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PIPELINE DAMAGE PREDICTIONS IN LIQUEFACTION ZONES USING LSN

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Abstract

Liquefaction is a major concern regarding earthquake damage to infrastructure. Recent earthquakes in New Zealand and resulting liquefaction caused significant damage to buried pipeline systems. Following the 4 September 2010 Mw=7.1 Darfield earthquake, five earthquakes (22 February 2011, Mw=6.2, 13 June 2011, Mw=5.3 at 1 p.m. and Mw=6.0 at 2:20 p.m. and 23 December 2011, Mw=5.8 at 1:58 p.m. and Mw=5.9 at 3:18 p.m.) and thousands of aftershocks have been recorded in the area of Christchurch, NZ. These earthquakes termed the Canterbury Earthquake Sequence (CES) are unprecedented in terms of repeated earthquake shocks with substantial levels of ground motion affecting a major city with modern infrastructure. This study focuses on the effects of 22 February 2011 Christchurch earthquake induced liquefaction on buried pipelines. Correlations were developed between pipe damage, expressed as repairs/km, and a recently developed parameter called liquefaction severity number (LSN). Cone Penetration Test (CPT) based liquefaction triggering procedures were used to calculate LSN values. Studies by Tonkin and Taylor [1,2] and van Ballegooy et al. [3, 4, 5, 6] have shown that LSN provides a good correlation with land and residential house foundation damage observations recorded in Canterbury. According to results obtained in this study for buried pipelines, LSN has reasonably good correlation with asbestos cement (AC), cast iron (CI) and polyvinyl chloride (PVC) pipeline damage.

Keywords: pipeline damage, Christchurch earthquake, liquefaction severity number (LSN)

1. Introduction

Recent earthquakes observation shows that pipeline damage was relatively heavy in the areas where permanent ground deformation (PGD) occurred, especially in areas affected by liquefaction. A common way to express pipeline damage is by a repair rate (RR), which is the number of pipeline repairs in an area divided by the length of the pipelines in the same area. There are many studies that have correlated pipeline damage (RR) with some type of demand parameter. The most common ones are peak ground velocity (PGV) as a proxy for transient ground deformation [7, 8, and 9] and lateral strain and/or angular distortion for PGD [10, 11, 12, 13, 14]. PGV and lateral strain and/or angular distortion have meaning in terms of pipeline response to earthquake-induced ground movement in terms of pullout and compressive damage at joints as well as excessive joint rotation. However, the prediction of lateral strain and angular distortion for pipeline damage estimates is difficult to perform and highly variable with current procedures. If Cone Penetration Test (CPT) based liquefaction vulnerability parameters, such as the Liquefaction Potential Index (LPI) or Liquefaction Severity number (LSN), correlate well with pipeline damage, they can be used for pipeline damage predictions in future earthquake shaking scenarios.

During the 2010 to 2011 Canterbury Earthquake Sequence (CES), Christchurch infrastructure was affected by severe liquefaction with large PGD levels. Fig. 1 shows observed liquefaction related land damage and residential house damage in Christchurch following the CES [3]. In addition to land residential housing damage, there was severe liquefaction-induced damage to the of the water distribution system in Christchurch. O'Callaghan [15] described pipeline failures in streets in liquefiable ground, tension failures due to rotation (Fig. 2a) and axial compression failures (Fig. 2b).

Fig. 1 Observed liquefaction related land damage and residential house damage in Christchurch following the CES [3]

a) Tension effects in AC pipe joint, Sewell Street Kaiapoi

b) Compression effects in AC pipe joint, Sewell Street Kaiapoi

Fig. 2 Pipeline system damage caused by liquefaction [15]

2. Liquefaction Severity Number (LSN)

As part of the earthquake recovery of Christchurch, an extensive geotechnical investigation programme was undertaken. As at March 2015, this included 18,000 CPT, 4,000 boreholes and 1,000 piezometers [16]. The data are available in the Canterbury Geotechnical Database (CGD) and available at https://canterburygeotechnicaldatabase.projectorbit.com. This study utilizes the LSN liquefaction vulnerability parameter for pipeline damage correlations. The studies by Tonkin and Taylor [1, 2] and van Ballegooy et al. [3, 4, 5, 6] have shown that this new liquefaction vulnerability parameter, provides a good correlation with the land and residential house foundation liquefaction induced damage observations recorded in Canterbury. The LSN parameter is calculated as:

$$LSN = 1000 \int \frac{\varepsilon_v}{z}\, dz \tag{1}$$

where “ε_v” is the calculated volumetric densification strain in the subject layer from Zhang et al. [17], and “z” is the depth to the layer of interest in meters below the ground surface.

LSN considers depth weighted calculated volumetric strain within soil layers as a proxy for the severity of liquefaction land damage likely at the ground surface. The published strain calculation techniques consider strains that occur where materials have a calculated triggering factor of safety against liquefaction (FoS) below 2.0. The LSN parameter increases continuously as the FoS decreases, rather than abruptly when the FoS reaches 1.0. One other aspect of the LSN parameter is that strains converge on a limiting value that depends on the initial relative density. Thus, the LSN tends to converge on a maximum value for a given soil profile as the PGA increases.

The extensive CPT data available from CGD were used for the estimation of LSN values at each CPT locations. The four most commonly used simplified CPT based liquefaction triggering methods in engineering practice are Robertson and Wride [18] as set out in Youd et al. [19], Seed et al. [20] as set out in Moss et al. [21], Idriss and Boulanger [22] and Boulanger and Idriss [23]. Van Ballegooy et al. [4, 5] compared these liquefaction triggering methodologies by analyzing the LSN values for all the CPTs available in the CGD for the main CES earthquakes and compared the results to the respective mapped land damage observations. The results showed that Boulanger and Idriss [23] gives the most consistent distribution of calculated LSN values between events for the observation categories of none-to-minor liquefaction-induced land damage and moderate-to-severe liquefaction-induced land damage. The LSN and land damage datasets for the CES events were combined into a single frequency bar chart shown in Fig. 3. This figure shows that at low estimated LSN values there is a high likelihood of none-to-minor land damage and a low likelihood of moderate-to-severe land damage. Conversely, at high LSN values there is a low likelihood of none-to-minor land damage and a high likelihood of moderate-to-severe land damage.

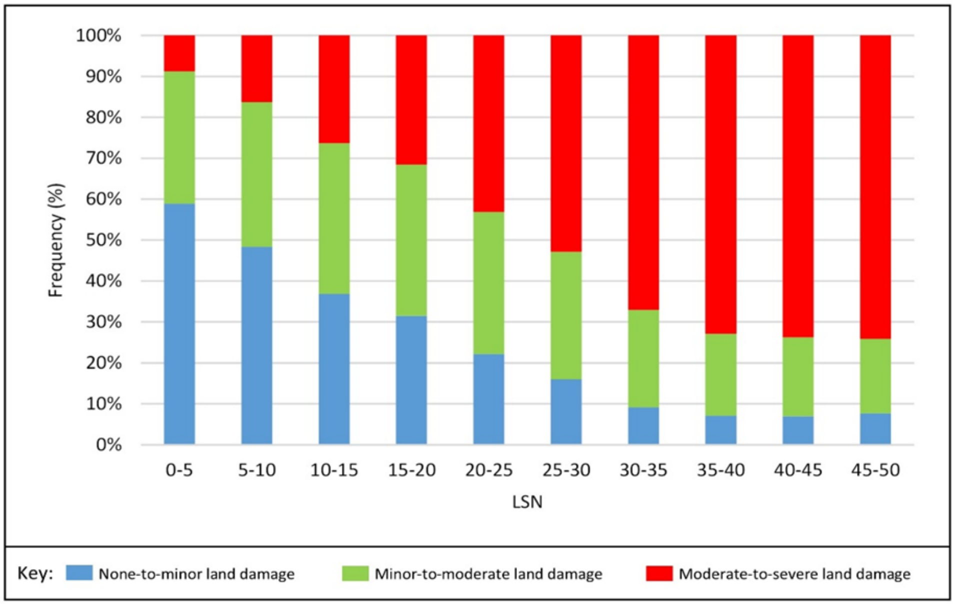

Fig. 3 Frequency bar chart showing the likelihood of none-to-minor, minor-to-moderate and moderate-to-severe land damage for different LSN intervals based on correlated back calculated LSN values with the land damage observations from the September 2010, February 2011 and June 2011 events [2,5]

3. Results

Geospatial data in the form of GIS maps of the Christchurch water distribution systems, locations of pipeline repair, and LSN maps were integrated into a master GIS file. For the water supply this study focuses on damage to water mains, which are pipelines with diameters typically between 75 and 600 mm, conveying the largest flows in the system. It does not include repairs to smaller diameter submains and customer service laterals. Geocoded data files for approximately 1,730 km of water distribution pipelines, respectively, as well as the repairs associated with each earthquake, were provided by the Stronger Christchurch Infrastructure Rebuild Team (SCIRT).

The water supply repair database is composed of continuous daily repair records for return of services covering the period from February 23, 2011 to May 14, 2012, when the 13 June 2011 and 23 December 2011 earthquakes and numerous aftershocks occurred. Which repair belongs to which earthquake is difficult to ascertain. O'Rourke et al. [10, 11] studied the cumulative frequency of repairs in the water distribution system during the CES and determined the end of repair activities directly related to each main seismic event. The total length of Christchurch pipelines was 1,730 km and distribution of pipes for pipe types were; 867 km AC, 194 km CI, 214 km PVC, 150 km MPVC and 305 km other types (steel, concrete, DI etc.).

Figs. 4 and 5 show the water pipelines and location of the repairs for 22 February 2011 Christchurch earthquake. Also shown in the figures are the interpolated LSN values for the same earthquake [5]. The estimated LSN values for the 22 February 2011 earthquake are based on the top 10 m of the soil profile and use the Boulanger and Idriss [23] liquefaction triggering methodology, using the 15th percentile Cyclic Resistance Ratio (CRR) curves. The Fines Content (FC) is estimated from the soil behavior type index (Ic) parameter assuming a FC-Ic correlation with a fitting parameter $C_{FC} = 0$ and an Ic cutoff value of 2.6 above which the soils are assumed to be too plastic in behavior to liquefy. Fig. 3 shows LSN ranges and observed land effects. The same LSN range was used for the pipeline damage assessment.

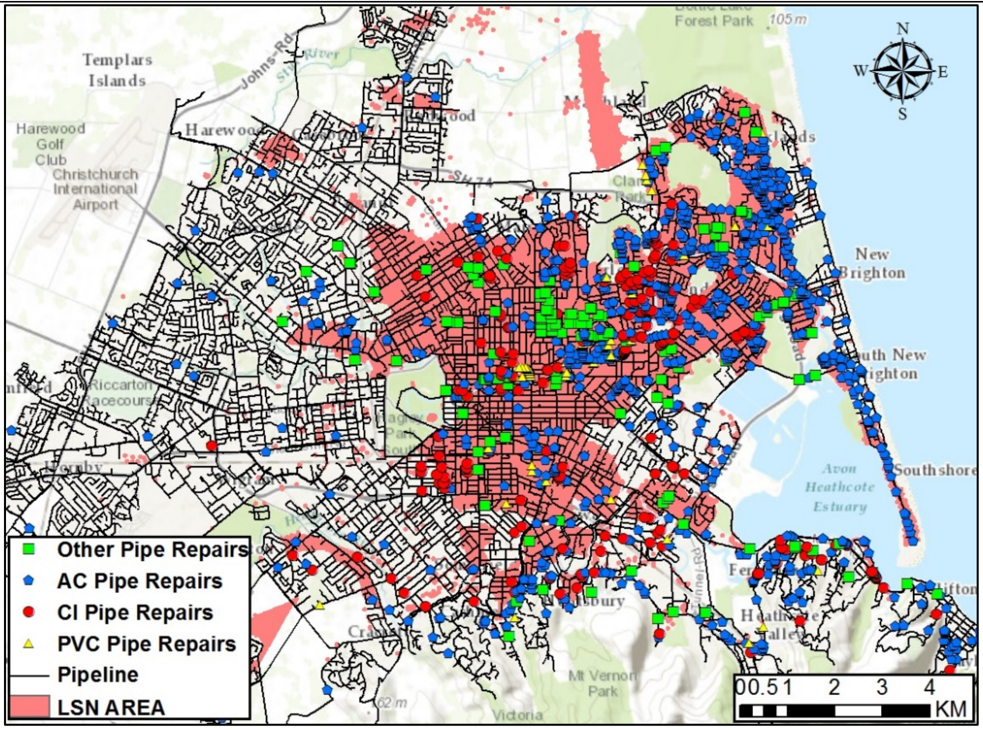

Fig. 4 Pipeline distribution and repairs superimposed on LSN zones for 22 Feb. 2011 earthquake

The interpolated LSN values shown in Fig. 5 were spatially matched with pipelines and repairs by using GIS to correlate LSN values with the pipelines and repairs. To be consistent with the LSN range given in Fig. 3, LSN intervals of 10 were used, and the screening criterion described by O'Rourke et al. [11] was used to produce meaningful correlations. The total length of pipelines in the area of interpolated LSN values is 490 km and distribution of pipelines with respect to pipe types are: 216 km AC, 80 km CI, 73 km PVC, 29 km MPVC and 92 km other types (steel, concrete, ductile iron etc.). A total 1,179 repairs were undertaken within the area of interpolated LSN values and nearly 90% of these repairs were AC, CI and PVC.

Figs. 6, 7, and 8 present RR versus LSN data for Christchurch and 22 February 2011 earthquake. The linear regressions and equations are shown in the figures for AC, CI and PVC water pipelines. Also shown in the figures are the Probabilities of Damage (PoD) for the pipelines. Correlations of RR for different pipe types vs. LSN were developed by counting the number of repairs and pipeline lengths for the particular pipe type in each LSN zone interval, and then calculating the RR associated with LSN intervals of 10. Using the screening technique described by O'Rourke et al. [11], 90% confidence and $\alpha = 50\%$, were applied to develop the linear regressions between RR and LSN. Sufficient RR data for AC, CI, and PVC water pipelines that passed the screening process were available to develop the regressions in the figures.

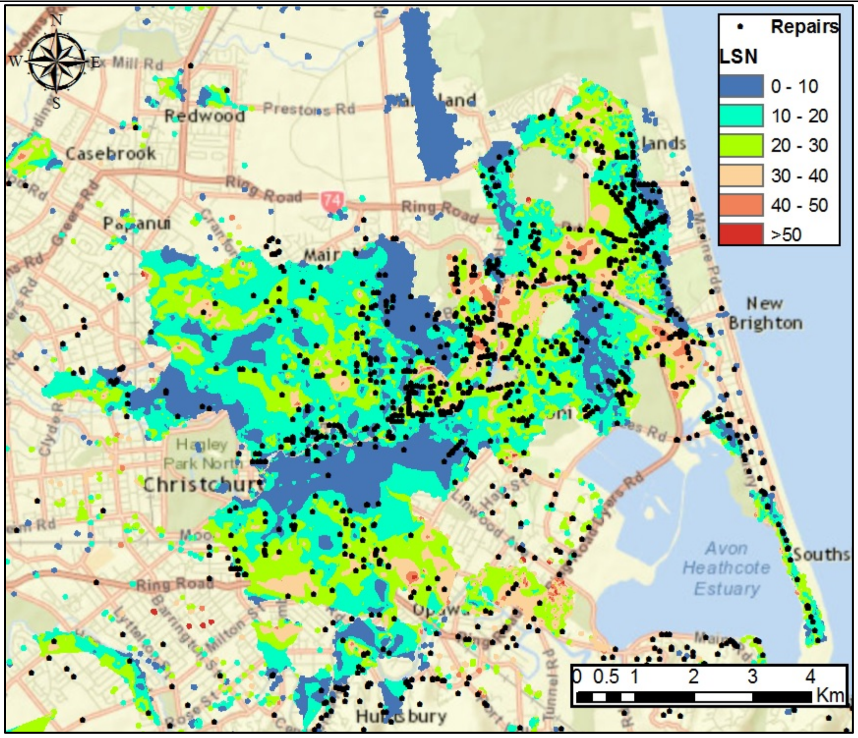

Fig. 5 Pipeline repairs superimposed on LSN distribution map for 22 Feb. 2011 Christchurch earthquake

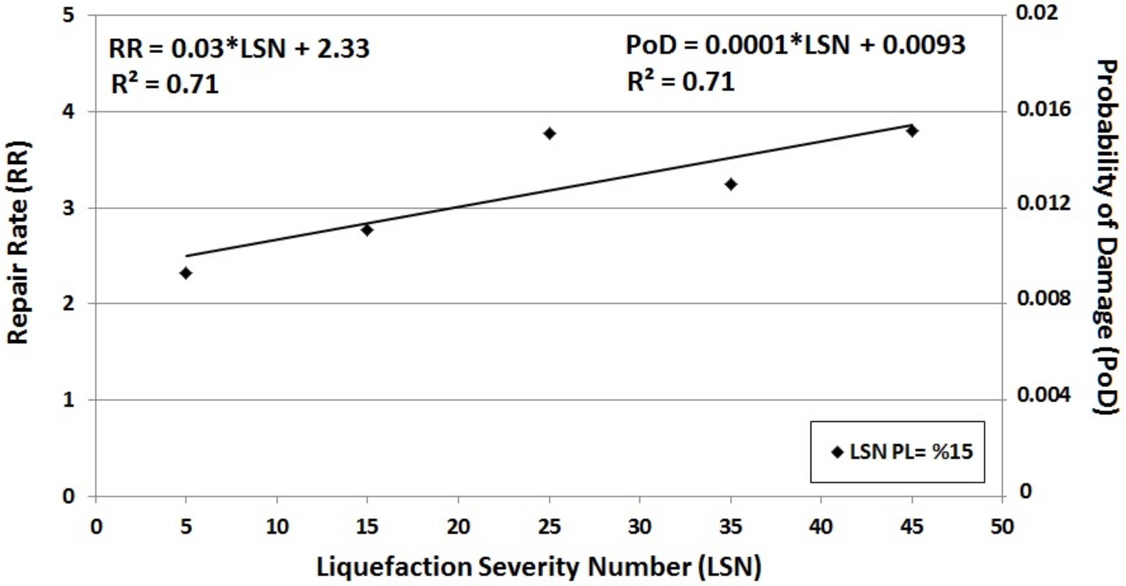

Fig. 6 RR and probability of damage vs. LSN relationships for AC pipelines

Pipeline damage ratios for each type of pipe were obtained by dividing the sum of pipe lengths needing repairs by the sum of all pipe lengths in each LSN interval. To estimate the sum of all pipe lengths for an LSN interval, the total pipeline length for each type of pipe in each LSN interval should be divided by the segment length of particular pipe type. The information from the field and pipe manufacturing processes indicates that the laying lengths of different pipe types are different. The typical laying lengths of AC and PVC pipes are 4 and 6 m, respectively. The typical lengths for CI pipes installed prior to and after 1940, are 3.7 m and 6 m, respectively.

By using these laying pipe lengths and the distribution of pipelines after and before 1940, equivalent pipe length for CI pipes is calculated as 5 m. The number of pipes in each LSN interval that needed repair is estimated by assuming that each repair corresponds to one damaged pipe. This assumption was substantiated by checking and confirming that the distances between repairs are greater than 6 m by using GIS. The pipeline damage ratio is simply the ratio of the number of damaged pipelines to the total number of pipelines in the same strain category zone. Toprak et al [13] presented similar parameters, referred to as probabilities of damage, for AC and CI pipelines in Avonside area in Christchurch as a function of PGD (i.e. lateral stain and vertical angular distortion).

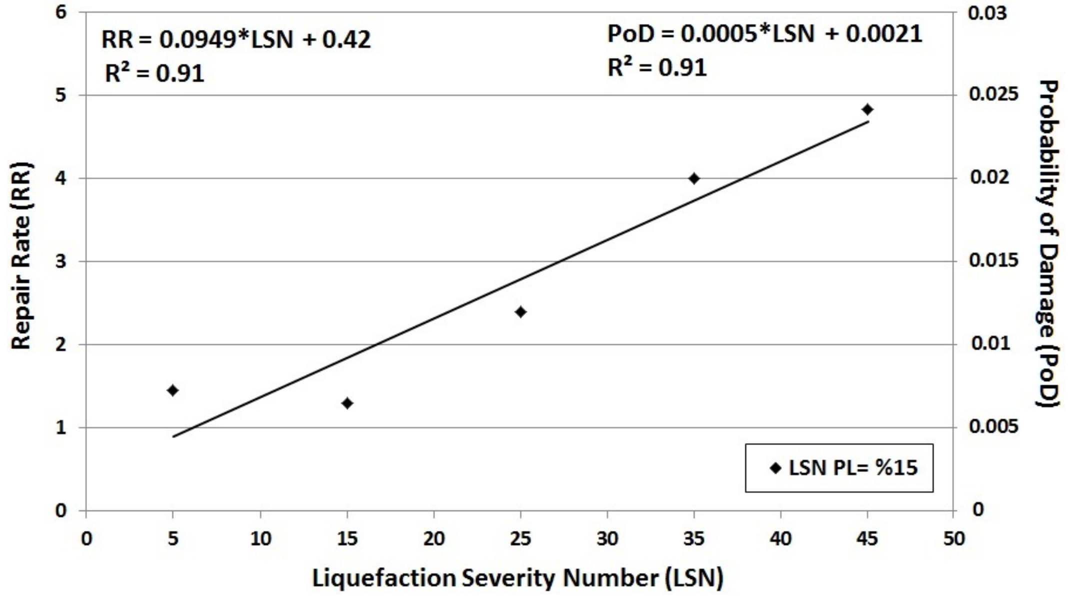

Fig. 7 RR and probability of damage vs. LSN relationships for CI pipelines

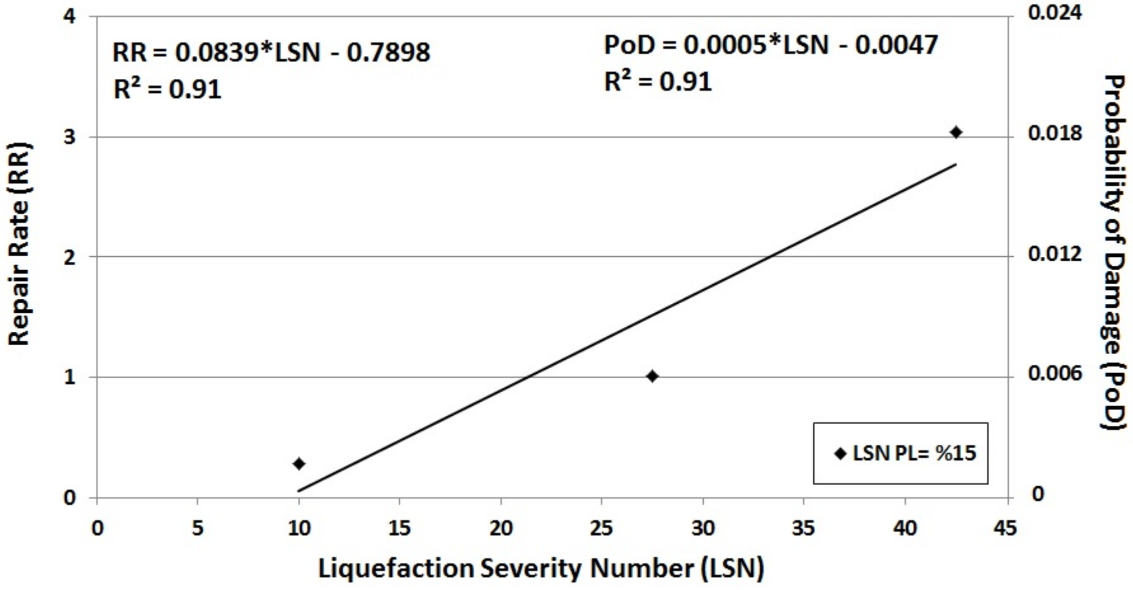

Fig. 8 RR and probability of damage vs. LSN relationships for PVC pipelines

4. Conclusions

This study presents preliminary pipeline damage correlations by using a new parameter for predicting liquefaction vulnerability (i.e. LSN). There is a strong correlation between pipeline damage for AC, CI and PVC pipelines and LSN as indicated by the relatively high r-squared values. AC pipelines have the highest RR, particularly at the lower LSN intervals, approximately twice as high as that for PVC pipelines. CI RRs plot between the trends for AC and PVC pipelines. At high LSN values, the RRs for AC, CI and PVC pipelines converge. When compared with pipeline damage relationship for lateral strains and PGV, the pipeline damage relationships with LSN provide comparable r-squared values.

The initial results presented herein show statistically significant regressions between pipeline damage, expressed as RR/km, and that LSN for AC, CI, and PVP pipelines. It is noted that the area of interpolated LSN values is biased towards the areas where there was liquefaction damage during the CES (i.e. CPT investigations were not undertaken in areas where there was no observed land damage). As a result, the correlations presented in Figs 6, 7 and 8 also include this bias. In areas where no land damage occurred, there was very low instances of pipe repairs. These areas typically comprise denser soils and/or deeper groundwater levels and would typically have much lower LSN values. Therefore, if this bias was allowed for in the analyses presented in Figs 6, 7 and 8, then the RR values at the lower LSN values is likely to reduce and thereby further strengthening the correlations. In addition, there are areas in Christchurch where the CPT-based liquefaction triggering methodologies over-predict the liquefaction relative to the observations. There are several studies that are looking into the over-prediction [e.g., 24] and how the liquefaction assessment methodologies can be improved. When the liquefaction methodologies improve, the spatial distribution of calculated LSN values is likely to change and will change the RR correlations presented in Figs 6, 7 and 8. Therefore, it is important to recognize that these correlations are specific to the Boulanger and Idriss [23] liquefaction triggering assessment methodology using the 15th percentile CRR curves.

The future studies will include pipe damage correlations development with the 50 and 85 percentile CRR curves using LSN parameter, as well as removing the bias by expanding the LSN interpolation areas into areas where there are denser soils and deeper ground water levels where there are significantly less CPT investigations. Also other common liquefaction parameters such as LPI and LPI_{ISH} will also be evaluated for the assessment of pipeline damage.

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6. References

[1] Tonkin & Taylor Ltd. (2013): Liquefaction Vulnerability Study. *Report Number:* 52020.0200/v1.0.

[2] Tonkin & Taylor Ltd. (2015): Canterbury Earthquake Sequence: Increased Liquefaction Vulnerability Assessment Methodology. *Report Number:* 52010.140.v1.0

[3] van Ballegooy S, Malan P, Lacrosse V, Jacka ME, Cubrinovski M, Bray JD, O'Rourke TD, Crawford SA, Cowan H (2014): Assessment of Liquefaction-Induced Land Damage for Residential Christchurch. *Earthquake Spectra*: February 2014, Vol. 30, No. 1, pp. 31-55.

[4] van Ballegooy S, Lacrosse V, Simpson J, Malan P (2015): Comparison of CPT-based simplified liquefaction assessment methodologies based on Canterbury Geotechnical Dataset. *12th Australia New Zealand Conference on Geomechanics*, Wellington, New Zealand.

[5] van Ballegooy S, Wentz F, Boulanger RW (2015): Evaluation of CPT-based liquefaction procedures at regional scale. *SDEE, Special Issue: Liquefaction in NZ/Japan.*

[6] Lacrosse V, van Ballegooy S, Bradley BA (2015). Effect of Liquefaction Triggering Uncertainty on Liquefaction Consequence. *Proceedings of the 6th International Conference on Earthquake Geotechnical Engineering*. Christchurch, New Zealand: ISSMGE

[7] O'Rourke TD, Toprak S, Sano Y (1998): Factors affecting water supply damage caused by the Northridge earthquake. *Proceedings of the Sixth u.s. National Conference on Earthquake Engineering*.

[8] Toprak S (1998): Earthquake Effects on Buried Lifeline Systems. Ph.D. Thesis, Cornell University, Ithaca, NY.

[9] Toprak S, Koc AC, Cetin OA, Nacaroglu E (2008): Assessment of buried pipeline response to earthquake loading by using GIS. *14th World Conference on Earthquake Engineering*, Paper 06-0077, Beijing, China.

[10] O'Rourke TD, Jeon SS, Toprak S, Cubrinovski M, Jung JK (2012): Underground lifeline system performance during the Canterbury earthquake sequence. *15th World Conference in Earthquake Engineering*, 2012, September. Lisbon, Portugal.

[11] O’Rourke TD, Jeon SS, Toprak S, Cubrinovski M, Hughes M, Ballegooy S, Bouziou D (2014): Earthquake response of underground pipeline networks in Christchurch, NZ. *Earthquake Engineering Research Institute, EERI*, Vol. 30, No. 1, pp. 183-204.

[12] Toprak S, Nacaroglu E, O'Rourke TD, Koc AC, Hamada M, Cubrinovski M, Jeon SS (2014): Pipeline damage assessment using horizontal displacements from air photo and LiDAR measurements in Avonside area, Christchurch, NZ. *2th European Conference on Earthquake Engineering and Seismology*, Istanbul, Turkey.

[13] Toprak S, Nacaroglu E, Koc AC (2015): Seismic damage probabilities for segmented buried pipelines in liquefied soils. *6th International Conference on Earthquake Geotechnical Engineering*, 1-4 November 2015 Christchurch, New Zealand.

[14] Toprak S, Nacaroglu E, Koc AC (2015): Seismic response of underground lifeline systems. *Perspectives on European Earthquake Engineering and Seismology Vol. 2*, Chapter:10, pp: 245-263, Editors: Ansal, Atilla (Ed.), ISBN: 978-3-319-16963-7 (Print) 978-3-319-16964-4 (Online).

[15] O’Callaghan FW (2014). Pipeline performance experiences during seismic events in New Zealand over the last 27 years. *Proceedings of the 17th Plastic Pipes Conference*, September 22-24, 2014, Chicago, Illinois, USA.

[16] Scott J, van Ballegooy S, Stannard M, Lacrosse V, Russell J (2015). The Benefits and Opportunities of a Shared Geotechnical Database. *Proceedings of the 6th International Conference in Earthquake Geotechnical Engineering*. Christchurch, New Zealand: ISSMGE.

[17] Zhang G, Robertson PK, Brachman RWI (2002): Estimating liquefaction induced ground settlements from CPT for level ground. *Canadian Geotechnical Journal*, 39, 1168–80.

[18] Robertson P, Wride C. (1998): Evaluating cyclic liquefaction potential using the cone penetration test. *Canadian Geotechnical Journal*, 35(3), pp.442-459.

[19] Youd T, Idriss I, Andrus R, Arango I, Castro G, Christian J, Dobry R, Finn W, Harder Jr L, Hynes M, Ishihara K, Koester JP, Liao SSC, and others. (2001): Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 127(10), pp.817-833.

[20] Seed RB, Cetin KO, Moss RES, Kammerer AM, Wu J, Pestana JM, Riemer MF, Sancio RB, Bray JD, Kayen RE, Faris A, (2003): Recent advances in soil liquefaction engineering: a unified and consistent framework. *26th Annual ASCE Los Angeles Geotechnical Spring Seminar, Keynote Presentation*, H.M.S. Queen Mary, Long Beach, California, April 30, 2003.

[21] Moss R, Seed R, Kayen R, Stewart J, Der Kiureghian A, Cetin KO (2006): CPT-based probabilistic and deterministic assessment of in situ seismic soil liquefaction potential. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(8), pp.1032-1051.

[22] Idriss IM, Boulanger RW (2008): Soil liquefaction during earthquakes. 1st ed. Oakland, Calif.:Earthquake Engineering Research Institute (EERI).

[23] Boulanger RW, Idriss IM (2014): CPT and SPT based liquefaction triggering procedures. *Report UCD/CGM-14/01*, Department of Civil and Environmental Engineering, University of California, Davis, CA, 134 pp.

[24] Stewart JP, Kramer SL, Kwak DY, Greenfield MW, Kayen RE, Tokimatsu K, Bray JD, Beyzaei CZ, Cubrinovski M, Sekiguchi T, Nakai S, Bozorgnia Y (2015): PEER-NGL Project: Open Source Global Database and Model Development for the Next-Generation of Liquefaction Assessment Procedures. 6th International Conference on Earthquake Geotechnical Engineering, 1-4 November 2015 Christchurch, New Zealand.