PIPELINE PERFORMANCE EXPERIENCES DURING SEISMIC EVENTS IN NEW ZEALAND, 1987 TO 2015

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ABSTRACT

Functioning pipeline systems are a cornerstone of urban human communities, to bring in the clean water on demand for drinking, washing and sanitary needs, and in turn remove the used water from drains, waste and storm water sources. If the pipe system is suddenly rendered non-functional, such as by seismic event, critical disruption of the community and public health danger can result. Of the many requirements for design carried by pipeline systems, seismic events impose arguably the most challenging of all demands on a buried pipeline asset. These include the extreme ground forces, with the variable ground movements that are possible, and the paramount need to restore function to damaged pipe systems, particularly drinking water pipes, as quickly as possible. Pipe system design, materials, installation methods, repair methodologies and practical implications of operation are all directly affected by seismic activity. This paper includes first-hand observations and experiences, specific to pipeline systems in New Zealand seismic events, covering a 27 year period, from 1987 to 2014, (Table 1) including the Edgecumbe earthquake of 1987, the Thompson Sound earthquake near Te Anau of 2000, the Christchurch/Canterbury area earthquakes during 2010 to 2012, and the Eketahuna earthquake of 2014. These events provide us with a unique opportunity to practically evaluate the seismic performance of pipe materials and joint systems, that either survived, were damaged and repaired, or were totally destroyed and abandoned, during New Zealand seismic events. This paper presents conclusions and recommendations from lessons learned during these events.

KEYWORDS

Seismic resilience, seismic performance, pipelines, earthquakes.

INTRODUCTION TO NEW ZEALAND PLATE TECTONICS

In the south-west Pacific Ocean, between 34^{o} and 47^{o} South, the islands of New Zealand are astride one of the most active tectonic plate boundaries on earth. Here, the Pacific Plate and the Australian Plate have been in continuous collision since mid-Oligocene times, over more than 25 million years. Seismic events caused by this Plate collision, occur frequently down the length of New Zealand, (Figure I and Figure II) as the accumulated stresses in the Plate boundaries induce fault rupture and release of seismic energy.

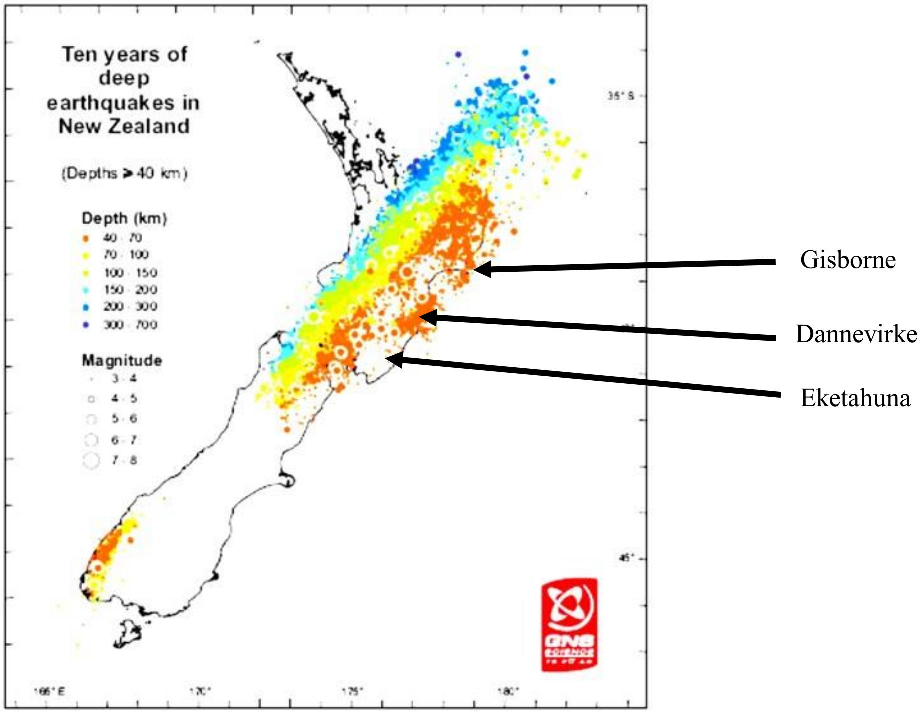

Figure I - History of deep earthquakes over the last 10 years in New Zealand with Epicenter positions of deep seismic events examined – GNS Science (2)

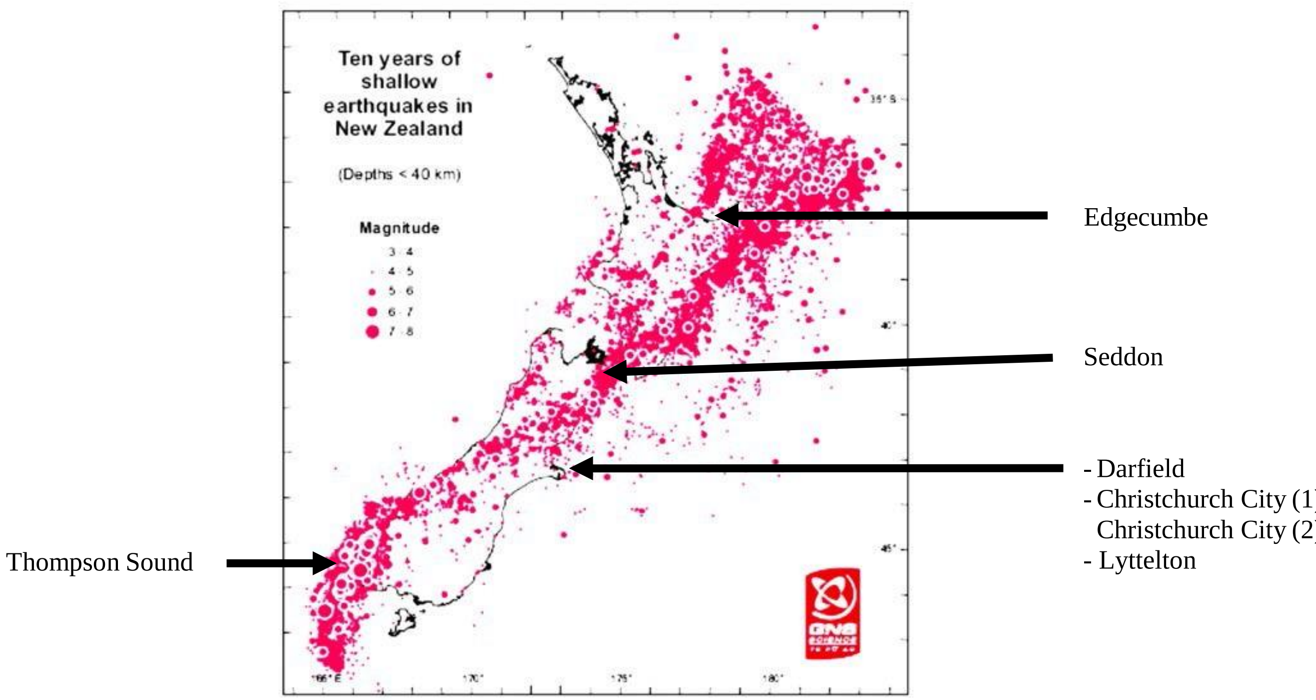

Figure II - History of shallow earthquakes over the last 10 years in New Zealand with Epicenter positions of seismic events examined – GNS Science (2)

SEISMIC EVENTS AND EFFECTS ON PIPELINES

Both deep and shallow earthquakes have caused pipeline damage, but it has generally been the shallower events, closely associated with the occurrence of liquefaction, which have caused the most severe pipeline damage. For example, the shallow Christchurch event of 2010 at M 6.3 and only 5 Km depth was much more damaging than the Dannevirke event of 1990, also M 6.3 but much deeper at 21 Km.

The influences of seismic effects from earthquake events (Table I) on pipelines examined in this paper (Table II) were closely related to depth of the epicentre, extent of visible ground liquefaction or lateral spread, and height of the water table, combined with directional orientation of the pipeline asset relative to the position of the epicentre.

Table I - Summary of Seismic Events included in discussion and observations

Earthquake Event Name / site observed	Magnitude (Richter Scale)	Date	Epicenter Depth (Km)
Edgecumbe	5.3 & 6.3	March 1987	10
Dannevirke /Palmerston North	6.3	May 1990	21
Thompson Sound / Te Anau	6.3	November 2000	18
Gisborne	6.8	December 2008	40
Darfield / Christchurch	7.1	September 2010	10
Christchurch City	6.3	February 2011	5
Christchurch City	5.6 & 6.3	June 2011	10
Lyttelton / Christchurch	6.2	December 2011	6
Seddon/Grassmere	6.5	July 21st 2013	17
Eketahuna / Carterton	6.1	January 2014	34

Table II - Pipe materials, applications and joint systems observed

Name	Pipe Material Type, and Application	Joint System
AC	Asbestos Cement watermain, pressure sewer main	“Supertite” RRJ coupling
CI	Grey cast iron watermain	“Gibault” style RRJ coupler bell and spigot, Lead wool or poured lead joints
CLS	Concrete lined spiral welded mild steel watermain, pressure sewer main	Butt welded or bell and spigot
RRRC	Reinforced concrete gravity sewer and stormwater	RRJ bell and spigot
EW	Glazed earthenware gravity sewer	Mortar jointed bell and spigot
VC	Vitrified clay gravity sewer	RRJ bell and spigot or coupler
PVC-U	Unplasticised PVC, watermain, gravity sewer	RRJ bell and spigot
PVC-M	Modified PVC watermain	RRJ bell and spigot
PVC-O	Biaxially orientated PVC watermain	RRJ bell and spigot
PE-100	MRS 100 Polyethylene watermain, pressure sewer	Butt Fusion, Electrofusion
PE-80	MRS 80 Polyethylene – water service laterals, ridermains	Mechanical restrained RRJ couplings
HDPE	MRS 80 and MRS 63 High Density Polyethylene, small diameter service laterals	Mechanical restrained RRJ couplings

PIPE PERFORMANCE IN LIQUEFACTION AREAS (Table III)

In the Waimakariri River flood plain extending under Christchurch City and Kaiapoi, sharply defined liquefiable ground zones exist, intermixed with non-liquefiable ground zones, at varying depths. The intensity of pipe damage observed alternated from often extensive, or total, in the liquefaction or lateral spread zones, to examples of minimal or no damage observed in the same pipes in adjacent non-liquefaction areas. A close association between approximate axial alignment of the pipe with the earthquake epicentre and type of pipe response was seen, in pipes of AC, CLS, and PVC-U at Edgecumbe, Carterton (Eketahuna event), Kaiapoi, Pines Beach / Kairaki Beach (Darfield event), and Christchurch. Resulting localised movements at pipe joints suggested the passage of rapidly alternating axial compressive or expansive movements in the liquefied ground. Pipes in streets aligned with the epicenter in liquefiable ground, displayed alternating expansive movement (Figure III), or axial compression (Figure IV, and Figure VI), whereas pipes positioned approximately tangential to the epicenter "around the corner", showed lateral shear effects. (Figure VII and Figure VIII)
Biaxially orientiated PVC (PVC-O) pressure pipe installed in 2010 to replace the destroyed AC sewer rising main at Charles St in Kaiapoi, (Figure VI) remained undamaged, during the Christchurch and Lyttelton events of 2011 and all subsequent aftershocks.

Figure III - Tension effects in AC pipe joint, Sewell Street Kaiapoi, axially aligned with the Darfield epicenter, 2010

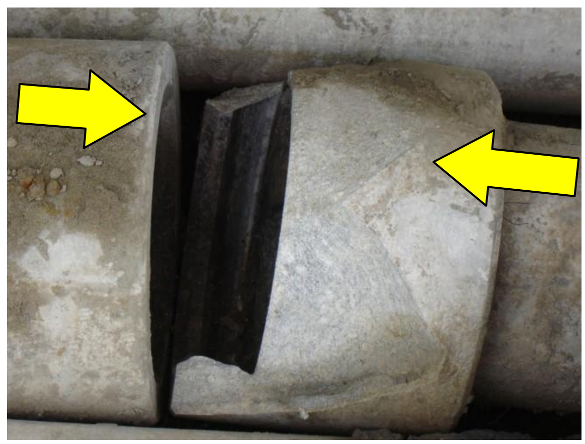

Figure IV - Compression effects in AC pipe joint, Sewell Street, Kaiapoi, axially aligned with the Darfield epicenter, 2010

Axial compressive/expansive movements within pipe joints in liquefied ground with no lateral spread were commonly only up to about 100 or 150 mm. Those pipe sockets able to accommodate the movement remained connected, but at points of pipe breakage in compression or joint separation, the liquefied ground rapidly invaded the pipe bore during the earthquake, then compacted and solidified as the passage of seismic energy ceased. In eastern Christchurch, difficulties in removing the solidified silt, together with widespread changes in ground levels, and pipe grades, directly influenced whether pipes were repaired or abandoned, and if replaced later, what replacement methodology was possible. For example, where the original pipeline grade had been changed or reversed, gravity sewer street reticulation mains could not be replaced by low impact trenchless methods such as bursting or lining; open cut was needed to restore the grade. In contrast, slumping and lateral spreading effects in liquefied ground, at Edgecumbe, Christchurch and Kaiapoi induced axial, shear and lateral pipe movements, of up to several metres. These movements occurred rapidly during the earthquake, over about 18 to 20 seconds, and more slowly from aftershocks during following days, with acute disruption to pipe assets and joints to structures, regardless of pipe material. None of the pipe materials or joint systems observed survived undamaged, where slumping or lateral spreading ground movement exceeded the displacement ability or yield limit of the pipe or joint affected. No examples of long lengths of pipe moving through the ground as a monolithic section were observed by the author. The damage sites were consistently localised to individual joints or positions on pipes, and breakage or separation occurred regardless of restrained or unrestrained joints being used, where the movement capability of the pipe or joint was exceeded.

Figure V - Compression distortion and separation of RRJ joints in CLS watermain, axially aligned with the Eketahuna epicenter, 2014

Figure VI – Compression fractures of pipe ends and joints in AC sewer rising main, Charles St, Kaiapoi, axially aligned with the Darfield epicentre, 2010 (Replaced with Biaxially Orientated PVC (PVC-O)

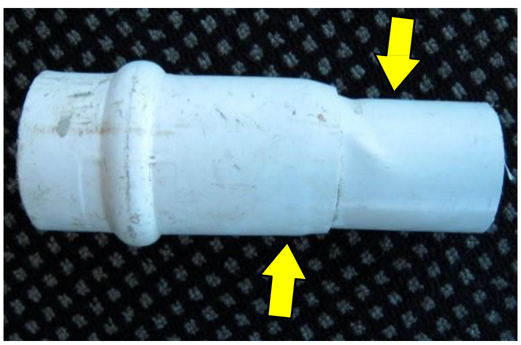

Figure VII –Shear effects with ductile response, in RRJ PVC-U of late 1970's age, Christchurch, 2010

Figure VIII – Shear effects in AC pipe joint, Jollie Street, Kaiapoi, with tangential alignment to the Darfield epicenter, 2010

PIPE PERFORMANCE IN NON-LIQUEFACTION AREAS (Table III)

The Thompson Sound earthquake of November 2000 impacted on gravity sewer pipes in non-liquefiable stony ground with low water table, in an old glacial moraine. RRJ pipe joints in a new, (pre-commissioning) 525mm RRRC gravity sewer pipeline were fractured at Te Anau town. A fast "rippling" movement visible on the surface caused a different mode of damage to that seen in liquefied ground, by breaking out sections of the pipe sockets at the inverts. This area close to the main Alpine Fault is highly active seismically, with typically 3 to 5 events per month, in the M4 to M7 range; up to 26 events per month of more than M4 have been recorded. Replacement RRJ PVC-U gravity sewer pipe installed at Te Anau in 2001 has remained undamaged, during all subsequent earthquake events at this site. In non-liquefied areas of Christchurch and Kaiapoi, damage to pressure and gravity pipes based on obvious visible leaks, was either much reduced or even absent in AC, RRRC, PVC and PE pipes. However the longer term performance of AC pipes and infiltration condition of apparently still functioning EW and VC gravity sewers and stormwater systems in these areas is unclear. At Edgecumbe, high infiltration noted recently in EW sewers remaining from the era installed before 1987, was linked to damage sustained in the 1987 earthquake. The Dannevirke earthquake caused extensive in-ground cracking of 4 inch EW gravity sewer house laterals over 40Km away in Palmerston North city, identified over time from increased infiltration of ground water and tree roots. At the large Pegasus residential subdivision near Kaiapoi, located in a recognised high liquefaction risk zone, ground compaction was deliberately "re-engineered", and water table height lowered during construction, which significantly reduced damaging effects from the Canterbury earthquakes on pipes and structures.

Table III - Mode of damage from ground movement, by pipe material, ground condition and seismic event

Pipe/joint type	**Compressive Phase movement in Liquefiable ground**	**Location/ Seismic Event**
AC pressure and sewer	Localised 45 deg compression fracture of rubber ring coupling joints and crushed pipe spigots. (Figure IV and Figure VI)	Edgecumbe Christchurch Kaiapoi
EW sewer	Disintegration of whole pipe into random shards, or localised brittle ring fracture of mortar sealed bell and spigot joints.	Edgecumbe Christchurch Kaiapoi
VC sewer	Disintegration of whole pipe into random shards localised brittle fracture of rubber ring bell and spigot joints.	Christchurch Kaiapoi
RRRC sewer	Localised "telescoped" brittle fracture of rubber ring bell and spigot joints.	Christchurch Kaiapoi
PVC pressure and sewer	Localised ductile pipe barrel section folding/buckling. Localised "telescoping" of joints (Figure X), (caused by the pipe spigot being driven through the socket bell, and beyond into the pipe bore itself). Ductile fracture of sewer service lateral junctions, ductile tearing at socket joints,	Christchurch Kaiapoi
PE-80 pressure	Localised ductile barrel section folding/buckling in service laterals	Christchurch
CI pressure	Disintegration of concrete encased pipe barrel and joints at elevated stream crossings from lateral spread, brittle fracture of couplings flanges	Christchurch
DI pressure	Localised distortion/disorientation of coupled barrel with DI coupling fractures, (in an aerial pipe bridge application), lateral spread movement beyond compressive capacity of material.	Christchurch
CLS pressure	Localised "telescoping" of joints and ductile tearing of the pipe wall (Figure IX), movement beyond compressive capacity of material. CLS pressure pipe systems. Localised distortion, buckling and separation of bell and spigot joints (Figure V).	Christchurch Carterton (Eketahuna)
GS	Localised barrel section folding/buckling, pipe sections folded and expelled from the ground in Kaiapoi, in pipes axially orientated with the epicentre.	Kaiapoi, Pines Beach
	Expansive Phase movement in Liquefiable ground	
AC, EW, VC, RRRC	Localised pull-out of couplers (CI and AC), joint separation.	Edgecumbe Canterbury
PVC	PVC pipe systems: Joint separation, or non-separation (where	Christchurch

	axial movement did not exceed spigot insertion length), movement beyond tensile capacity of material. (Figure X)	
CI pressure	Localised pull-out of couplers, displacement of screw gland joints and lead wool packed joints.	Christchurch
DI pressure	Joint separation, movement beyond tensile capacity of material.	Christchurch
CLS, GS	Separation where movement beyond tensile capacity of material.	
PE-100	Separation at Electrofusion joints where movement beyond tensile capacity of material.	Christchurch
PE-80, HDPE	Separation of service laterals at restrained mechanical joints where movement beyond tensile capacity of material. Tensile separation of pipe barrel where lateral spread movement beyond tensile capacity of material.	Christchurch
	Lateral Shear movement in Liquefiable ground	
AC	Localised shearing of spigot inside the bell assembly. Pipe barrel often left in reasonable condition, but with the end cracked off and separated. (Figure VIII)	Kaiapoi Christchurch Edgecumbe
EW, VC, RRRC	Localised fracture and separation of bell and pipe barrel.	Gisborne Palmerston Nth Dannevirke Christchurch
PVC	Ductile distortion of pipe and joint, no leaking. (Figure VII and Figure XI)	Gisborne Kaiapoi Christchurch
CI	Fracture of pipe barrel at flange connections.	Christchurch
DI	Localised distortion/disorientation of coupled barrel sections with DI coupling fractures, (in an aerial pipe bridge application), movement beyond compressive capacity of material.	Christchurch
CLS	CLS pressure pipe systems: Localized “telescoping” of joints, tearing and “unraveling” of the spiral weld in the pipe barrel from movement beyond compressive capacity of material.	Christchurch Carterton (Eketahuna)
	Slumping or Lateral Spread in Liquefiable ground	
RRRC	Settlement off grade, pipe barrel fracture, joint fracture, lateral separation, separation from structures	Christchurch
PE-100 pipe systems	Tensile separation at electrofusion joints where movement beyond tensile capacity of joint at the fitting. Tensile separation (yield and break) of pipe, used as a liner in rehabilitation of CI watermain, where movement was beyond tensile capacity of pipe barrel.	Christchurch
PVC	Tensile separation of the pipe at bell and spigot joints where movement exceeded axial movement capacity of joint.	Christchurch Kaiapoi
PE	Tensile separation of PE service laterals and rider mains at restrained mechanical couplers and fittings where movement beyond tensile capacity of the pipe.	Christchurch
CI	Tensile separation of pipe, where movement beyond tensile/flexural capacity of pipe barrel	Christchurch

	Non-liquefiable ground	
RRRC	Localised fracture of pipe sockets (bell) at the invert position. Partial pullout of pipe spigot	Te Anau
EW	Widespread infiltration of ground water and tree roots during following years from cracking in pipes and sockets.	Palmerston Nth (Dannevirke event)

Figure IX - Compressed joint movement in CLS water main, Christchurch

Figure X – Compressed ductile joint movement in PVC-u water main, Christchurch

Pipe material behaved in surprising ways. In Christchurch, DN 100 PVC-M pressure pipe, manufactured in 1996, was displaced by sudden lateral spread and squashed behind a large concrete sewer chamber in the Avon river bank (Figure XI). The pipe was found to be still under pressure with reduced flow. The RRJ "Z" joint in the middle of the displaced pipe section which had "pulled" longitudinally about 15 mm, but had permitted the expansive movement, undamaged.

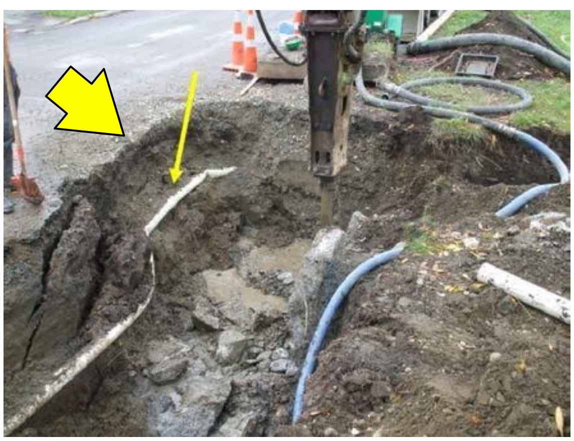

Figure XI - Distorted but still operational, DN100 PVC-M water pipe with joint, Christchurch

Figure XII - Ductile axial compression folding in PVC-U pipe, Gayhurst Road overbridge

At the Gayhurst Road over bridge crossing the Avon River in Avonside, Christchurch, lateral spread rapidly drove PVC-U watermain axially into the bridge abutment, to cause ductile axial buckling (Figure XII), and disintegration of the CI pipe and joints in the bridge. The crossing connections were quickly repaired with PVC pipe and mechanical couplers, requiring low operator skill, and no electricity to install.

CHANGES IN BURIED PIPELINE LEVELS AND GRADES

At Edgecumbe and Christchurch, changes in grades and levels of buried gravity pipes occurred, caused by ground settlement or elevation, and flotation of connections to chambers and structures. Levels changed repeatedly in some locations with major aftershocks. Grade change effectively rendered gravity pipes of any material non-functional, and imposed ease of repair as the essential consideration, not the choice of pipe material or joint system. It also forced redesign in some affected sites, away from the previous "gravity model" to pressure or vacuum options.

PLASTIC PIPE SYSTEMS OVERVIEW

At Edgecumbe, 20% of the watermain network was socket and spigot PVC-U but only 5% of the network repair costs were attributed to PVC pipe -Nicholson R (4). Following the Eketahuna and Seddon events, no failures of PVC-U, PVC-M or PVC-O watermains were reported. At Te Anau, spigot and socket RRJ PVC gravity sewer pipe installed in 2001 has remained undamaged, where up to 26 events per month of more than M4 have been recorded. The watermain network in Christchurch before the February 2010 earthquake was 52.7% AC, 26.4% PVC, 1.8% steel and only 1% PE. By contrast, the water submain network was 84.6% PE, 10.4% GI and only 3.3% PVC. However the average percentage of affected length of PVC and PE pipes across all ground conditions for these networks was similar at 1.8% PVC and 2.5% PE in watermains, and 2.3% PVC and 2.5% PE in submains. Both PE pipes and PVC pipes suffered significantly less damage (three to five times less on average) than AC, steel, GI and other pipe materials. -Cubrinovski M et al (6, 7*).* Minimal or no damage was observed in PVC and PE pipes in non-liquefied areas.

Biaxially orientated PVC (PVC-O) pressure pipe installed in 2010 to replace the destroyed AC sewer rising main at Charles St in Kaiapoi, (Figure VI) remained undamaged, during the Christchurch and Lyttelton events of 2011 and subsequent aftershocks. No seismic failures were reported from the relatively limited PE gas pipe network in Christchurch. PVC and PE pipelines laid in late 2011 between the February 2011 and December 2011 events had no damage reported. However, like all pipe materials observed, the consistent conclusion from observation is that PVC and PE have their mechanical limits and when those limits are exceeded, should be expected to fail or require substantial repair, similar to other pipe materials. PVC-U gravity sewer pipes and fittings are currently widely used in Christchurch City for new residential subdivision developments, and network rebuild. VC and EW pipes are now not used in the Christchurch area, including for industrial lines where PVC-u has been adopted. In the liquefiable east-central and eastern zones of Christchurch, where the weakened ground cannot reliably support thrust blocks, or even open trenches, fusion joined PE is the predominant replacement pressure watermain pipe material used. In other non-liquefiable areas of western, northern and southern Christchurch City, conventional spigot /socket RRJ PVC is widely used for open cut installation, as the work footprint advances beyond repairs/reinstatement and into "green fields" works for new residential subdivision and commercial developments. In neighboring Waimakariri District and Selwyn District, also affected by the Canterbury earthquakes, PVC-U pressure pipes are approved for new and replacement open cut water mains in non-liquefiable zones, with PE-100 the predominant material for pressure sewers, and trenchless drilled installation. In other South Island Council regions, south-west, west and North-east of the Canterbury/Christchurch zone, and exposed to seismic risk from the main Alpine fault itself, pipes in PVC-O, PVC-U, PVC-M and PE are widely accepted and used. Restrained joint PVC-U and Fusible PVC™ have also been used for trenchless replacement of EW Gravity Sewers.

SEISMIC PERFORMANCE STANDARDS

In mid-2010, prior to the Christchurch September 2010 earthquake, Standards New Zealand, revised the New Zealand Standard NZS 4404 "Land Development and Subdivision Infrastructure" NZS 4404:2010, and included a clause called "Seismic Design" which includes the statement "*Historical experience in New Zealand earthquake events suggests that suitable pipe options, in seismically active areas, may include rubber ring joint PVC or PE pipes"*.

CONCLUSIONS AND RECOMMENDATIONS

Observations of pipelines have shown that nothing is completely earthquake proof. Seismic movements are beyond human control, and will happen anyway, hence the need to accommodate them with resilient design choices. This is especially true in highly liquefiable areas, and in lateral spread sites; here there is simply no such thing as "earthquake proof" pipe! Flexible pipes such as PVC and PE generally performed well, with significantly fewer breaks and leaks observed compared with other commonly used non-flexible pipes. However, the basic fact remains that any pipe in any material may get broken or damaged in an earthquake event, which places a bigger onus on practicality and ease of repair as the most vital consideration. In liquefiable sites choose pipe materials and joint types for fastest and most practical repair, especially for drinking water delivery. In particular, assume wet dirty conditions, no road or bridge access, raining or mid-winter timing, low skill emergency staff, poor light or at night, with no electrical power, in running raw sewerage or water, or under water, and deep asset location. Pipes must be compatible with mechanical joints and joint systems that are actually available and affordable, without needing electrical or heat fusion processes and dry clean site conditions. Use resilient "flexible" pipes, joints, structures and designs that accommodate movement, in any seismic risk area. The more rigid a component or joint is, the more likely that it will suffer damage. Restraint joints alone do not remove the failure risk – the key need is whether the pipe and joint can accommodate the movement, which happens anyway. No pipe material observed, survived totally undamaged where either the compressive or expansive ground movement exceeded the movement capability or yield limit of the pipe or joint. Design pipelines to manage assumed or certain movement or failure such as near rigid structures, bridges, stream or river banks, or crossing active fault lines, and locations likely to lose road access/bridge access or electrical power resources for substantial periods.

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