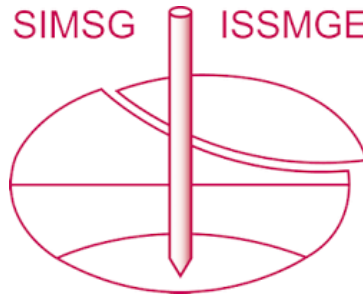


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Liquefaction demand parameters best correlated to damage on buried pipeline networks: The case study of Christchurch

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ABSTRACT: During the 2010-2011 Canterbury Earthquake Sequence (CES), liquefaction caused extensive damage to buried pipelines all over Christchurch City. The overall damage to the pipelines, usually denoted as Repair Rates (RR, the number of repairs per km of the pipeline length), was a result of interaction of two main factors, namely; the vulnerability of the pipelines (identified with different pipeline types, pipeline material, pipeline diameters and pipeline lengths) and severity of liquefaction observed in the city of Christchurch. The latter can be represented by adopting different indices, such as Liquefaction Potential Index (LPI), Liquefaction Severity Number (LSN) and soil settlements. The following study focusses on the February 2011 Christchurch earthquake induced liquefaction damage on buried Asbestos Cement (AC) pipelines of the Christchurch city water supply system. Correlations representing the relationship between RR and liquefaction severity indices are presented. Also, special effort was made to identify the Intensity Measures (IMs) that best correlate with the liquefaction-induced pipeline damage, based on the efficiency and sufficiency criteria set up by Luco & Cornell (2002).

1 INTRODUCTION

Extensive damage to pipelines was observed due to liquefaction during the Canterbury Earthquake Sequence (CES) 2010-2011 in Christchurch City, New Zealand. Pipeline damage, usually expressed as Repair Rates (RR), the ratio of number of repairs to the pipeline length in km, is a result of two main factors; namely vulnerability of pipelines (identified with different pipeline types, pipeline material, pipeline diameters and pipeline lengths) and earthquake hazard including ground motions, permanent ground deformations and indices defining the measure of liquefaction severity (Bagriacik et al., 2018). Several past studies have developed correlations between RRs of pipelines and Intensity Measures (IM), also showed that brittle pipelines are more vulnerable to damage comparatively to ductile pipelines (Cubrinovski et al., 2014). IMs like Peak Ground Velocity (PGV), which represents transient ground deformations (Toprak et al., 2017), Permanent Ground Deformation (PGD), angular distortion, lateral strain, Liquefaction Severity Number (LSN), settlement have been used in developing fragility curves for pipeline damage (Eguchi, 1991; Eidingner, 1998; Isoyama et al., 2000; O'Rourke et al., 2012; Toprak et al., 2017; Bagriacik et al., 2018). Eguchi, 1991 was the first

to develop relationship between RR and PGD for different pipe materials (Eguchi, 1991). Angular distortion and lateral strain were used by O'Rourke et al., 2012, which have showed good correlation with pipeline damage, but are typically difficult to measure and their predictions are variable due to their dependency on surveying instruments (Toprak et al., 2017).

To find the most appropriate IM representing the Damage Measure (DM) of the structure, Luco & Cornell (2002) recommended two parameters namely, efficiency and sufficiency. Shakib et al., 2016, applied the Luco & Cornell (2002) method to find the most appropriate IM for buried pipelines, not including liquefaction during the analysis.

This study aims to develop correlations between RRs of AC (Mains) pipeline network of Christchurch City and Liquefaction Severity Indicators (mentioned in our study as Liquefaction Demand Parameters (LDP)) for the 22nd February 2011 earthquake. The LDPs utilized in this study are settlement, LSN, Liquefaction Potential Index (LPI) and Liquefaction Potential Index as given by Ishihara (LPI_{ISH}) (Tonkin & Taylor, 2013). The Luco & Cornell (2002) criteria of efficiency and sufficiency are adopted to identify the most appropriate LDP.

2 DATASET OF LIQUEFACTION-INDUCED DAMAGES ON WATER SUPPLY PIPELINE NETWORK IN CHRISTCHURCH

Six major seismic events hit Christchurch during the CES period as shown in Figure 1; 4th September 2010 (Mw = 7.1), 22nd February 2011 (Mw = 6.2), 13th June 2011 (2 earthquakes; Mw = 5.3 at 1 pm; Mw = 6.0 at 2:20 pm) and 23rd December 2011 (2 Earthquakes; Mw = 5.8 at 1:58 pm, Mw = 5.9 at 3:18 pm). The 22nd February 2011 earthquake, whose epicenter was located 4-10 km away from the Christchurch Business District, was the most damaging for the city of Christchurch (Cubrinovski et al., 2014).

The CES caused widespread liquefaction, for observed PGA as low as 0.57g, in alluvial silts and fine grained sand deposits with high water tables (1-2m depth), mostly present in eastern and central Christchurch (Cubrinovski et al., 2015; Quigley et al., 2013). Approximately more than 87% of land damage was seen due to severe subsidence, as a result of lateral spreading, sand ejecta to the ground surface, post liquefaction volumetric densification and differential ground settlements (Cubrinovski, et al., 2015; van Ballegooy, et al., 2014). These earthquake induced widespread manifestation of soil liquefaction including large permanent ground deformations causing severe damage to underground pipelines, an example shown in Figure 3b.

The water supply pipeline network in Christchurch City is divided into mains, submains, crossovers, and trunk mains, buried at varying depths ranging from 0.8m to 1.0m. Each type of pipeline network is constructed of different types of pipeline construction materials, pipe diameters and pipeline lengths with laying year ranging from 1890 to 2011, as listed in Table 1 (Cubrinovski et al., 2011). It can be seen that AC pipelines are the most commonly used pipeline construction material.

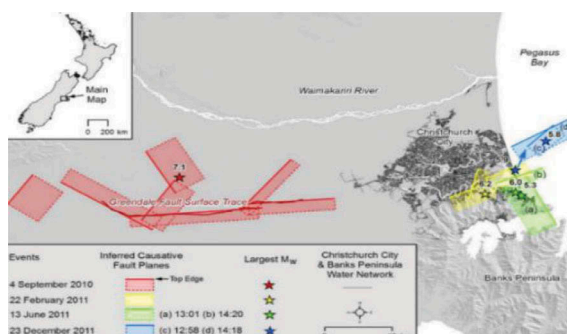


Figure 1. Map showing the city of Christchurch and the events of the Canterbury Earthquake Sequence (Map reproduced from Cubrinovski et al., 2014)

Table 1. List of pipe materials with their lengths in km and range of diameters in mm.

Pipe Construction Materials		Length (km)	Diameters (mm)
Asbestos Cement	AC	857	25 to 375
Cast Iron	CI	190	38 to 375
Modified Polyvinyl chloride	MPVC	150	50 to 300
Polyvinyl Chloride	PVC	281	15 to 600
Others	(steel, concrete, DI)	400 approx.	13 to 550

A GIS (Geographical Information System) database of Christchurch pipeline network and pipeline repair data (as shown in Figure 2a) was prepared by Christchurch City Council (CCC) and Stronger Christchurch Infrastructure Rebuild Team (SCRIT). Figures 2b and 3a show the layout of AC pipeline network and a network of AC pipelines with repairs, respectively. Large number of repairs can be seen in eastern and central parts of Christchurch city. The GIS database of the pipeline network included pipeline diameter, lengths, material, types and year the pipes were laid. The pipeline repair data included number of repairs for each pipeline, repair dates, description of the damage and number of days required for repair. The repairs for each earthquake of the CES, vary drastically with February 2011 event being the most damaging earthquake with approx. 3000 number of repairs. With earthquakes occurring in series, it is difficult to identify which repair was caused due to which earthquake. This led us to assume repair dataset between 22nd Feb 2011 and 13th June 2011 as complete. Repairs observed for AC (mains) pipelines were approx. 850 nos.

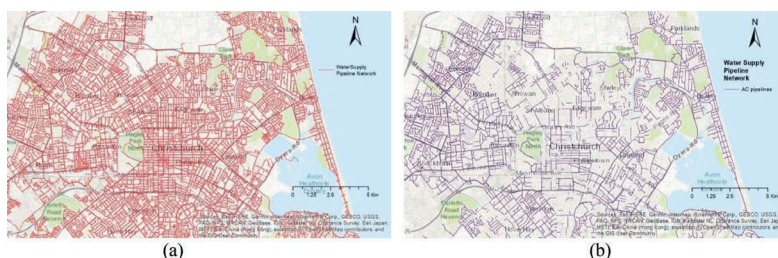


Figure 2. (a) Map showing the Water Supply Pipeline Network of Christchurch. (b) Map showing AC pipelines (Map retrieved from New Zealand Geotechnical Database ([2018]) “Liquefaction evaluation of CPT investigations”, Map Layer CGD0050, retrieved [2018] from <https://www.nzgd.org.nz/>)

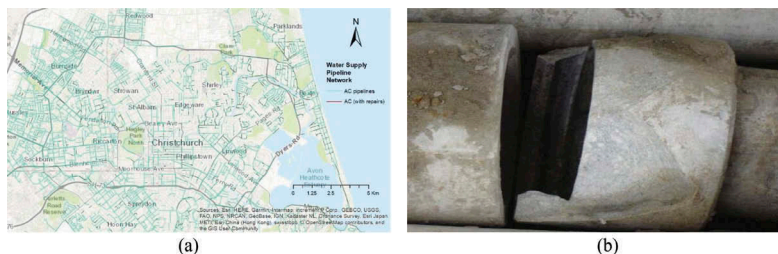


Figure 3. (a) Map showing the AC pipeline network superimposed with AC pipelines with repairs (Map retrieved from New Zealand Geotechnical Database ([2018]) “Liquefaction evaluation of CPT investigations”, Map Layer CGD0050, retrieved [2018] from <https://www.nzgd.org.nz/>) (b) Compression effects in AC pipe joint, Sewell Street Kaiapoi (Reproduced from Toprak et al., 2017)

3 LIQUEFACTION DEMAND PARAMETERS (LDP) IN CHRISTCHURCH AREA

A large scale geotechnical investigation program was undertaken after each earthquake during CES, this included 15649 Cone Penetration Tests (CPT) between September 2010 and March 2013. This database is available in New Zealand Geotechnical Database at <https://nzgd.org.nz>. CCC and Tonkin & Taylor (2013) developed an analysis tool, based on Boulanger and Idriss (2014) liquefaction triggering method to develop independent regional-scale maps of different liquefaction vulnerability indicators using the CPTs conducted during CES, hereinafter called Liquefaction Demand Parameters (LDP), for a range of earthquake scenarios, groundwater table surfaces and soil properties (Tonkin & Taylor, 2013). The LDPs are as follows:

- Settlement (S) - Based on Zhang et al., 2002
- Liquefaction Severity Number (LSN) - As defined in Tonkin & Taylor, 2013
- Liquefaction Potential Index (LPI) - As defined by Iwasaki et al., 1978
- Liquefaction Potential Index as given by Ishihara (LPI_{ISH})-Using the Ishihara inspired LPI method developed by Maurer et al., 2014a.

For each earthquake scenario these indicators were mapped with a selection of liquefaction triggering input parameters (Tonkin & Taylor, 2013):

1. Probability of Liquefaction, PL (PL = 15%, PL = 50% and PL = 85%).
2. Fines content versus I_C relationship calibration parameter, C_{FC} ($C_{FC} = 0$ and $C_{FC} = 0.2$).
3. PGA distribution given by Cornell and Bradley (Tonkin & Taylor, 2013; Bradley et al., 2012b; Bradley et al., 2012c), individually.

Lacrosse et al., 2015 observed that eastern Christchurch generally correlates with PL = 15% and wester Christchurch correlates more closely to PL = 85%. The geo-spatial data dividing the city of Christchurch for these PLs is not complete (Lacrosse et al., 2015). Hence, we consider PL = 50% to represent the entire city of Christchurch. PGA distribution given by Bradley et al., 2012b and Bradley et al., 2012c and Fines Content versus calibration parameter given by $C_{FC} = 0$ is utilized in our study. Geospatial dataset in the form of GIS maps of LDP values at each CPT location, water supply pipeline network and water supply pipeline repairs were integrated into a master GIS file. The location points where LDPs were calculated are concentrated in the region of eastern and central Christchurch, as shown in Figure 4a. This created an inherent skewness in the dataset utilised for our analysis. These LDP values were interpolated over the entire area of Christchurch using kriging interpolation, shown in Figure 4a, and extracted at the locations of AC pipeline repair points. Figure 4b shows LSN interpolated zonation's superimposed with points of repairs for AC pipelines for Christchurch City.

4 IDENTIFICATION OF OPTIMAL LDP BEST RELATED TO DAMAGES ON PIPELINES BASED ON EFFICIENCY AND SUFFICIENCY CRITERIA

4.1 General approach

Probabilistic seismic demand analysis tool is utilized in evaluating the exceedance of an Engineering Demand Parameter (EDP) or Damage Measure (DM) for a given structure, for a certain value of Intensity Measure (IM) (Shakib et al., 2016). The correlation of exceedance of the EDP and IM depends on the ability of IM to represent the intensity of the earthquake. Luco et al. (2002) & Luco et al., (2007) developed an analytical method to find an IM which appropriately represents the exceedance of an EDP or DM. Two parameters namely, efficiency and sufficiency of the IM, were put forth in finding the most appropriate IM. Efficiency of an IM results in a small variability of the structural DM and sufficiency of an IM leads to an EDP or DM which is independent of earthquake magnitude (M) and the source to the site (structure) distance (R) (Shakib et al., 2016). In our study, efficiency and sufficiency approach were applied empirically by utilizing IMs taken as the LDPs and DM or EDP taken as Repair Rates (RR).

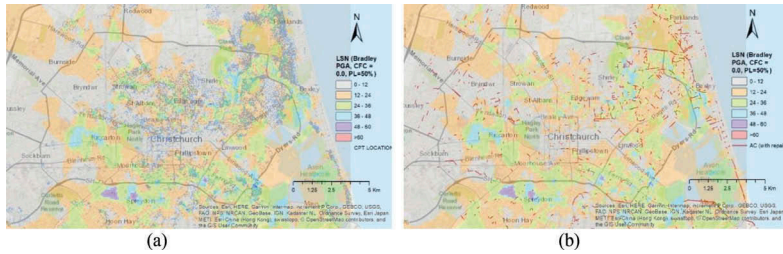


Figure 4. (a) Map showing interpolated LSN map from the points of CPT locations. (b) Map showing LSN map superimposed with the AC pipelines (with repairs)(Maps retrieved from New Zealand Geotechnical Database ([2018]) “Liquefaction evaluation of CPT investigations”, Map Layer CGD0050, retrieved [2018] from <https://www.nzgd.org.nz/>)

The correlation of the EDP and IM can be assumed in the power form (Shakib et al., 2016; Luco et al., 2002).

$$EDP = a(IM)^b \quad (1)$$

Which transforms into

$$LN(EDP) = Ln(a) + b * Ln(IM) \quad (2)$$

The constants a and b in Equation 2 are found by linear regression on EDP and IM. Thus, efficiency is determined using regression analyses of the natural logarithm of Repair Rates (Ln(RR)) on the natural logarithm of corresponding values of each LDP (Ln(LDP)). It is characterized in terms of the dispersion of the residuals, given by standard deviation of the residuals (Shakib et al., 2016). Sufficiency is determined by the statistical significance of the trend of the residuals from regression between LDP and magnitude or distance, individually, given by p-value. In our case study, we utilised only the February 2011 earthquake and hence the distances between the pipelines and the epicentre of the earthquake is same for all LDPs. Due to these restrictions, the significance i.e. the p-value by regressing RR and magnitude, remains the same over all LDPs. As for distance, a data driven solution was developed by averaging the distance to the epicentre of the earthquake each LDP zone. This was done by taking a ratio of sum of distances between pipelines and earthquake epicentre to the count of the pipelines in each LDP zone. This was plotted against the residuals of the RR to find the p-value.

4.2 Results

4.2.1 Repair Rates (RR) and LDPs correlations

Repair Rate and LDP relationships were developed by adding all repairs for each zone of the LDP and divided by the sum of length of the pipeline in that zone. The screening criteria given by O’Rourke et al., 2012, was used is setting the range of the bins for LDP zonation. The trend of regression between RR and LDP shows LPI to have the highest r-squared values. High r-square values are indicators of good correlation between RR and LDP. There is a general increasing trend in the RR as the LDP value increases, which indicates the increase in the severity of liquefaction and is consistent with the theory of increasing IM increases the level of damage. However, LSN and LPI_{ISH} shows a decreasing trend, which is an indication of the influence LSN and LPI_{ISH} zonation intervals and skewness of the data-points. Maximum RR lies between 2-2.5/km, the variability of the observed maximum values of RR depend on the choice of LDP interval bins considered during LDP interpolation in ArcGIS.

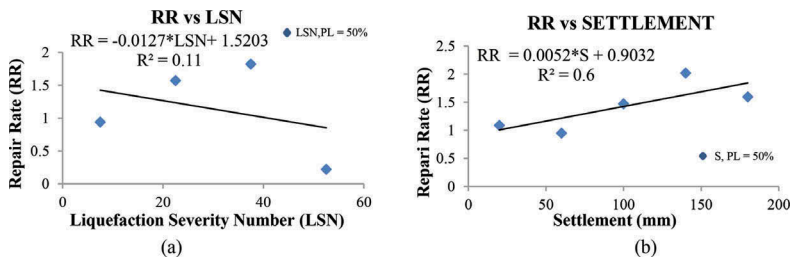


Figure 5. (a) Repair Rates vs LSN values for AC pipelines. (b) Repair Rates vs Settlement values for AC pipelines.

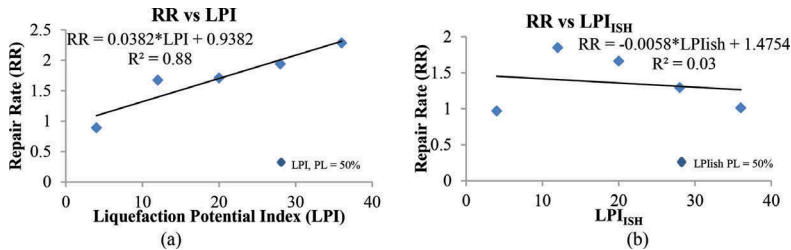


Figure 6. (a) Repair Rates vs LPI values for AC pipelines (b) Repair Rates vs LPI_{ISH} values for AC pipelines.

4.2.2 Luco & Cornell (2002) Approach:- Efficiency

Standard deviation results obtained by regression analysis on RR and LDPs are shown in Table 2. LPI showed the lowest standard deviation with 0.082 and LSN the highest with 0.89. The results are consistent with the r-squared values obtained from regression between RR and LDP.

4.2.3 Luco & Cornell (2002) Approach:- Sufficiency

From Figure 7, no difference is observed in the p-value for the regression between RR residuals and magnitude. As for distance, seen in Figure 8, the highest p-values are observed for settlement and LPI with 0.89 and 0.85 respectively. LPI shows a combination of high p-values given as a measure for sufficiency and low standard deviation values given as a measure of efficiency.

5 CONCLUDING REMARKS

- There is a visible bias in the locations of the CPTs and hence in the location of LDP values. This bias is also visible in the RR vs LDP relationships developed, with many AC pipelines (with repairs) being misrepresented by the values of LDP.

Table 2. Regression analysis results for efficiency calculation.

LDP	Standard Deviation of the Residuals, σ	p-value for Magnitude	p-value for Distance
Settlement	0.20	1	0.89
Liquefaction Potential Index (LPI)	0.082	1	0.85
Liquefaction Potential Index as given by Ishihara (LPI_{ISH})	0.28	1	0.62
Liquefaction Severity Number (LSN)	0.89	1	0.45

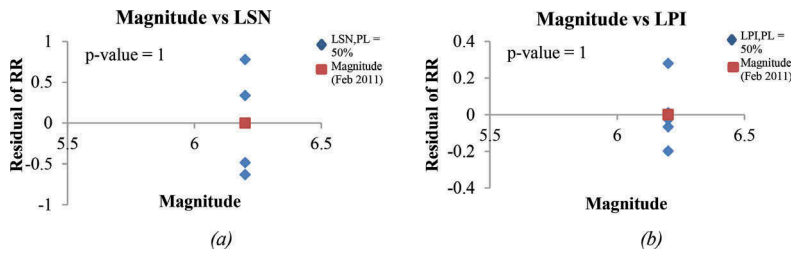


Figure 7. Magnitude vs Residual values of RR for (a) LSN (b) LPI for AC pipelines.

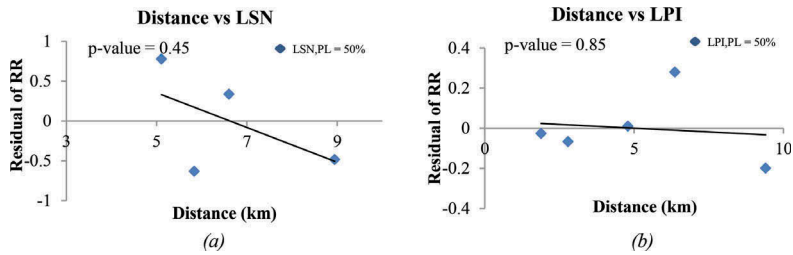


Figure 8. Distance vs Residual values of RR for (a) LSN (b) LPI for AC pipelines.

- The higher values of the LDPs are not repeatedly observed, which is a result of them being lost during interpolation of LDP over an area.
- If CPT dataset was available for the areas where there was minor or no liquefaction observed on the ground surface, it would reduce the bias observed during interpolation of the LDP values, since the number repairs in this region would not be high and LDP values would be low and also help develop stronger RR vs LDP relationships.
- The trend or the correlation of the RR and LDP is highly dependent on the LDP zonation taken into consideration.
- The bias of the CPT dataset is seen in the standard deviation results of efficiency.
- LPI was observed to be the most appropriate LDP for the given dataset of pipeline repairs and Liquefaction Demand Parameters (LDP).
- Sufficiency parameter for magnitude does not have any input, hence weakening the efficiency and sufficiency approach in identifying the most appropriate LDP.
- Sufficiency calculated with distance includes a large uncertainty, since distance was averaged over each zone of LDP and not truly reflecting reality.
- The application of Luco & Cornell (2002 & 2007) approach for empirical and large pipeline dataset is not trivial and does include large number of uncertainties.
- Reduction in the bias of the dataset, may lead to better and stronger resulting correlations of RR and LDPs. The dataset can be balanced by using sampling techniques of under-sampling, over-sampling and Synthetic Minority Over-sampling Technique (SMOTE).
- Further work includes, applying the similar efficiency and sufficiency approach for a larger dataset including all water supply pipelines materials, LDP calculated with $C_{FC}=0.2$ and Cornell PGA.
- Developing fragility curves for water supply pipelines and LDP resulted from step 11, by using machine learning techniques.

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