FLEXIBLE POLYETHYLENE PIPELINES FOR SEISMIC RESILIENCE

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ABSTRACT

Polyethylene pipe included in Christchurch water and gas reticulation systems performed extremely well in the 2010/11 Canterbury earthquakes. Based on this performance, polyethylene pipe has been used more extensively for repair and reconstruction works. This has required careful consideration of aspects of the design and construction to ensure that the high level of performance is replicated for the wider range of applications.

This paper outlines the design and construction procedures and processes employed by CCC and SCIRT to ensure effective performance in challenging soil conditions for large diameter gravity and pressure pipelines. These processes were utilised on the PM105 project, which included 1940m of DN710 polyethylene pressure main and 1500m of DN800 and DN900 polyethylene trunk sewer.

The increased use of polyethylene pipe to provide seismically resilient solutions requires careful consideration of a range of first principle design requirements ranging from ground conditions, material specification and potential failure modes of the pipelines.

Construction control is an essential component of ensuring the design performance of polyethylene pipelines. Particular attention is required to the material quality and the integrity of welded joints.

KEYWORDS

Polyethylene, Seismic Pipeline Design Liquefaction, PE100, SCIRT, Christchurch, Earthquakes

1 INTRODUCTION

Polyethylene has been used in many different forms for over fifty years. PE100 is the current form of the material for the construction of flexible plastic water and wastewater pipe systems. Polyethylene is widely recognized as having good flexible seismically resilient properties and this is supported by its performance in recent major earthquakes throughout the world.

The Pump Station / Pressure Main 105 project involved approximately 1940m of DN710 pressure main and 1500m of gravity trunk sewer design and both constructed from polyethylene pipe to connect new development in south western Christchurch to the existing trunk sewer network. The pipeline route included three crossings under NZTA controlled roads and a railway crossing.

2 PERFORMANCE OF POLYETHYLENE PIPES IN THE CANTERBURY 2010/2011 EARTHQUAKES

O'Rourke et al (2012) highlighted the prevalence of un-damaged polyethylene pipes in the water and gas networks located in areas of high to severe liquefaction and noted that all other pipes types in the same areas had a high average repair rate of nearly 1 repair / km of main.

Prior to the earthquakes, Christchurch had approximately 23.5 km of polyethylene watermains and wastewater pipes greater than 100mm diameter. A further 30 km off water and waste water pipes had been laid prior to the December 2011 earthquake to replace damaged water mains and sewer rising mains in areas most severely affected by liquefaction and lateral spread. Only two repairs have been recorded to all of these pipelines between September 2010 and January 2012.

Figure 1 shows the proximity of the polyethylene water and wastewater mains relative to the worst areas of liquefaction as assessed after the February 2011 earthquake.

3 POYETHYLENE MATERIAL PROPERTIES

Elastic deformations of between 10-20% are generally accepted as yield limits for polyethylene, with ultimate yield limits of 400-500%. AWWA M55 (2006) guidelines suggest that polyethylene pipes have similar compressive strength to its tensile strength.

These rates only apply for comparatively slow rates of loading of the order of 50-100mm/min, which may be applicable liquefaction induced settlements and lateral spread loads. Seismic propagation strains will be transferred at rates in excess of 1000 mm/sec through earthquake waves. Simuro and Naoto (2008) found that the tensile compressive and tensile yield strains of polyethylene pipe were between 10-15% over a range of tensile and compressive testing speeds.

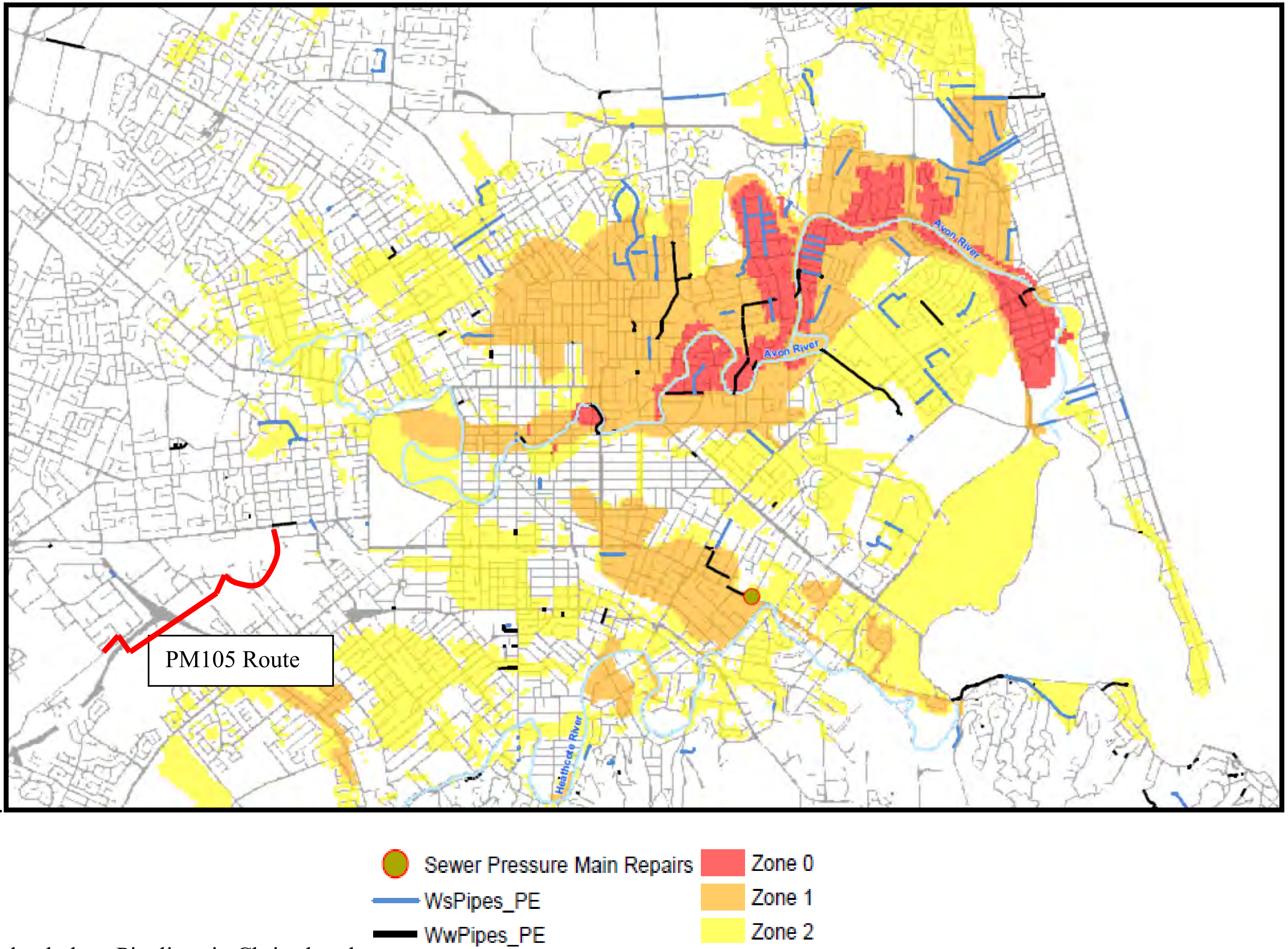

Figure 1: Polyethylene Pipelines in Christchurch

4 PM105 PROJECT

PS/PM105 project was undertaken by Stronger Christchurch Infrastructure Re-build Team (SCIRT) for Christchurch City Council (CCC) to advance servicing of ultimately up to approximately 15,000 houses in south western Christchurch. New development in this area has accelerated with the 2010/2011 earthquakes and subsequent red-zoning of properties in eastern Christchurch.

The overall project consisted of

- Construction of a new 550 L/s wastewater pumping station
- Inlet sewers to collect upstream pumping main discharges (Approximately 300m of DN800 ID gravity pipe)
- 1940m of DN710 (600 ID) Polyethylene pumping main
- 1240m of DN800 and DN900 ID gravity pipe downstream of the pumping main discharge to connect to the downstream gravity trunk sewer network

The project duplicates a deep gravity trunk sewer main that was constructed in the early 1970's. An alternative route was selected over two thirds of the pipeline route to locate the pipeline in a green field corridor away from high use traffic roads and to provide greater system redundancy. This route included crossings under the Christchurch Southern motorway and the downstream section of pipe is located in a busy arterial traffic route and involved crossing under a rail line.

Figure 2: PM105 Pipeline Route

The pipelines were constructed between August 2012 and September 2013 by the Fulton Hogan. The pumping station is due for completion January 2014.

5 GROUND CONDITIONS

Variability of ground conditions is a fundamental characteristic of Christchurch soils with changes in soil types over short distances.

Ground investigations showed four distinct zones of different ground conditions ranging from unconsolidated water bearing gravels to silty clay, soft silts and liquefiable sands. These areas are reflective of the historic river courses of the Waimakariri River laying down gravel deposits in recent river channels with swampy soils located to either side of these former river courses.

While the pipe line route is away from areas that suffered damage in the 2010/2011 earthquakes as shown on figure 1. This is partly reflective of the pipeline route being located away from built up areas and the distance from the earthquake epicenters.

Limited settlements and liquefaction was observed along the pipe line route during the 2010/2011 Canterbury Earthquake sequence. Ground settlements around manhole lids have been observed at of the order of 100mm at both ends of the project in Wrights Road and Wigram Road. Settlements in the Southern motorway embankment under construction alongside the pressure main were of the order of 300-500mm

6 SEISMIC CONDITIONS

6.1 SEISMIC PROPAGATION

Seismic propagation forces were estimated according to the ALA (2005), and using maximum measurements recorded in the February 2011 earthquake as a design peak ground velocity.

$$\varepsilon = \frac{PGV}{c} \qquad (1)$$

ε = Seismic Ground Strain %

PGV = Peak Ground velocity measured at 1.1 m/s measured at Pages Road February 2011

c = Seismic Wave Celerity 50 m/s in soft soils, 4000 m/s Rock

Seismic wave forces are dependent on the magnitude and direction of the peak ground velocity and wave speed, which will vary with the earthquake epicenter location and soil conditions.

6.2 LIQUEFACTION

There are four potential actions on pipelines; associated with liquefaction.

- Settlement
- Flotation
- Pipe buckling
- Lateral Spread

6.2.1 PIPE BUCKLING

Flexible pipe structural design relies on the support of the surrounding soils to maintain the roundness of the pipe. There is limited understanding of the performance of flexible pipes in liquefiable soils. However, out of roundness of pipes has not been a widespread failure mechanism observed in flexible pipelines in Christchurch.

In liquefiable soils, pipes are designed in accordance with AS/NZS 2566.1 (1998); for soft ground conditions with the use of well compacted granular materials as pipe bedding and surround. Construction requirements such as sheet piling and trench shielding also limit the support to the pipe and can be the major influence on the loads on the pipe (Ref Janson(2003)).

6.2.2 FLOTATION

Flotation of both pipes and structures is a well-documented seismic action on water and wastewater infrastructure and is probably the most commonly identified impact of liquefaction on pipelines and structures.

While a number of pumping station structures were lifted in the 2010/2011 earthquakes, limited widespread flotation of manholes is thought to have occurred in Christchurch.

Widespread loss of grade occurred in most pipe types throughout Christchurch. It is very difficult to form a common understanding of the pre-dominant mechanism that has caused the observed damage. Regardless of the actual mechanism, both mechanisms can induce tensile forces and increase joint stresses. This is exhibited with pulling apart of pipe joints in rubber ring jointed pipe types.

Polyethylene does have a density lighter than water, so pipelines are at risk of flotation even in hydrostatic conditions. The presence of non-liquefiable cover above the pipeline is generally sufficient to prevent manhole structures are designed with additional concrete to concentrate the weight resisting the uplift forces.

Open cut trench construction provides greater security from damage due to flotation. As with ground settlement, a well-constructed pipe foundation and the use of non-liquefiable backfill is considered good practice to protect against flotation as much as reasonably practical.

Directional drilling of pipeline in liquefiable soils does rely on tensile actions on the pipeline, the frictional resistance of the pipeline and the weight of the non-liquefiable soils above the pipe to restrain.

6.2.3 LIQUEFACTION INDUCED SETTLEMENT

The design of pipes and structures to resist flotation needs to be balanced with the potential settlement associated with both liquefaction and soft soil conditions. The mechanisms associated with liquefaction induced settlement are as discussed for flotation effects.

The stiffness of thick walled polyethylene pipe does limit its flexibility at rigid structures. Polyethylene pipe is commonly recognized as being able to bend at a radius of between 15-20 times the pipe diameter prior to inelastic deformation of the pipe. The table below shows the larger the pipe the less flexibility and longer length required to achieve deflection without buckling the pipe.

Table 1 Polyethylene Pipe Flexibility - Deflections at 15 x pipe diameter Bending Radius

Distance between Fixed points	Vertical Deflection DN180 OD	Vertical Deflection DN355 OD	Vertical Deflection DN710 OD
0.5	0.06 m	0.03 m	0.01 m
1.0	0.12 m	0.06 m	0.03 m
2.0	0.23 m	0.12 m	0.06 m
4.0	0.45 m	0.24 m	0.12 m
8.0	0.81 m	0.46 m	0.24 m

This flexibility capacity assumes even settlement over the length of pipe. While this assumption may be valid for settlements associated with liquefied ground induced settlements, particular consideration is required for differential settlements at structures or for connections to existing pipelines where additional provisions may be required to achieve the required flexibility, this may include using mechanical couplers or EBAA joints such as ‘Flex-tend’.

Alternatively if the buckling of the pipe with settlement at the connection to a structure is acceptable, a flanged connection at the structure interface to allow easy repair if the polyethylene connection is damaged

6.2.4 LATERAL SPREAD

Aside from direct fault line displacements, lateral spread induces the most severe seismic related forces pipelines and result in both compressive and tensile forces with the weight of large volumes of soil acting on pipes creating both tensile and compressive forces.

The PM105 pressure main crossed Curletts Stream approximately halfway along the pressure main length. The soils in this area indicated some potential for lateral spread during a significant seismic event. Likely strains on the pipe were estimated at less than 2.0% using the procedure included in ALA (2005).

7 PRESSURE MAIN DESIGN CONSIDERATIONS

7.1 PIPE SELECTION

The ground conditions and drilling installation requirements were the determining factors for the pipe selection as maximum operating pressures of the pipeline are only 2.5 bar. Solid Wall SDR 13.6 (PN12.5) pipe was selected for directional drilling requirements and the soft ground conditions.

Polyethylene pipe suited the greenfield nature of the pipeline route with long strings of pipe able to be jointed above ground and installed in an open trench, or by directional drilling, where soil types and groundwater levels did not suit trench construction.

7.2 PIPELINE PROFILE

The pressure main profile was designed to balance construction costs, future accessibility with depth of pipeline and future maintenance requirements and reliability with the number of air valves. Much of the pressure main route is located in areas of soft sandy silts, which suited drilled construction and avoided widespread de-watering.

A slightly deeper profile was selected to suit directionally drilled construction with only a two air valves required over the length of the pressure main. A third air valve was subsequently added to relieve potential negative pressure conditions identified at the end of the pressure main.

7.3 TRENCHLESS CONSTRUCTION

7.3.1 DIRECTIONAL DRILLING

The green field nature of the pipeline route and silty sand soils provided good directional drilling conditions to avoid trenching and de-watering.

Wire tracing was employed by the contractor to allow continuous monitoring of the pilot bore head. This enables continuous adjustment of the head with ground conditions. This provided reliable drilled grades as flat as 1:300 despite pockets of cohesiveless sands and organic material encountered.

Photograph 1: Directional Drilling Operations

7.3.2 THRUSTINGS

The pipeline route included crossings under the Southern Motorway (x 2), SH 76 (Curletts Road) and the railway crossing in Matipo Street. The pipeline was required to be installed in a thrusted steel casing under these transport routes. A minimum casing cover of 2.5m was selected to limit risks of surface disturbance.

This construction method was adopted owing to the comparatively short lengths and variable ground conditions. This included un-consolidated gravels (Southern Motorway at Wigram Road), and soft silty sands. The Southern Motorway Crossing at Annex Road included running sands, silty clays with tree stumps and gravels all within space of sixty metres.

A limitation of pipe thrusting is the ability to control the direction of the thrusted casing. However, this is not so critical for a pressure main construction where the grade can be adjusted.

While some surface disturbance was encountered owing to pockets of unconsolidated gravels and tree stumps, the selected construction method enabled the pipeline to be installed without closure of these important transport links.

7.4 PIPE FITTINGS

Bends and fittings were fabricated using the same pipe resin material to ensure welding compatibility between the pipeline and fittings. Polyethylene pipe fittings were de-rated in accordance with PIPA POP006. Each fitting was factory pressure tested and weld testing was periodically undertaken to demonstrate weld performance.

This enabled segmental bends to be fabricated to suit the final angles required to join the pipe.

8 GRAVITY PIPELINE

8.1 PIPE SELECTION

PM105 project included approximately 1500m of DN800 gravity trunk sewer connecting to the pump station and downstream of the rising main to the existing downstream trunk sewer. Twin walled profile structured wall pipe with integral polyethylene manholes was selected for both the improved seismic performance and corrosion protection that it offered.

In liquefiable soils, pipes were structurally designed for soft ground conditions and SN16 pipe was selected. Otherwise, SN8 pipe was selected.

8.2 GRAVITY PIPE JOINTING REQUIREMENTS

The relevant standard in New Zealand for polyethylene pipes used for gravity drains is AS/NZS5065. There are differences in the requirements for polyethylene gravity pipe joints across a range of international standards. This is perhaps reflective of the limited use of polyethylene for gravity drains and the general lower operational importance of secure leak tight pipe joints for gravity pipe systems by the water and wastewater sector.

Polyethylene pipes provide the potential for secure leak tight sewer systems and fully welded polyethylene pipe has been specified by Sydney Water (2012) to achieve leak-tight sewer systems.

The inclusion of seismic performance requirements raises the importance of providing secure welded pipe joints that will maintain the required joint performance following future seismic events

AS/NZS 5065 (2005) includes two performance criteria for electro-fusion socket joints

- Minimum Fusion Depth
- Ductile performance of the electro-fused joint

These two performance requirements serve to provide confidence in long term water tightness and strength of the pipelines. This differs from most European polyethylene pipe standards such as EN12666, where the jointing requirements are based on the same instantaneous pressure tests as for rubber ring jointed gravity pipes and provide no allowance for material creep and long term strength and leak tightness of the pipe joint.

Extrusion welding was also used for connection to manholes, in trench modifications, manhole construction and direct connections to the sewer. To achieve the performance requirements in AS/NZS5065:2005, additional extrusion welding was carried out to the pipe sockets. The German DVS welding standards provided invaluable independent guidance on requirements for extrusion welding.

As pipe joints were required to be completed in the pipe trench, the joint integrity was controlled with a pressure test to one bar and periodic destructive weld testing to confirm consist welding performance.

8.3 MANHOLE STRUCTURES

Polyethylene manholes were specified to provide an integrally joined system for strength, water tightness and corrosion protection. Full man access shafts were provided for the gravity pipelines for future maintenance or repair/rehabilitation access.

ASTM1759 (2010) was used as the basis of the polythene manhole shaft design. This was verified by Franks PKS Easy Schacht Design software.

Pre-cast manhole lids were used with specially constructed load rings to ensure traffic loads were not transmitted through the PE shaft. This system was also used on concrete riser shafts on the 1600 mm diameter Western Interceptor Sewer in Christchurch constructed in 2010/2011. Monitoring throughout the earthquakes demonstrated that the separation between the manhole lid and riser shaft has been maintained.

Seismic propagation forces dictated the selection of 50 mm chamber wall thickness selected to ensure sufficient connection strength with a 25 mm extrusion weld on either side of the shaft wall.

8.4 SETTLEMENT ALLOWANCES

For this project four different jointing systems were used to connect to adjacent structures and other pipe line materials.

- Polyethylene manhole structures were used to allow the access structures to be integral with the continuous welded pipeline.
- Polyethylene thrust flanges were used to connect to concrete manhole structures and the end of the gravity pipelines
- Flexible EBAA joints were used to connect the pressure main and gravity inlet sewer to the pumping station, which is a fully piled structure and is fully restrained against settlement and flotation.
- Stub flanges and backing rings were used to connected flanged ductile iron connections at the ends of the pressure main (EBAA joint and flanged spool at the discharge chamber)
- Mechanical couplers were used to connect to adjacent rigid pipelines to allow differential settlement between the two gravity pipelines

9 CONSTRUCTION CONTROL

Polyethylene is a pipeline material that requires particular construction control to achieve a quality installed product. The complexities of the jointing processes for polyethylene are much greater than many other pipeline materials and require a good understanding of both the material characteristics and processes required to achieve a quality joint.

Polyethylene welding is an empirically based procedure that requires a combination of material quality consistency and jointing procedure and process.

CCC has put considerable emphasis on pipe manufacturers to provide their manufacturing quality assurance records pipe supply. This includes demonstrating that their pipes are fit for purpose by the manufacturer completing welded joints. The response from the pipe welders has indicated that there has been a noted improvement in pipe material since these requirements were introduced.

Polyethylene is a thermally responsive material, and the dimensions and geometry of the pipe can be affected by environmental conditions. Consequently, these properties need to be confirmed for the pipe along with the environmental conditions prior to joining to ensure the proven empirical conditions are replicated within the specified tolerances.

Data logging equipment, supplemented by manual records are used to demonstrate the consistency of both pipe geometry and welding processes. Automatic welding machines can assist in achieving consistent welding conditions, but they are only as good as their programming and it is necessary to understand the ability of the machine to achieve the required processes.

Periodic destructive testing provides a definitive measure that the required standard of welded joint is achieved. This currently implemented with a 5 % sampling rate (one test every twenty welds).

Only fully qualified and experienced welders are permitted on Council and SCIRT projects. SCIRT has introduced additional self-regulation with administration of a register of welders on SCIRT projects. This includes the auditing of new welders by some of the most experienced welders to ensure consistent quality of workmanship. A best practice group consisting of experienced welders, site engineer's quality mangers, designers and Council representatives meets regularly to administer the welders register, discuss welding or material issues identified. This group also maintains a register of pressure testers that have the experience and suitable equipment to carry out the correct hydrostatic testing of polyethylene pipelines.

10 POLYETHYLENE PIPELINE LIMITATIONS AND CONSTRAINTS

All pipeline materials have advantages and disadvantages compared with other pipeline materials and polyethylene is no exception. Polyethylene pipelines provide a continuous integrally jointed pipeline that provides a strong flexible pipeline.

The specialist nature of polyethylene pipe welding does create construction continuity inefficiencies with different plant and staff required for pipe-laying and pipe jointing. These considerations lend polyethylene pipeline construction to suit construction methodologies where the pipe jointing may be separated from pipe laying phases of the pipeline construction. Trenchless construction or open cut construction on greenfield sites allow long strings of pipe to be jointed prior to installation. Constraints, such as traffic management or dewatering requirements limit the continuity of the welding processes and require additional consideration to create the right environment to complete the welded pipe joints cost effectively.

For the PM105 project, this included completing the construction of the gravity pipeline on three fronts to maintain welder productivity. Trenchless drilled construction and open cut construction suited the greenfield nature of the pressure main route to separate the pipe line construction from the pipe jointing.

The integrity of pipelines can be limited by the availability and practicalities of the available repair methods. Considerable effort can be required to manage flows to prepare a pipeline in service along with obtaining specialist skills and repair couplers to complete repair a welded pipeline. This is an integral part of the design to include enough redundancy to be designed into the reticulation network to permit repairs of the pipeline in a reasonable manner.

While welded joints are the more economical solution, mechanical couplings may be used to repair or join polyethylene pipelines. The specification of and availability of fully restrained couplers to reliably join pipelines to the same standard as a welded construction is currently limited in New Zealand for larger sized fittings and pre purchase is required.

Owing to the limitations and difficulties completing or repairing fully welded pipe joints, a high degree of certainty is required in the ability of the welding process to provide reliable pipe joints.

Photograph 2: Open Cut construction on a 'green-field' site

11 CONCLUSIONS

Polyethylene pipes performed extremely well in the 2010/2011 earthquakes and minimal pipe damage occurred the polyethylene water and sewer mains located in some of the most severely affected areas of Christchurch.

The flexible material characteristics and the ability to achieve a continuous integral pipeline with welded pipe joints can provide seismically resilient pipelines.

The greatest seismic effects are associated with liquefied soils. Detailed ground information is required to assess the susceptibility of the pipeline route to seismic impacts. Seismic loads on pipelines include settlement flotation, buckling and propagation effects.

Particular design requirements are required around the connection of polyethylene pipelines to other pipelines and structures and the ability of connections to be restrained against longitudinal forces induced in the pipeline.

Flexible pipe structural design for soft ground conditions and trench construction with well-constructed trench foundation and properly compacted pipe surround and backfill is considered best practice for pipes constructed in liquefiable soils to mitigate against pipe flotation and liquefaction induced settlement.

Larger diameter polyethylene pipes may be less flexible than smaller diameter pipes. Particular attention is required when considering the flexibility of connections to structures and pipelines.

Polyethylene pipe is well suited to greenfield construction sites and drilled trenchless construction, where specialist welding and pipe-laying activities may be separated to allow construction efficiencies. Specific construction methodologies and jointing procedures need to be considered where site constraints prevent long strings of pipe to be jointed together.

Designing for seismic actions on pipelines does require consideration of national and international standards to provide for the anticipated seismic actions. This is particularly relevant to requirements for gravity pipe joints that are traditional accepted to a lesser standard than the pipe strength.

Successful construction of polyethylene pipelines requires good quality control of pipe material characteristics, environmental responses of the material as well as welding process.

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REFERENCES

ALA, 2005, American Lifelines Alliance Seismic Guidelines for Water Pipes, G & E Engineering Systems Report No 80-01-01 rev 0, March 2005. Prepared for NBS & FEMA

AS/NZS 2566.1(1998) Buried Flexible Pipelines Part 1 Structural Design

AS/NZS 5065 : 2005, Polyethylene & Polypropylene Pipe and Fittings for Drainage and Sewerage Applications

AWWA M55 2006, PE Pipe – Design and Installation American Water Works Association Manual M55

ASTM F1759-97, 1997, Standard Practice for Design of High Density Polyethylene (HDPE) Manholes for Subsurface Applications

ATV A 127 Guidelines for Static Calculations on Conduits and Pipelines (German)

EN 12666-1: 2011 Plastic Pipe Systems for Non Pressure Underground Drainage and sewerage – Polyethylene (PE) Part 1 Specification for Pipes, Fittings and System

Jansen, Lars Eric (2003) Plastic Pipes for Water supply and Sewage Disposal 4th edition

O'Rourke, T.D., Jeon, S,-S, Topak, Cubrinoski M., Jung, J.,K, (2012) Underground Lifeline Systems Performance during the Canterbury Earthquake Sequence, 15 WCEE Lisboa 2012

PIPA POP 6, 2006 Plastics Industry Pipe Association Australia Industry Guidelines De-rating Requirements for Fittings Version 5.01

Sydney Water 2012, Technical Specification for Leak Tight Sewer Systems

Toshiko Simura, Tominaya Naoto, 2008 Evaluation of Earthquake Resistance of Polyethylene Pipes, 2008 International Gas Union Research Conference