition similar to what existed prior to the earthquake. This involved undertaking further repairs and patching. In some cases, pipes were relaid or rehabilitated by structural lining due to the extent of damage sustained.

A lot more damage was required to be repaired to reinstate the system to the pre-earthquake condition than was required to restore service. For example, in areas that did not liquefy up to ten times more damage required repair.

Again the amount of damage depended on the performance of the ground and varied depending on pipe materials.

- Pipes in areas that did not liquefy suffered a lot less damage than pipes in areas that liquefied. Pipes in areas of lateral spread suffered the most damage, e.g. for concrete pipes 1% required relay/rehabilitation due to damage in areas that did not liquefy, 10% in areas of liquefaction and 40% in areas of lateral spread;

- Asbestos cement and earthenware pipes suffered more damage and were more likely to be relaid or rehabilitated than concrete pipes. PVC pipes sustained the least amount of damage. Damage to PVC pipes could typically be repaired through patching or spot repairs rather than relays or rehabilitation;

- All pipes in areas of liquefaction or lateral spread were susceptible to dipping. The extent of dipping was unaffected by pipe material, with about 40% of all pipes being affected. The amount of asbestos cement and earthenware pipes recorded as containing dips but no damage was less than for other materials but this was because a lot of the dipped pipes needed to be relaid because they were also damaged;

- Where pipes required relay/rehabilitation due to damage, approximately half were suitable for rehabilitation with structural lining in areas where there was no liquefaction. About a quarter were suitable for such rehabilitation in areas where liquefaction or lateral spread occurred.

Pipes with dips have been scheduled separately in this report as they will not always require repair. It may be more appropriate to accept the dip, acknowledging that more frequent jetting may be required to remove material that might accumulate at the dip. This may be the case in pipelines where:

- The consequence of the pipe blocking is not high; and

- The existing pipeline can tolerate frequent jetting. This is more likely to be the case with PVC, PE or concrete pipes and less likely the case with earthenware or asbestos cement pipes where frequent jetting may damage the pipe wall. Lined pipelines can also tolerate more frequent jetting.

1.3 Application of Findings to Improve Resilience

1.3.1 Restoration of Service

Prediction of the amount of damage that might need to be repaired to restore service enables asset managers to establish which parts of the system might be affected by an earthquake. They can also estimate the time it will take to restore service. This information assists:

- Communication with stakeholders
- Planning response activities
- Identifying priorities and estimating the amount of resources that might be required
- Prioritising renewal works to improve resilience

Table 1-1 provides damage rates for estimating the likely extent of damage that may need to be repaired to restore service. It is likely that most of this damage could be repaired by CIPP patching with some spot repairs by open cut excavation being required where pipes cannot be patch repaired – for example where pipes have been displaced or where pipe fragments or other debris protrudes into the pipe barrel.

Table 1-1: Damage Rates for Restoring Service

Ground Conditions	Pipe Material	Damage Rate (Breaks/10km)
Shaking only, no liquefaction (for PGA in the range of 0.2 – 0.3g)	All	Nominal, 0.3
Liquefied	AC & EW	250
	RCRRJ	70
	PVC	20
Lateral Spread	AC & EW	500
	RCRRJ	160
	PVC	50

Further research is required to establish damage rates for peak ground accelerations above 0.3g in areas that do not liquefy.

1.3.2 Reinstatement of Condition

Prediction of the additional amount of damage that might need to be repaired to reinstate the system to the pre-earthquake condition enables asset managers to:

- Quantify the amount of damage that will be required to be repaired, e.g. for insurance and planning purposes
- Prioritise renewal works to improve resilience

Table 1-2 provides damage rates for estimating the likely extent of additional damage that may need to be repaired to return the system to a condition that is similar to what existed prior to the earthquake.

Table 1-2: Damage Rates for Reinstating Condition

Ground Performance	Pipe Material	Frequency of works to reinstate condition		
		Spot Repair Breaks/10km	Relay/Rehab (% of Length)	Dip (<25%) (% of Length)
Shaking only, no liquefaction (for PGA in the range of 0.2 – 0.3g)	AC & EW	9	6%	Minimal
	RCRRJ	1	0.6%	4%
	PVC	0.5	Minimal	4%
Liquefied	AC & EW	35	40%	30%
	RCRRJ	12	10%	39%
	PVC	3	Minimal	39%
Lateral Spread	AC & EW	-	100%	-
	RCRRJ	-	40%	40%
	PVC	-	5%	50%

It is likely that all asbestos cement and earthenware pipes with dips greater than 25% will need to be relaid. It may be more appropriate to accept the dips in concrete and PVC pipes, acknowledging that more frequent jetting may be required to remove material that might accumulate at the dip.

Approximately half of the pipes requiring relay or rehabilitation may potentially be suitable for rehabilitation by structural lining. Lining may also be u a dipped pipe to be regularly cleaned. If dips are to be removed, then the pipes will usually need to be relaid.

Further research is required to establish damage rates for peak ground accelerations above 0.3g in areas that did not liquefy, as there was insufficient information to determine this.

2 Background

2.1 Darfield Earthquake

The magnitude 7.1 Darfield earthquake occurred at 4:36 am on 4 September 2010. The epicentre of the earthquake was located to the south east of Darfield, as shown in Figure 2-1. The earthquake was relatively shallow, at a depth of about 10 kilometres. It caused extensive damage to parts of Christchurch and Kaiapoi, as well as at locations closer to the epicentre (GNS Science, 2016).

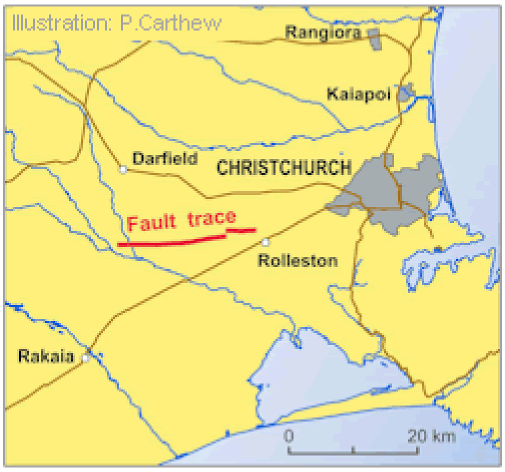


Figure 2-1: Location of Darfield Earthquake

Figure 2-2 shows the Kaiapoi wastewater network with overlays of the estimated peak ground accelerations (O'Rourke, Toprak, Cubrinovski, Jung, & Jeon, 2012) and areas where liquefaction and lateral spread (Tonkin & Taylor Ltd, 2013) were recorded.

Peak ground accelerations in Kaiapoi ranged from 0.2 to 0.3g.

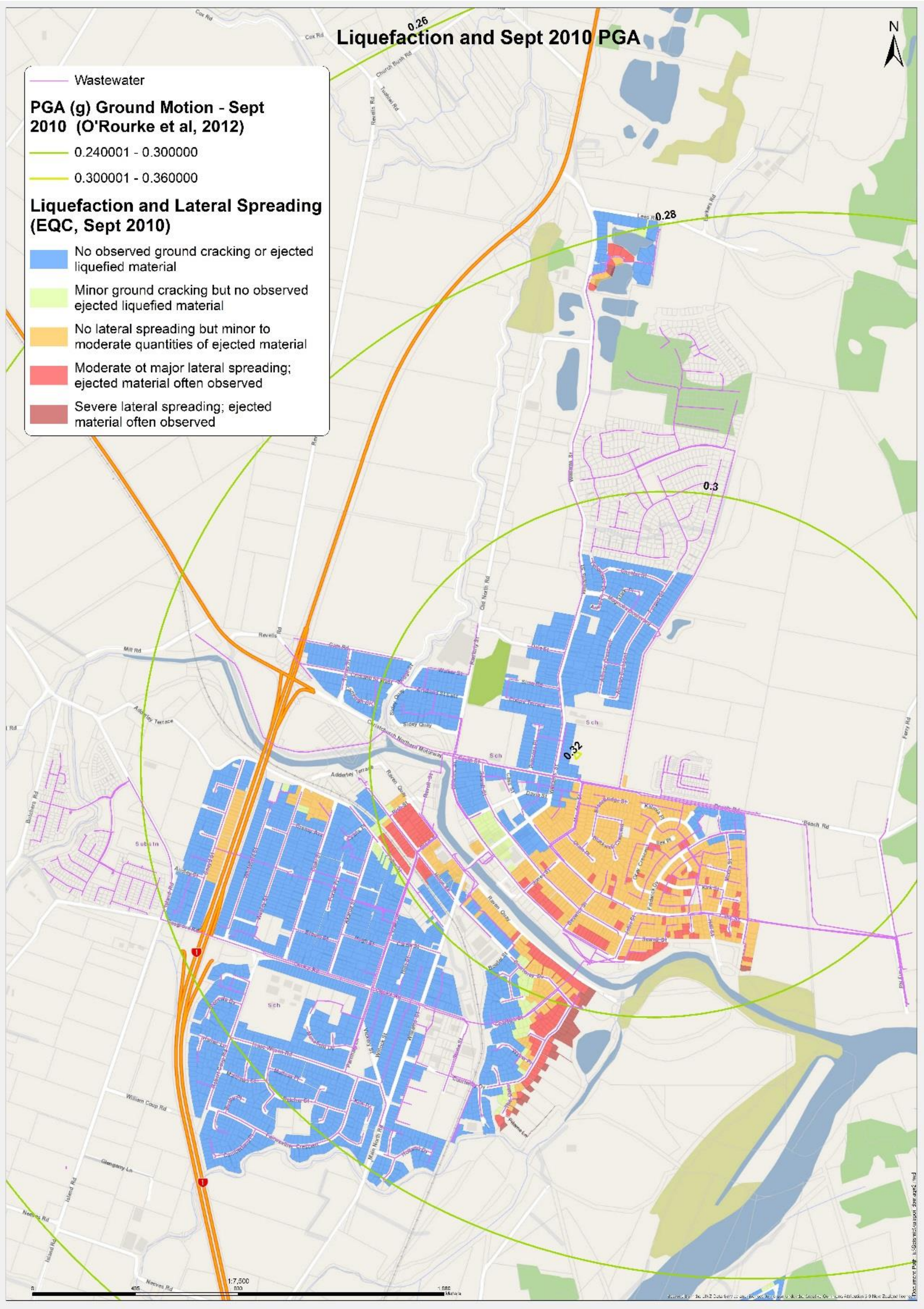


Figure 2-2: Kaiapoi Wastewater Network and Peak Ground Accelerations and Liquefaction and Lateral Spread Resulting from the Darfield Earthquake

2.2 Overview of Wastewater Network

The Kaiapoi wastewater network includes 42km of pipework. The majority of the pipes are 150mm & 225mm diameter.

Figure 2-3 provides an overview of the pipe materials in the network and the proportion of the network that was subjected to liquefaction or lateral spread. The majority of pipes are reinforced concrete pipes (55%) followed by PVC (30%). There are also earthenware and asbestos cement pipes.

Only 12km of pipework (28%) is located in areas where either liquefaction or lateral spread occurred.

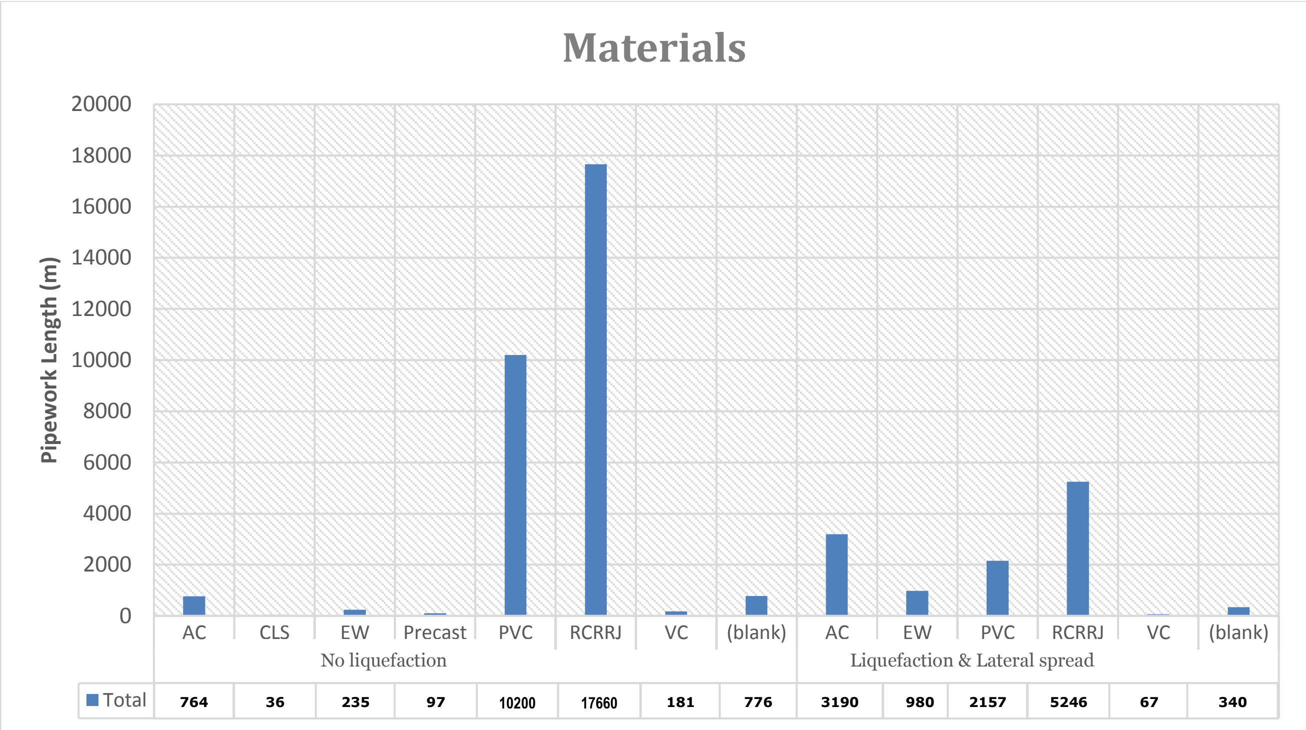


Figure 2-3: Overview of Pipe Materials

2.3 Ground Performance

The earthquake caused sections of land to liquefy and in some cases for lateral spread to occur. Areas of liquefaction and lateral spread noted by (Tonkin & Taylor Ltd, 2013) are indicated in orange & red areas in Figure 2-2.

Wotherspoon compared the extent of liquefaction predicted by analysis undertaken prior to the Darfield Earthquake with what actually occurred, as shown in Figure 2-4 (Liam M. Wotherspoon, 2012). Whilst there are differences between the extent of liquefaction recorded by Wotherspoon (Figure 2-4) and that noted by Tonkin & Taylor (Figure 2-2) these differences are not significant.

The predicted extent of liquefaction corresponds reasonably well with what actually occurred. The locations where the ground liquefied, but this had not been predicted, were located in reclaimed land which had been built over historic streams.

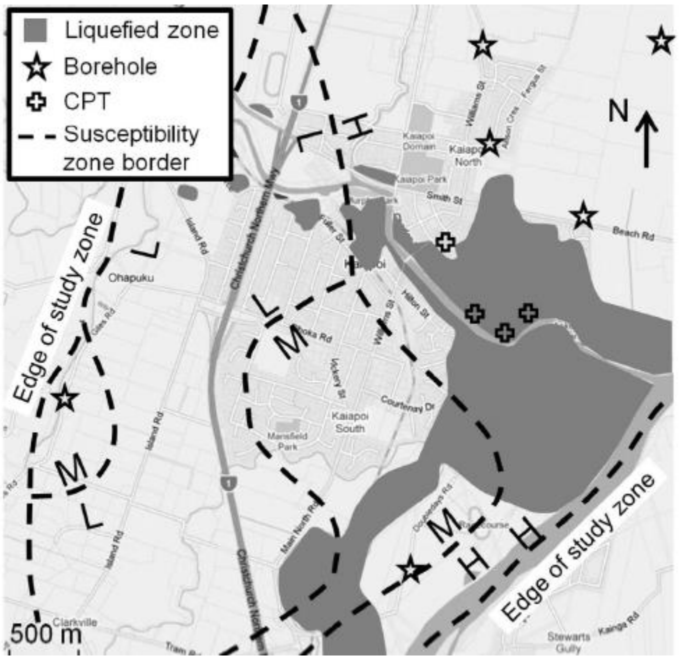


Figure 2-4: Map of Kaiapoi indicating high (H), medium (M) and low (L) liquefaction susceptibility zones defined by Christensen (2001) and areas that liquefied during 2010 Darfield event (Liam M. Wotherspoon, 2012)

2.4 The Impact of the Earthquake on the Wastewater System

The earthquake caused the wastewater system to be damaged and service to be lost, in some cases for up to 22 days. Loss of service was generally associated with areas affected by liquefaction or lateral spread.

Liquefied material entered the system through gully traps, pre-existing faults and earthquake related damage in both the private and public sections of the wastewater network. The liquefied material blocked the system and stopped service.

The liquefied material had to be flushed from the pipelines and damaged sections repaired. Flushing and damage repair often had to be undertaken several times before service could be restored.

Restoration works involved repairing pipes by spot excavation or by the installation of CIPP patches. These works were primarily undertaken to limit the amount of liquefied material entering into the system and to reduce the likelihood of further blockages occurring.

Additional assessments were undertaken after service had been restored to identify further works needed to return the system to a condition similar to what existed prior to the earthquake. This involved undertaking further spot repairs or patching. It was also proposed that sections of pipe be relaid or rehabilitated due to the extent of damage.

Pipe damage was assessed by ProjectMax Ltd in 2010 either as part of the restoration works or for scoping of reinstatement works. This report is based on those assessments.

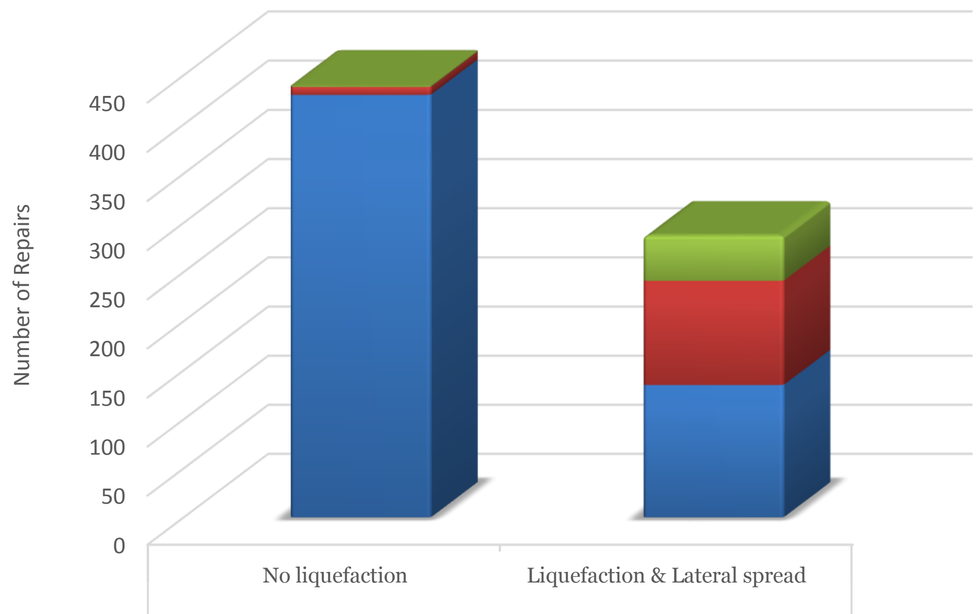
In some cases, ProjectMax noted that pipes had sustained dips or minor damage due to the earthquake but they considered that this damage was not severe enough to warrant repair.

3 Restoring Service

3.1 Works Required to Restore Service

Immediately after the earthquake works were undertaken to restore service. Pipes were repaired by spot excavation and by the installation of CIPP patches. These works were primarily undertaken to limit the amount of liquefied material entering into the system and reduce the likelihood of further blockages occurring.

Figure 3-1 shows the number of repairs required to restore service. The vast majority of the repairs were undertaken in areas where Tonkin & Taylor observed liquefaction or lateral spread.



	No liquefaction	Liquefaction & Lateral spread
Spot Repair by Excavation	1	46
Patch	8	106
Do Nothing	430	135

Figure 3-1: Restoration Works (Based on Liquefaction Areas Recorded by Tonkin & Taylor)

3.2 Review of Works to Restore Service in Areas that Did Not Liquefy

Only four of the pipes that required repair to restore service were located in areas where Tonkin & Taylor did not observe liquefaction or lateral spread. One of these pipes required multiple repairs. Figure 3-2 shows the location of these pipes. The pipes were all concrete.

Three of these pipes were located in areas where Wotherspoon noted liquefaction. Therefore, for analysis purposes these three pipes have been treated as being within areas of liquefaction.

Only one of these pipes, at Wesley Street, was located where neither party observed liquefaction or lateral spread. This pipe required a patch to be installed to seal a faulty joint with running infiltration. The damage to this pipe represents a damage rate of 0.3 breaks per 10km.

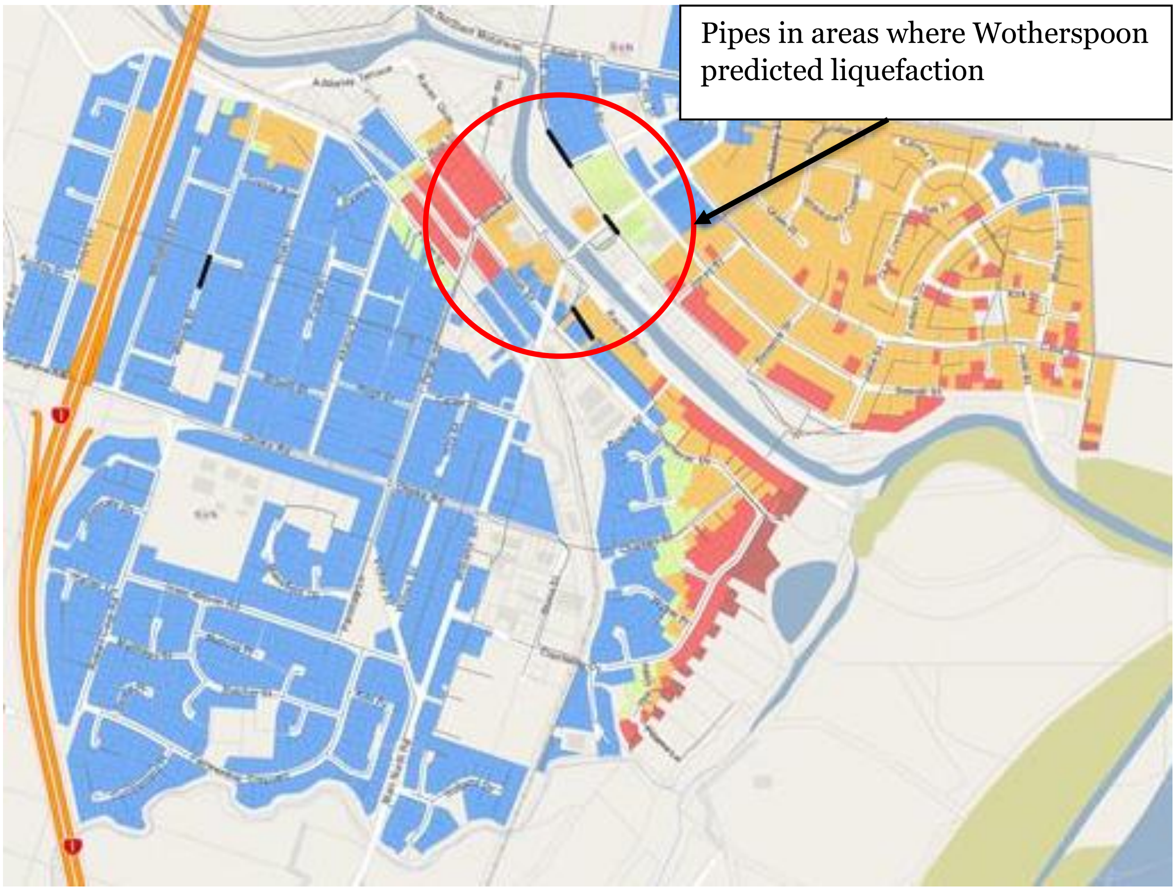


Figure 3-2: Damage in Areas where Tonkin & Taylor did not record liquefaction

3.3 Review of Works to Restore Service in Areas of Liquefaction or Lateral Spread

Figure 3-3 shows the quantity of restoration works undertaken in the areas where liquefaction or lateral spread occurred.

The majority of repairs (85%) were undertaken on asbestos cement or earthenware (AC/EW) pipes, even though these pipes make up only 38% of the network. 77% of the asbestos cement and earthenware pipes required repair, compared to 39% of reinforced concrete pipes and only 15% of PVC pipes.

The damage sustained on asbestos cement and earthenware pipes that was required to be repaired to restore service represents a break rate of 255 breaks per 10km. All of this damage was sustained in areas subjected to liquefaction. There were no asbestos cement or earthenware pipes installed in areas where lateral spread occurred.

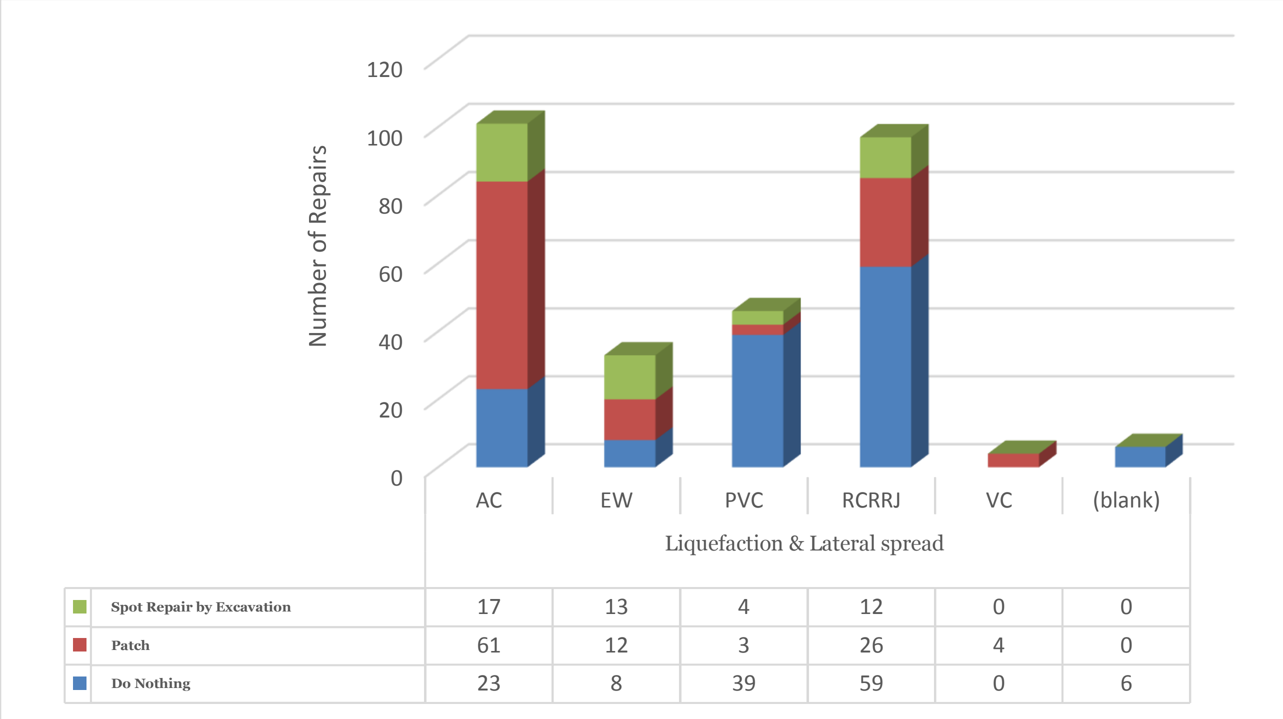


Figure 3-3: Restoration Works in Areas Where Liquefaction or Lateral spread occurred

3.3.1 Further Analysis of PVC & Concrete Pipes in Areas of Liquefaction & Lateral Spread

Table 3-1 shows the amount and type of damage sustained by PVC and concrete pipes that was required to be repaired to restore service. Damage in areas that liquefied and those where lateral spread occurred are shown separately.

Table 3-1: PVC and RCRRJ Pipe Damage from Liquefaction or Lateral Spread

Pipe Material	Ground Performance	Joint Faults (no.)	Connection Faults (no.)	Unknown Faults (no.)	Break Rate (Breaks/10km)
RCRRJ	Liquefied	27	1	2	69
	Lateral Spread	10	-	5	160
PVC	Liquefied	2	-	-	17
	Lateral Spread	3	2	-	50

This analysis indicates that:

- PVC pipes performed better than concrete pipes in both liquefied ground and when lateral spread occurred. The same conclusion was made by Cubrinovski, Hughes, & O'Rourke (2014) for PVC pipes and pipes from other ductile materials in watermains;
- Damage rates in areas of lateral spread were 2 to 3 times that experienced when only liquefaction occurred. This is similar to the Christchurch water system where double to triple the number of breaks occurred;

- The majority of the faults occurred at pipe joints with only three faults occurring at lateral connections. No faults were specifically recorded as occurring at manholes, although some of these faults may have been recorded as pipe faults.

3.3.2 Proposed Break Rates to Restore Service

In view of the above, it is proposed that the damage rates in Table 3-2 be used for predicting the amount of damage required to be repaired to restore service.

The proposed damage rate for asbestos cement pipes and earthenware pipes in areas of lateral spread has been determined by multiplying by two the damage rate for these materials in areas where only liquefaction occurred, as only nominal lengths of asbestos cement pipes and earthenware pipe were located in areas of lateral spread. This is in line with the increased break rate observed in PVC but the ratio is smaller because asbestos cement and earthenware pipes are more sensitive to permanent ground movements due to liquefaction and lateral spreading does not add as much damage to the already damaged pipes.

Table 3-2: Damage Rates to Restore Service

Ground Conditions	Pipe Material	Break Rate (Breaks/10km)
Shaking only, no liquefaction[1]	All	Nominal, less than 0.3
Liquefied	AC & EW	250
	RCRRJ	70
	PVC	20
Lateral Spread	AC & EW	500
	RCRRJ	160
	PVC	50

1 For a PGA of 0.2-0.3g

4 Works Required to Reinstate to Pre-Earthquake Condition

4.1 Overview

Further CCTV was completed once service had been restored and an assessment was undertaken to establish the works required to return the network to its pre-earthquake condition. Table 4-1 summarises the types of additional works proposed to be undertaken.

Table 4-1: Types of Work Required to Reinstate Condition to Pre-Earthquake Condition

Code	Description of Required Works
Patch 2	CIPP patches in addition to those required to restore service. Proposed on pipelines that only had a few isolated areas damage, typically at joints, and the damage did not displace the joint or protrude into the pipeline.
Spot Repair by Excavation 2	Spot repairs by excavation in addition to those required to restore service. Proposed on pipelines that only had a few isolated areas damage, which was not suitable for repair with CIPP patches. Spot repairs were typically proposed where there was displacement at pipe joints or the damage protruded into the pipeline.
Rehabilitation	Rehabilitation by lining. This was proposed when the pipeline: • contained damage that was too extensive for patching or spot repairs, i.e. more than 3 sections of damage, and • there was no displacements (<10%), protruding damage (<10%) or dips (<25%)
Relay	Relaying by opencut excavation. This was proposed when the pipeline: • contained damage that was too extensive for patching or spot repairs, i.e. more than 3 sections of damage, and • there were displacements (<10%), protruding damage (<10%) or dips (<25%)
Dip>25%	The pipeline is not damaged, but is dipped by more than 25% of the diameter.
Accept	The pipeline contained minor damage which appeared to have been caused by the earthquake, e.g. cracking where there was no evidence that it extended through to the outside of the pipe wall, or the pipe was dipped by less than 25% of the diameter.
No earthquake damage	The pipeline did not contain any damage that appeared to have been caused by the earthquake.
Re-inspect	CCTV inspection was not clear enough to make a decision

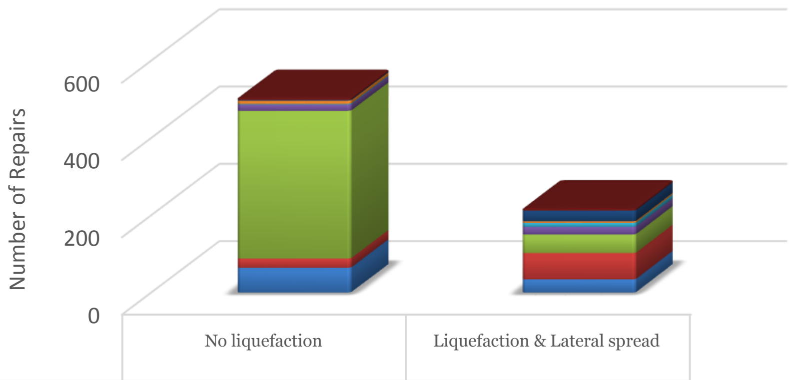
Dips have been scheduled separately as they will not always require repair. It may be appropriate to accept some dips, acknowledging that more frequent jetting may be required to remove material that might accumulate at dips.

This may be the case in pipelines where:

- The consequence of the pipe blocking is not high; and
- The existing pipeline can tolerate frequent flushing. This is more likely to be the case with PVC, PE or concrete pipes and less likely the case with earthenware or asbestos cement pipes where frequent jetting may damage the pipe wall.

Figure 4-1 shows the quantum of further works required to reinstate the system to pre-earthquake condition.

The vast majority of damage occurred in areas where liquefaction or lateral spread occurred.

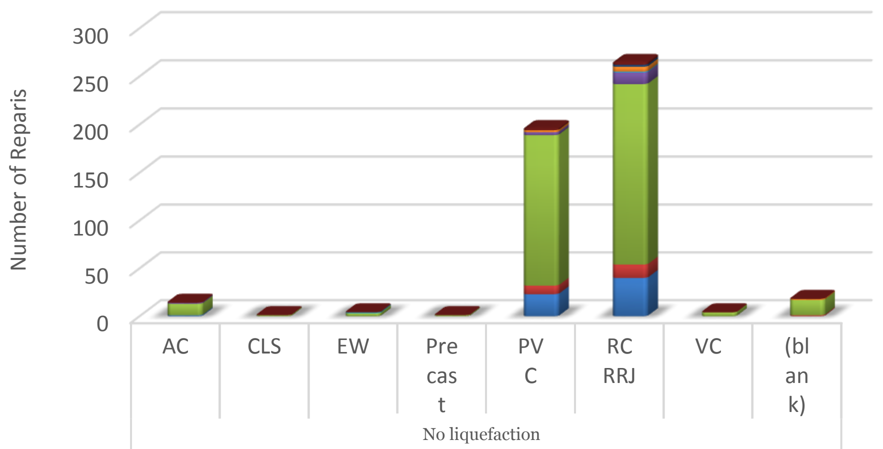


	No liquefaction	Liquefaction & Lateral spread
Spot Repair by Excavation 2	5	5
Relay	2	28
Reinspect	8	4
Rehabilitate	2	10
Patch 2	16	20
No Earthquake Damage	382	48
Dip >25%	24	68
Accept	64	34

Figure 4-1: Total works Required to Reinstate to Pre-Earthquake Condition

4.2 Review of Works to Reinstate Condition in Areas that Did Not Liquefy

Figure 4-2 shows the quantum and category of works required to reinstate the network to its pre-earthquake condition in areas that did not liquefy.



	AC	CLS	EW	Precast	PVC	RC RRJ	VC	(blank)
Spot Repair by Excavation 2	0	0	0	0	2	3	0	0
Relay	0	0	0	0	0	2	0	0
Reinspect	0	0	0	0	2	5	0	1
Rehabilitate	0	0	1	0	0	1	0	0
Patch 2	1	0	0	0	3	12	0	0
No Earthquake Damage	12	1	3	1	157	188	4	16
Dip >25%	0	0	0	0	9	14	0	1
Accept	1	0	0	0	23	40	0	0

Figure 4-2: Works Required to Reinstate to Condition in Areas that did not liquefy

Table 4-2 shows the frequency of damage. This is expressed in terms of:

- Break rates (Breaks/10km) where spot repairs or patches are required; or
- Percentages of the pipe type affected where the full length of the pipeline is affected.

For simplicity, Table 4-2 and similar subsequent tables have been grouped as follows:

- ‘Patching’ and ‘Spot repair by excavation’, refering to this grouping as ‘Spot Repair’;
- ‘Rehabilitation’ and ‘Relay’, refering to this grouping as ‘Relay/Rehab’.

Table 4-2: Frequency of Works Required to Reinstate Condition in Areas that did not Liquefy

Pipe Material	Frequency of works to reinstate condition			
	Spot Repair Breaks/10km	Relay/Rehab (% of Length)	Dip (% of Length)	Acceptable Defects (% of Length)??
AC & EW	8.5	6%	-	8%
RCRRJ	0.85	0.6%	4%	15%
PVC	0.5	-	4%	14%

Key observations are:

- A lot more damage needed to be repaired to reinstate the network to its pre-earthquake condition than was required to restore service, i.e. 8.5 breaks/10km for AC & EW to reinstate condition compared to 0.3 breaks/10km to restore service. This is to be expected as wastewater networks can normally continue to function even when they have sustained significant damage. This is particularly the case in areas where the ground did not liquefy and damage did not need to be sealed to prevent liquefied material from entering and blocking the system;

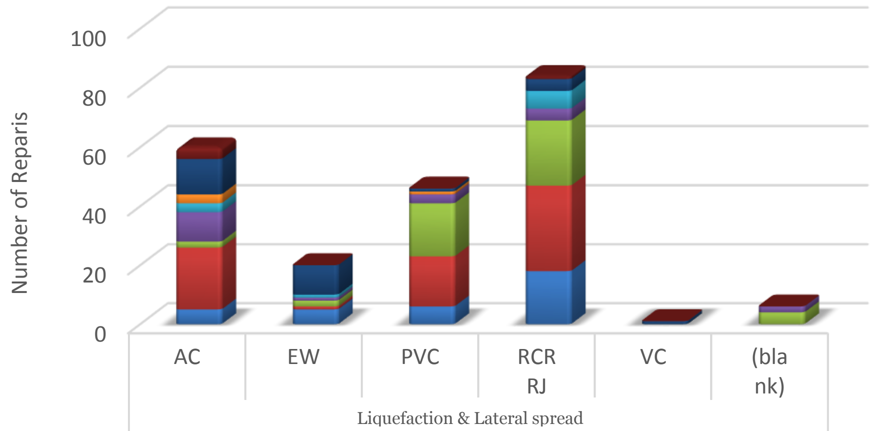
- Asbestos cement and earthenware pipes are ten times more likely to require relay or rehabilitation than concrete or PVC pipes. This reflects the brittle nature of these pipes and that their jointing systems are less able to accommodate movements;

- Where pipes required relay or rehabilitation, about half were suitable for rehabilitation by structural lining, ie 2 out of 4;

- No dips were recorded on earthenware or asbestos cement pipes. These pipe materials and jointing systems are less able to accommodate ground movements. As such they are more likely to break than dip, as can be seen from Table 4-2 where ten times as many AC & EW pipes required to be relayed than concrete pipes.

4.3 Review of Works to Reinstate Condition in Areas of Liquefaction and Lateral Spread

Figure 4-3 shows the quantum and category of further works required to reinstate the network to the pre-earthquake condition in areas where liquefaction or lateral spread occurred.



	AC	EW	PVC	RCR RJ	VC	(blank)
Spot Repair by Excavation 2	4	0	0	1	0	0
Relay	12	10	1	4	1	0
Reinspect	3	0	1	0	0	0
Rehabilitate	3	1	0	6	0	0
Patch 2	10	1	3	4	0	2
No Earthquake Damage	2	2	18	22	0	4
Dip >25%	21	1	17	29	0	0
Accept	5	5	6	18	0	0

Figure 4-3: Works to Reinstate Condition in Areas of Liquefaction or Lateral Spread

The frequency of this damage is shown in Table 4-3 with damage split between areas of liquefaction and areas of lateral spread.

Table 4-3: Frequency of Works Required to Reinstate Condition in Areas of Liquefaction and Lateral Spread

Pipe Material	Ground Performance	Frequency of works to reinstate condition			
		Spot Repair Breaks/10km	Relay/Rehab (% of Length)	Dip (% of Length)	Acceptable Defects (% of Length)??
AC & EW	Liquefied	35	36%	31%	9%
RCRRJ	Liquefied	12	10%	39%	22%
RCRRJ	Lateral Spread	-	42%	40%	9%
PVC	Liquefied	2.6	-	39%	18%
PVC	Lateral Spread	-	5%	53%	14%

Key observations are:

- Fewer spot repairs were required to reinstate to the pre-earthquake condition than were required to restore service (35 breaks/10km to reinstate AC & EW pipes compared to 255 breaks/10km to restore service) This is different from when the ground did not liquefy, which reflects the fact that most damage in liquefied areas had to be repaired to stop liquefied material from running in and blocking the pipes;

- More breaks and relays were required to be repaired to reinstate to the pre-earthquake condition in liquefied areas than in areas that did not liquefy (85 breaks/10km for AC & EW pipes in liquefied areas compared to 35 breaks/10km in areas that did not liquefy);

- Asbestos cement and earthenware pipes required significantly more spot repairs than concrete and PVC pipes. Spot repairs are generally required in areas of liquefaction. Fewer spot repairs were required where lateral spread occurred, as pipes in these areas tended to require more frequent relay or rehabilitation;

- Pipes needed to be relaid more often in areas where lateral spread occurred. 42% concrete pipes needed to be relaid due to damage in areas of lateral spread compared to 10% in areas that only liquefied;

- Almost all asbestos cement and earthenware pipes in areas of liquefaction needed to be relaid either due to damage or dips. Only 18% of asbestos cement and earthenware pipes contained no earthquake damage or acceptable defects;

- PVC pipes suffered a lot less damage requiring relay than other pipe types (5% of PVC pipes in areas of lateral spread required relay due to damage compared to 42% of concrete pipes). This also concurs with the conclusions made by (Cubrinovski, et al., Horizontal Infrastructure Performance and Application of the Liquefaction Resistance Index Methodology in Christchurch City through the 2010-2011 Canterbury Earthquake Sequence, 2015) and (East & Lowe, 2014) for wastewater pipes in liquefied areas;

- Where pipes required relay or rehabilitation due to damage, about 25% were suitable for rehabilitation with structural lining, ie 10 out of 38;

- The amount of dips greater than 25% does not vary significantly between material types. This is to be expected as it is a function of ground performance rather than material type. The amount of dips does not vary significantly between areas of lateral spread and liquefaction. Overall the average rate of dips is approximately 40%.

4.3.1 Proposed Frequency of Works to Reinstate Condition

In view of the above, it is proposed that the break rates in Table 4-4 are to be used for predicting the further amount of damage required to be repaired to reinstate condition after service has been restored.

Table 4-4: Rates for Predicting Damage Requiring Repair to Reinstate

Ground Performance	Pipe Material	Frequency of works to reinstate condition		
		Spot Repair (Breaks/10km)	Relay/Rehab (% of Length)	Dip (<25%) (% of Length)
Shaking only, no liquefaction (for PGA in the range of 0.2 – 0.3g)	AC & EW	9	6%	Minimal
	RCRRJ	1	0.6%	4%
	PVC	0.5	Minimal	4%
Liquefied	AC & EW	35	40%	30%
	RCRRJ	12	10%	39%
	PVC	3	Minimal	39%
Lateral Spread	AC & EW	-	100%	-
	RCRRJ	-	40%	40%
	PVC	-	5%	50%

5 Conclusions

Damage has been categorised as follows:

- Restoration – damage that stopped the wastewater system from functioning and was required to be repaired to restore service;
- Reinstatement – further damage, on top of damage repaired to restore service, that was required to be repaired to reinstate the system to its pre-earthquake condition.

5.1 Restoration Works

The performance of the wastewater system was influenced significantly by the behaviour of the ground and varied depending on pipe material.

- In areas that did not liquefy, service generally continued without interruption. Only minimal damage was required to be repaired;
- In areas affected by liquefaction or lateral spread the wastewater system was generally unable to function until the pipes had been repaired and unblocked;
- About two to three times more breaks occurred in areas of lateral spread than in areas of liquefaction;
- The majority of damage occurred at pipe joints. Damage within the pipe barrel tended to be limited to earthenware and asbestos cement pipes. Damage was observed at lateral connections in only three cases. No faults were specifically recorded at manholes, although some of these faults may have been recorded as pipe faults;
- Asbestos cement and earthenware pipes sustained about three times more damage than concrete pipes. Concrete pipes sustained three times more damage than PVC pipes.

5.2 Reinstatement Works

The amount of damage depended on the performance of the ground and varied depending on pipe materials.

- Pipes in areas that did not liquefy suffered a lot less damage than pipes in areas that liquefied. Pipes in areas of lateral spread suffered the most damage, e.g. for concrete pipes 1% required relay/rehabilitation due to damage in areas that did not liquefy, 10% in areas of liquefaction and 40% in areas of lateral spread;
- Asbestos cement and earthenware pipes suffered more damage and were more likely to require to be relaid or rehabilitated than concrete pipes. PVC pipes sustained the least amount of damage. Damage to PVC pipes could typically be repaired through patching or spot repairs rather than relays or rehabilitation being required;
- Where pipes required relay/rehabilitation due to damage in areas where there was no liquefaction, approximately half were suitable for rehabilitation with structural lining. About a quarter were suitable for rehabilitation in areas where liquefaction or lateral spread occurred;

- All pipes in areas of liquefaction or lateral spread were susceptible to dipping. The amount of dipping was unaffected by pipe material, with about 40% of pipes being affected. However, the amount of asbestos cement and earthenware pipes recorded as containing dips but no damage was less than for other materials as a lot of the dipped pipes needed to be relaid because they were also damaged.

Pipes with dips have been scheduled separately in this report as they will not always require repair. It may be more appropriate to accept the dip, acknowledging that more frequent jetting may be required to remove material that might accumulate at the dip. This may be the case in pipelines where:

- The consequence of the pipe blocking is not high; and

- The existing pipeline can tolerate frequent jetting. This is more likely to be the case with PVC, PE or concrete pipes and less likely the case with earthenware or asbestos cement pipes where frequent jetting may damage the pipe wall.

5.3 Frequency of Damage

5.3.1 Restoration of Service

Table 5-1 provides damage rates for estimating the likely extent of damage that may need to be repaired to restore service. It is likely that most of this damage could be repaired by CIPP patching with some spot repairs by open cut excavation being required where pipes have displayed or damage protrudes into the pipe barrel.

Table 5-1: Damage Rates for Restoring Service

Ground Conditions	Pipe Material	Damage Rate (Breaks/10km)
Shaking only, no liquefaction **(for PGA in the range of 0.2 – 0.3g)**	All	Nominal, 0.3
Liquefied	AC & EW	250
	RCRRJ	70
	PVC	20
Lateral Spread	AC & EW	500
	RCRRJ	160
	PVC	50

Further research is required to establish damage rates for peak ground accelerations above 0.3g in areas that do not liquefy.

5.3.2 Reinstatement of Condition

Table 5-2 provides damage rates for estimating the likely extent of damage that may need to be repaired, after service is restored, to return the system to a condition that is similar to what existed prior to the earthquake.

Table 5-2: Damage Rates for Reinstating Condition

Ground Performance	Pipe Material	Frequency of works to reinstate condition		
		Spot Repair (Breaks/10km)	Relay/Rehab (% of Length)	Dip (<25%) (% of Length)
Shaking only, no liquefaction (for PGA in the range of 0.2 – 0.3g)	AC & EW	9	6%	Minimal
	RCRRJ	1	0.6%	4%
	PVC	0.5	Minimal	4%
Liquefied	AC & EW	35	40%	30%
	RCRRJ	12	10%	39%
	PVC	3	Minimal	39%
Lateral Spread	AC & EW	-	100%	-
	RCRRJ	-	40%	40%
	PVC	-	5%	50%

It is likely that all asbestos cement and earthenware pipes with dips greater than 25% will need to be relaid. It may be more appropriate to accept the dips in concrete and PVC pipes, acknowledging that more frequent jetting may be required to remove material that might accumulate at the dip.

Approximately half of pipes requiring relay or rehabilitation due to damage in areas where liquefaction did not occur may be suitable for rehabilitation by structural lining. About a quarter of the pipes in areas where liquefaction or lateral spread occurred may be suitable for rehabilitation. If dips are to be removed, then the pipes will need to be relaid.

Further research is required to establish damage rates for peak ground accelerations above 0.3g in areas that did not liquefy.

6 Bibliography

Bredley, B. A., & Hughes, M. (2012). *Conditional Peak Ground Accelerations in the Canterbury Earthquakes for Conventional Liquefaction Assessment*. Christchurch: Department of Building and Housing.

Cubrinovski, M., Hughes, M., & O'Rourke, T. D. (2014). Impacts of liquefaction on the potable water system of Christchurch in the 2010-2011 Canterbury (NZ) earthquakes. *Journal of Water Supply: Research and Technology - AQUA*, 95-105.

Cubrinovski, M., Hughes, M., Bradley, B., McCahon, I., McDonald, Y., Simpson, H., . . . O'Rourke, T. (2011). *Liquefaction Impacts on Pipe Networks*. Christchurch: University of Canterbury.

Cubrinovski, M., Hughes, M., Bradley, B., Noonan, J., McNeill, S., English, G., & Sampedro, I. G. (2015). *Horizontal Infrastructure Performance and Application of the Liquefaction Resistance Index Methodology in Christchurch City through the 2010-2011 Canterbury Earthquake Sequence*. Christchurch: University of Canterbury.

East, A. J., & Lowe, A. C. (2014). *Investigation into the loss of grade of the Christchurch Wastewater Pipe Network after the 2010-11 Earthquakes*. Christchurch: University of Canterbury.

GNS Science. (2016, September 7). *2010 Darfield (Canterbury) Earthquake*. Retrieved from GNS Science: http://www.gns.cri.nz/Home/Our-Science/Natural-Hazards/Recent-Events/Canterbury-quake/Darfield-Earthquake

Liam M. Wotherspoon, M. J. (2012). Relationship between observed liquefaction at Kaiapoi following the 2010 Darfield earthquake and former channels of the Waimakariri River. *Engineering Geology 125*, 45-55.

O'Rourke, T. D., Toprak, S., Cubrinovski, M., Jung, J. K., & Jeon, S. S. (2012). 15th World Conference on Earthquake Engineering 2012 (15WCEE). *Underground lifeline system performance during the Canterbury earthquake sequence*. Lisbon: Sociedade Portuguesa de Engenharia Sismica.

Tonkin & Taylor Ltd. (2013). *Liquefaction vulnerability study*. Earthquake Commission.