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PIPELINE PERFORMANCE EXPERIENCES DURING SEISMIC EVENTS IN NEW ZEALAND OVER THE LAST 27 YEARS

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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 stormwater 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 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, including the Edgecombe earthquake of 1987, Christchurch City and 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, or were damaged and repaired, or were totally destroyed and abandoned, specific to New Zealand seismic conditions. This paper presents conclusions and recommendations from lessons learned during these events.

INTRODUCTION TO NEW ZEALAND PLATE TECTONICS

In the south-west Pacific Ocean, between 34^o and 47^o South, New Zealand's North Island and South Island 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 induce fault rupture and seismic energy release.

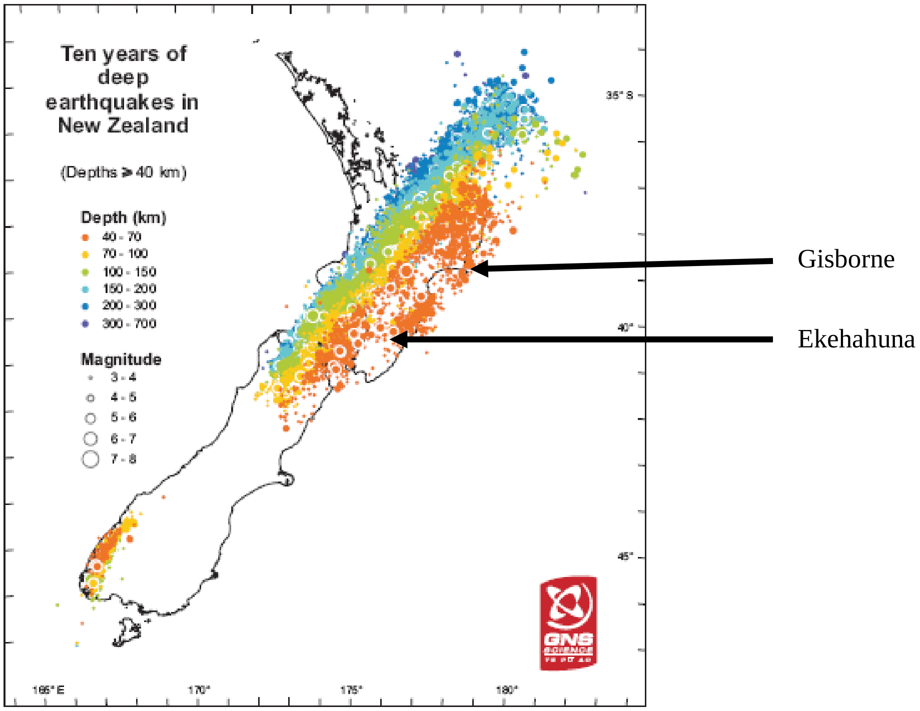

Figure I - History of deep earthquakes over the last 10 years in New Zealand with Epicentre positions of seismic events examined – GNS Science (2)

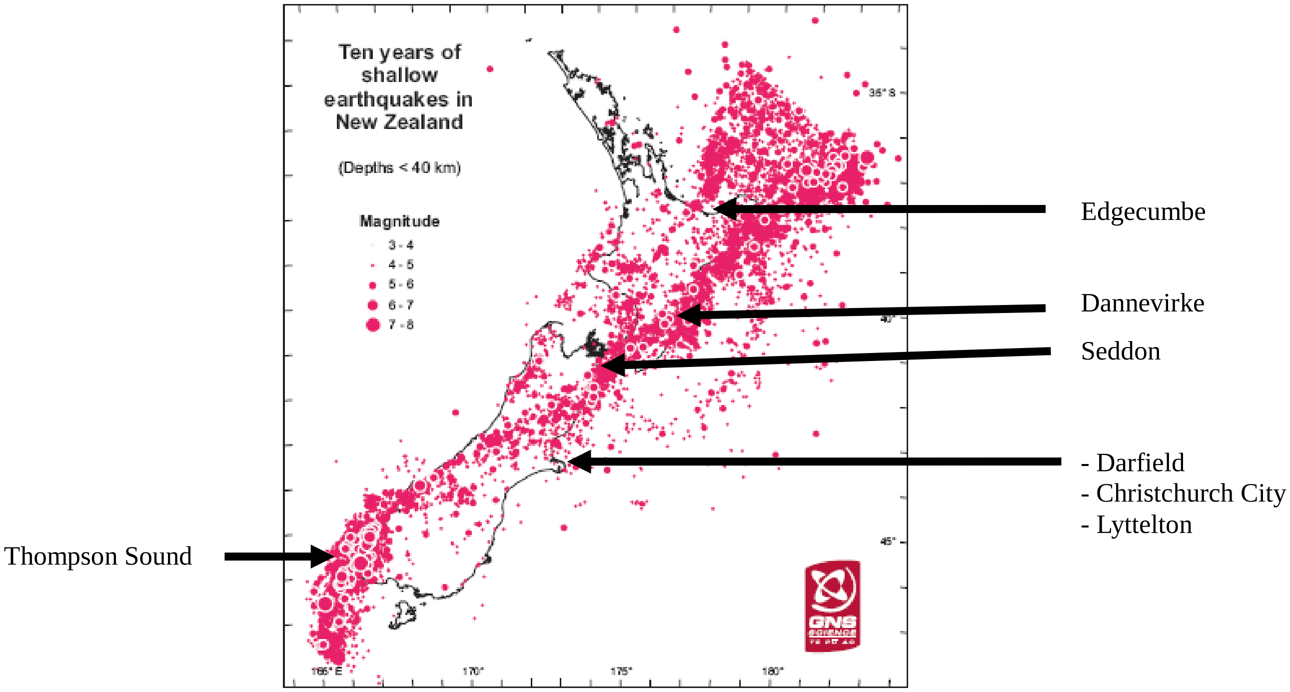

Figure II - History of shallow earthquakes over the last 10 years in New Zealand with Epicentre positions of seismic events examined – GNS Science (2)

SEISMIC EVENTS AND EFFECTS ON PIPELINES

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

The extent of seismic effects from earthquake events (Table I) on pipelines examined in this paper (Table II)were closely related to the depth of the epicentre, extent of visible ground liquefaction and lateral spread, height of the water table, and 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
Edgecumbe	5.3 & 6.3	March 1987	10 Km (6.2 miles)
Dannevirke /Palmerston North	6.3	May 1990	21 Km (13 miles)
Thompson Sound / Te Anau	6.3	November 2000	18 Km (11.1 miles)
Gisborne	6.8	December 2008	40 Km (24.8 miles)
Darfield / Christchurch	7.1	September 2010	10 Km (6.2 miles)
Christchurch City	6.3	February 2011	5 Km (3.1 miles)
Christchurch City	5.6 & 6.3	June 2011	10 Km (6.2 miles)
Lyttelton / Christchurch	6.2	December 2011	6 Km (3.7 miles
Seddon/Grassmere	6.5	July 21st 2013	17 Km (10.5 miles)
Eketahuna / Carterton	6.1	January 2014	34 Km (21.1 miles)

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
DI	Ductile Iron watermain	"Gibault' style RRJ coupler bell and spigot
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	Mechanical restrained RRJ

	diameter service laterals	couplings
GI	Galvanised iron	Threaded coupler and spigot

PIPE PERFORMANCE IN LIQUEFACTION AREAS (Table III)

In the Waimakariri River flood plain extending under Christchurch City and Kaiapoi town, 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 movement was seen, in pipes of AC, CLS, and PVC at Edgecumbe, Carterton (Eketahuna event), Kaiapoi, Pines Beach (Darfield event), and Christchurch. Resulting localized movements at pipe joints suggested the passage of rapid alternating axial compressive or expansive movements in the liquefied ground Pipes in streets aligned with the epicenter in liquefiable ground displayed expansive movement (Figure III), or axial compression (Figure IV), whereas pipes positioned tangential to the epicenter “around the corner” showed lateral shear effects.

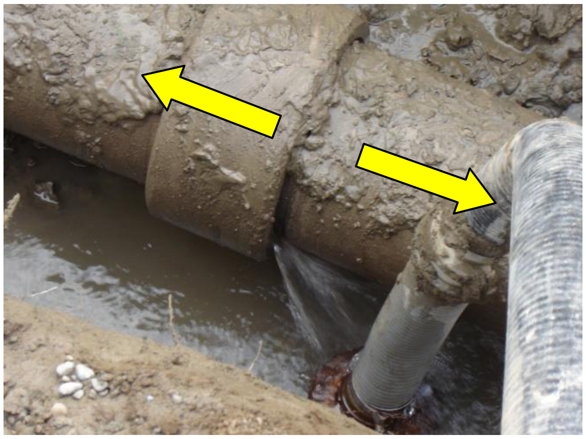

Figure III - Tension effects in AC pipe joint, Sewell Street Kaiapoi, axially aligned with the Darfield/Christchurch epicenter

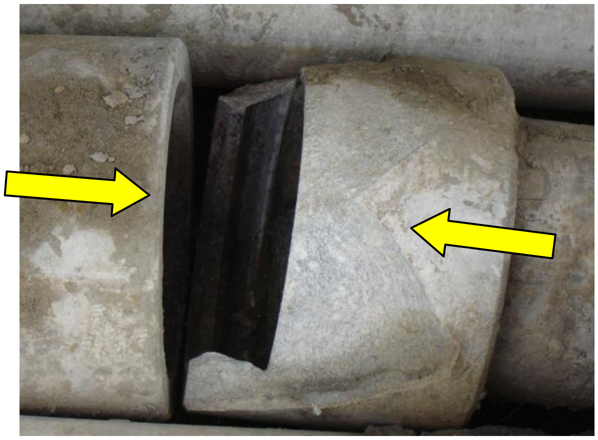

Figure IV - Compression effects in AC pipe joint, Sewell Street Kaiapoi, axially aligned with the Darfield/Christchurch epicenter

Axial compressive/expansive movement in pipe joints, in liquefiable ground with no lateral spread, was most commonly only up to about 100 to 150 mm or 4 to 6 inches. 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 itself, then compacted and solidified as the passage of seismic energy ceased. Difficulties in removing the solidified silt, changes in area ground levels and altered pipe grades and ease of repair directly influenced whether pipes were repaired, replaced or abandoned. In contrast, slumping and lateral spreading effects in liquefied ground, at Edgecumbe, Christchurch and Kaiapoi induced large axial and lateral pipe movements, up to several metres or yards. These movements occurred at high velocity during the earthquake itself, over about 10 to 20 seconds, and more slowly during following days and aftershocks, 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 the slumping or lateral spreading ground movement exceeded the displacement ability 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 localized 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 gasketed joints in CLS watermain, axially aligned with the Eketahuna epicenter

PIPE PERFORMANCE IN NON LIQUEFACTION AREAS (Table III)

The Thompson Sound earthquake impacted pipes in non-liquefiable stony ground with low water table, in an old glacial moraine. Gasketed pipe joints in a new, pre-commissioning DN 525 or 21 inch RRRC gravity sewer were fractured at Te Anau town. A fast “rippling” movement visible on the surface caused a different mode of damage to that seen in liquefaction ground, by breaking out sections of the pipe socket inverts. This area near the main Alpine Fault is highly active seismically, with typically 3 to 5 events per month, in the M4 to M7 range. Replacement rubber ring joint bell and spigot PVC pipe has survived undamaged during all subsequent earthquake events at Te Anau to the present day. In non-liquefiable areas of Christchurch and Kaiapoi, pipe damage to pressure watermains based on visible leaks was either much reduced or even absent in AC, RRRC PVC and PE pipes. However the infiltration condition of apparently still functioning EW and VC gravity sewers and stormwater systems in these areas is unknown. 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 DN 100 or 4 inch EW gravity sewer house laterals in Palmerston North city, identified over time from a large increase in infiltration of ground water and tree roots. At the large Pegasus residential subdivision near Kaiapoi, a recognized high liquefiable risk zone, water table height was lowered and ground composition/compaction was deliberately "re-engineered" during construction, which almost eliminated damaging effects of the earthquakes on pipes and structures. Yet extensive liquefaction appeared in the unmodified land immediately outside the Pegasus property boundary.

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	Localized 45 deg compression fracture of rubber ring coupling joints and crushed pipe spigots.	Edgecumbe Christchurch, Kaiapoi
EW sewer	Disintegration of whole pipe into random shards, or localized brittle ring fracture of mortar sealed bell and spigot joints.	Edgecumbe, Christchurch Kaiapoi
VC sewer	Disintegration of whole pipe into random shards localized brittle fracture of rubber ring bell and spigot joints.	Christchurch, Kaiapoi
RRRC sewer	Localized "telescoped" brittle fracture of rubber ring bell and spigot joints.	Christchurch, Kaiapoi
PVC pressure and sewer	Localized ductile pipe barrel section folding/buckling. Localized "telescoping" of joints (Figure IX), (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	Localized 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	Localized 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	Localized "telescoping" of joints and ductile tearing of the pipe wall (Figure VIII), movement beyond compressive capacity of material. CLS pressure pipe systems. Localized distortion, buckling and separation of bell and spigot joints (Figure VII).	Christchurch Carterton (Eketahuna)
GI	Localized 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	Localized pull-out of couplers (CI and AC), joint separation.	Edgecumbe, Canterbury
PVC	PVC pipe systems: Joint separation, or non - separation (where axial movement did not exceed spigot insertion	Christchurch

	length), movement beyond tensile capacity of material.	
CI pressure	Localized 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
	Liquefiable ground - Lateral Shear movement	
AC	Localized shearing of spigot inside the bell assembly. Pipe barrel often left in reasonable condition, but with the end cracked off and separated.	Kaiapoi Christchurch Edgecumbe
EW, VC, RRRC	Localised fracture and separation of bell and pipe barrel.	Gisborne Palmerston Nth Dannevirke Christchurch
PVC	Ductile movement of pipe and fittings, no leaking.	Gisborne Kaiapoi Christchurch
CI	Fracture of pipe barrel at flange connections.	Christchurch
DI	Localized 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)
	Liquefiable ground - Slumping or Lateral Spread	
RRRC		Christchurch
PE-100 pipe systems	Tensile separation at electrofusion joints where movement beyond tensile capacity of joint at the fitting. Tensile separation of pipe, used as a liner in rehabilitation of CI, where movement 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 material.	Christchurch
CI	Tensile separation of pipe, where movement beyond tensile/flexural capacity of pipe barrel	Christchurch
CLS		Christchurch
	Non-liquefiable ground	
RRRC	Localized fracture of pipe sockets (bell) at the invert	Te Anau

	position.	
EW	Widespread infiltration of ground water and tree roots during following years from cracking in pipes and sockets.	Palmerston Nth (Dannevirke event)

Figure VI - Compressed joint movement In CLS water main, Christchurch

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

Pipe material behaved in surprising ways. In Christchurch, DN 100 (4 inch) PVC-M pressure pipe, manufactured in 1996 was pushed sideways by sudden lateral spread and squashed behind a large concrete sewer chamber in the Avon river bank. (Figure VIII). The pipe was found to be still under pressure with reduced flow. The bell and spigot rubber ring joint in the middle of the displaced pipe section which had “pulled” longitudinally about 15 mm, but had permitted the expansive movement, undamaged.

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

At the Gayhurst Road overbridge crossing the Avon River in Christchurch, lateral spread rapidly drove PVC watermain axially into the bridge abutment, to cause ductile axial buckling (Figure IX), and disintegrated the CI pipe and joints in the bridge. The crossing connections were quickly repaired with PVC pipe and mechanical couplers, requiring low operator skill no electricity to install, and no road access to the site.

Figure IX - Ductile axial compression folding in PVC pipe, Gayhurst Road over bridge

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 floatation of connections to chambers and structures. Levels changed repeatedly in some locations with major aftershocks. Grade change effectively rendered any gravity pipe 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 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 bell 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, bell and spigot PVC gravity sewer pipe installed in 2001 has remained undamaged. 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 (5, 6*).* Minimal or no damage was observed in PVC and PE pipes, in non liquefaction areas

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 bell and spigot PVC is widely used, for open cut install, as the work foot print advances beyond repairs/reinstatement and into new “green fields” works for new residential subdivision and commercial developments.

In neighboring Waimakariri District and Selwyn District, also affected by the Canterbury earthquakes PVC-O or PVC-U pressure pipes are commonly used for new and replacement open cut water and sewer 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.

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 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 in design. Especially true in highly liquefiable areas; 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 the practicality and ease of repair as the most vital consideration.

Design pipes for fastest and most practical repair in liquefiable sites. 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 joints that are actually available and affordable, without needing electrical or heat fusion processes and dry clean site conditions. Use "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 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 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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