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Development of pipeline damage assessment tools using liquefaction-induced ground movements and CPT-based liquefaction metrics

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ABSTRACT: Correlations of pipeline damage, expressed as repairs/kilometer, with liquefaction-induced ground movements and CPT-based liquefaction vulnerability metrics are developed using the most detailed and accurate geospatial data pertaining to the 22 February 2011 earthquake in Christchurch, NZ. The geospatial database includes pipeline repair records and networks, Light Detection And Ranging (LiDAR) surveys, maps of observed liquefaction effects and CPT testing data across the Christchurch area. A methodology is presented to segregate the additional pipeline damage caused by liquefaction-induced effects (RR_{add}) from the amount of pipeline damage that would likely have occurred without liquefaction. Correlations of RR_{add} with the combined effects of liquefaction-induced lateral ground displacement and ground settlement are developed by use of LiDAR survey data. The effectiveness of CPT-based liquefaction vulnerability index parameters in pipeline damage correlations is investigated by correlating RR_{add} with the Liquefaction Severity Number (LSN). Correlations are organized into two frameworks that can be used for the design, planning and risk management of infrastructure in pre-earthquake situations, and to improve decision making, emergency response and recovery planning in post-earthquake situations.

1 INTRODUCTION

This paper presents a framework for application of pipeline damage correlations in pre- and post- earthquake situations to improve pipeline performance evaluations. The most detailed and accurate geospatial data pertaining to the 22 February 2011 earthquake in Christchurch, NZ, (i.e. pipeline repair records and networks, LiDAR surveys, maps of observed liquefaction effects and CPT testing data throughout the Christchurch area) are employed for this purpose.

The development of correlations in this study builds on the methodology of previous correlations between pipeline damage and liquefaction-induced ground surface deformations (i.e. ground surface angular distortion and ground surface lateral strain) using LiDAR survey data (Bouziou 2015, Bouziou & O'Rourke 2015, Bouziou et al. 2015). While ground surface angular distortions and lateral strains are directly related to pipeline deformations and damage, they are very difficult to predict and cannot be measured easily or directly. Liquefaction-induced vertical and lateral ground surface displacements are positively correlated with liquefaction-induced ground surface angular distortion and lateral ground strain, respectively (i.e. larger vertical displacements and lateral movements result in an increased likelihood of higher angular distortions and lateral strains). Vertical and lateral ground surface displacements are also easier and more straight forward to estimate and can be measured directly after an earthquake using remote sensing technologies.

Ground surface displacements, derived from LiDAR surveys, are used in this study to develop correlations between pipeline damage, expressed as repair rate (repairs/kilometer), with liquefaction-induced settlement and lateral displacement. The resulting correlations can be used to improve decision-making and may assist in post-earthquake rapid identification of areas where pipeline damage is more likely to have occurred.

Cone Penetration Tests (CPT) are useful in assessing the potential liquefaction vulnerability in different earthquake scenarios and provide vulnerability indices that can be used in predictive pipeline damage correlations. The extensive database of more than 25,000 CPT in the Christchurch area is used in this study to correlate pipeline repair rates with the Liquefaction Severity Number (LSN), a well-established CPT-based liquefaction vulnerability index parameter (van Ballegooy et al. 2014).

A methodology for assessing liquefaction-induced pipeline damage in addition to that predicted from seismic ground waves, expressed as the repair rate of additional damage (RR_{add}), is presented so that the effects of liquefaction on pipeline damage are segregated from the effects of transient ground deformation (TGD). This work uses an improved dataset of repairs affected by the 22 Feb. 2011 earthquake that benefits from relocating and/or de-clustering mislocated repairs as well as multiple registrations.

The findings of this work are organized into two frameworks that can be used for: a) the design, planning and risk management of infrastructure in pre-earthquake situations, and b) improved decision-making, emergency response and recovery planning in post-earthquake situations.

2 GEOSPATIAL DATABASE

2.1 *Pipeline network*

Approximately 1700 km of water pipelines, geocoded by Christchurch City Council (CCC) and Stronger Christchurch Infrastructure Rebuild Team (SCIRT), are used in this study to represent the pipeline network before the 22 Feb. 2011 earthquake. Any damage in the water supply system due to the occurrence of the 4 September 2010 earthquake was reinstated before the 22 Feb. 2011 earthquake. Hence, it was assumed that the spatial dataset of the water supply system developed by SCIRT, and sourced originally by CCC, is representative of the system before the occurrence of the 22 Feb. 2011 earthquake.

Figure 1 shows the distribution of different types of pipelines in the Christchurch water supply system at the time of the 22 Feb. 2011 earthquake. As outlined in Bouziou (2015), the

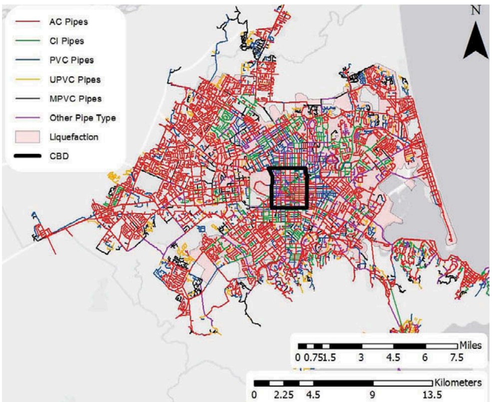


Figure 1. Potable water mains in Christchurch according to pipe type at the time of the 22 Feb. 2011 earthquake.

three major pipe types of water mains in the Christchurch water supply system as of 22 Feb. 2011 were: a) asbestos cement (AC), b) cast iron (CI), and c) polyvinyl chloride (PVC) pipes. The present study focuses on these three main pipe types.

The spatial dataset includes information about the type, diameter, material, length, and year of installation for each pipe in the network. The water supply system under study includes water mains with diameters mainly between 75 and 600 mm, conveying the largest flows in the system. It does not include the smaller diameter submains because accurate repair records for these pipes were not available at the time of this study. Pipelines located in the Port Hills area are excluded from the analyses because pipeline damage during the 22 Feb. 2011 earthquake in this area is attributed to non-liquefaction-related ground deformations such as landslides and rock falls (Bouziou 2015).

2.2 *Pipe repair records*

The water repair database provided by SCIRT includes information on continuous daily repair records for re-establishment of services between February 23, 2011 and March 11, 2013. Water supply system repair records in the latest and more complete dataset provided by SCIRT (February 23, 2011, to April 15, 2011) were evaluated with respect to the 22 Feb. 2011 earthquake according to the methodology developed by O'Rourke et al. (2014).

The geographical distribution of the recorded repairs in the Christchurch water supply system related to the 22 Feb. 2011 earthquake is shown in Figure 2. Similar to visual observations of the damage following the 22 Feb. 2011 earthquake, the majority of repairs are located within the zone of observed liquefaction effects, indicating that liquefaction was the predominant cause of pipeline damage.

2.2.1 *Relocating and de-clustering of pipe repair records*

Several repairs provided by SCIRT were located far from their actual position in the pipeline network resulting in mislocated repair records. Some repair records were clustered at different locations such that the repairs were registered multiple times in the geospatial data set. Such repair records were relocated and/or de-clustered to improve the dataset. During relocation, the actual location of the repair was determined approximately based on the unique pipe identifier that was included in both the repair and the network geospatial datasets. Using the common pipe identifier, each mislocated repair was moved to its actual pipe segment. During de-clustering, repairs located within a 2m-radius from each other, which is less than the typical length of a pipe segment, were merged into one single repair point in the data set.

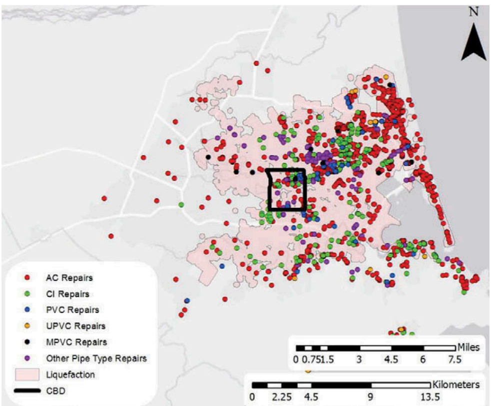


Figure 2. Geographic distribution of repairs on water mains in Christchurch due to the 22 Feb. 2011 earthquake in relation to areas of observed liquefaction effects.

2.3 *Areas of observed liquefaction effects*

The areas of observed liquefaction effects for the 22 Feb. 2011 earthquake were interpreted from aerial photography and site observations available through the Canterbury Geotechnical Database. Observed liquefaction effects include sand ejecta, as well as ground cracking, lateral spreading and differential surface settlement. Some areas outside this zone may have experienced liquefaction without surface manifestations. Hence, the areas identified with liquefaction provide only an estimate of the extent of liquefaction in Christchurch after the 22 Feb. 2011 earthquake.

As explained by Bouziou (2015), the areas of observed liquefaction effects were expanded to account for a zone of influence at the perimeter of the liquefaction areas that affects underground pipelines equal to 125m. This distance is approximately one-half a typical street length in a residential neighborhood and is consistent with the distance that significant pull-out forces can be transmitted longitudinally along underground pipelines (O'Rourke and Liu 1999). These areas are illustrated in Figures 1 and 2 and referred to hereafter as the LIQ Zone.

2.4 *Ground surface displacements*

The airborne LiDAR data collected before and after the 22 Feb. 2011 earthquake by AAM Brisbane (AAM) Pty and New Zealand Aerial Mapping (NZAM) Ltd were paired to derive vertical and horizontal ground surface movements during the 22 Feb. 2011 earthquake.

2.4.1 *Vertical ground surface displacements*

The LiDAR elevation point clouds were used by Tonkin + Taylor Ltd to develop bare earth digital elevation models (DEMs) at 5-m spacing by averaging the ground-return elevations. These DEMs were further corrected for tectonic movement using a dislocation model by GNS Science (2013) for the 22 Feb. 2011 earthquake to obtain elevation changes caused by liquefaction effects. The LiDAR point clouds have mean and median error of less than 50mm, suggesting reasonable accuracy as a whole (Tonkin & Taylor 2015).

2.4.2 *Horizontal ground surface displacements*

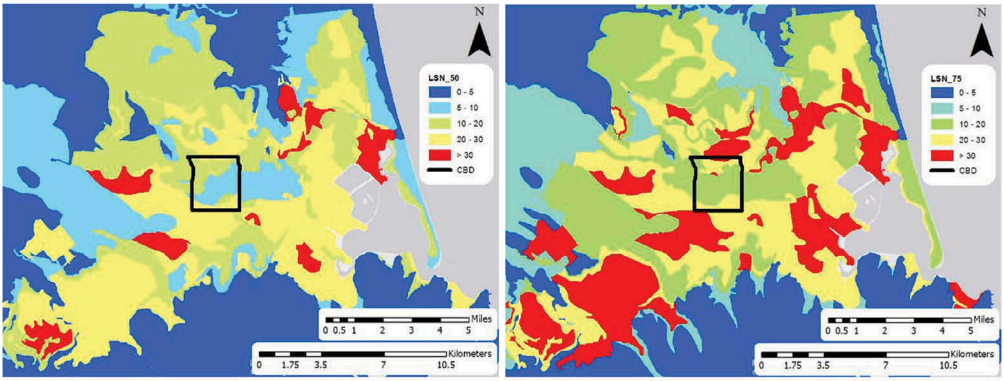
Horizontal displacements were derived from the gridded LiDAR by sub-pixel correlation using 64x64 pixel windows developed by Imagin'Labs Corporation, Pasadena, CA, and California Institute of Technology (Beavan et al. 2012). In addition to destripping and discarding of poor correlation values to improve their quality, the LiDAR sets of horizontal ground surface movement were filtered using a modified version of the Non-Local mean filter to reduce noise (Beavan et al. 2012) and, similar to vertical ground surface displacements, they were corrected for tectonic movement to obtain liquefaction-induced lateral displacements. The LiDAR dataset of horizontal displacements during the 22 Feb. 2011 earthquake has a horizontal accuracy at 40 to 55 cm (Beavan et al. 2012). LiDAR lateral displacements on 4-m spacing grids are consistent with the scale of a typical pipeline length of 6m, provide higher resolution of the strain fields affecting pipelines (Bouziou 2015), and are used in this paper to correlate pipeline damage with liquefaction-induced lateral displacements.

2.5 *Liquefaction vulnerability parameter data*

The Liquefaction Severity Number (LSN) is a CPT-based liquefaction vulnerability index parameter developed by van Ballegooy et al. (2014) to evaluate liquefaction-induced land damage. Following a comparative study of the existing liquefaction vulnerability index parameters by van Ballegooy et al. (2014), it was concluded that the LSN is the most suitable tool for predicting future land damage performance in Canterbury and provides the best correlations with the observations made therein. LSN is defined as:

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

where ε_v is the calculated post-liquefaction volumetric reconsolidation strain entered as a decimal and z is the depth below the ground surface in meters. LSN is calculated as the



(a) (b)

Figure 3. Map of: a) 50th percentile, and b) 75th percentile LSN values by area of SEGP. The Christchurch Central Business District (CBD) is circumvented with black line.

summation of the post-liquefaction volumetric reconsolidation strains calculated for each soil layer divided by the depth to the midpoint of that layer. The value of LSN is theoretically between 0 (representing no liquefaction vulnerability) to values greater than 40 which represent extreme liquefaction vulnerability (Tonkin & Taylor 2013).

Tonkin & Taylor (2013) developed a regional liquefaction vulnerability model based on the LSN parameter to predict liquefaction damage in different earthquake scenarios in Christchurch using an extensive database of more than 25,000 CPT that were undertaken following the CES. The entire Christchurch area was divided into polygons of similar expected ground performance (SEGP) by considering their geomorphology, location of waterways, ground surface elevation, depth to ground water and geotechnical characteristics (mainly CPT and borehole logs). LSN values were calculated at each CPT location based on the Boulanger & Idriss (2014) liquefaction triggering method using the 50th percentile probability of liquefaction (P_L) cyclic resistance ratio curve (CRR) and were subsequently grouped together for each SEGP. LSN distributions versus earthquake shaking, expressed as Peak Ground Acceleration (PGA), were developed for each SEGP. Among these LSN distributions, the 50th and 75th percentile values of LSN in each SEGP are selected in the present study to investigate the effectiveness of LSN application in pipeline damage correlations. The values of the 50th and 75th percentiles of LSN by area of SEGP are shown in Figures 3a and 3b, respectively.

3 PIPE REPAIR RATE CORRELATIONS

3.1 *Methodology for assessing the additional pipeline damage caused by liquefaction-induced effects*

Pipeline damage in areas of observed liquefaction is primarily attributed to liquefaction effects. TGD also have a contributing effect that is evaluated and removed from pipeline damage correlations in this study. A methodology for assessing liquefaction-induced pipeline damage in addition to that attributed to seismic ground waves, expressed as the repair rate of additional damage (RR_{add}), is developed and applied in pipeline damage correlations with liquefaction-induced ground displacements and LSN.

Repairs related to TGD effects are estimated by use of repair rate correlations with the Geometric Mean of Peak Ground Velocity (GMPGV), developed by Bouziou (2015) for AC and CI pipelines. GMPGV is defined as the mean of the natural logs of the two maximum values of horizontal PGV recorded at a station. Repair rate correlation with GMPGV is not provided by Bouziou (2015) for PVC pipelines due to insufficient number of repairs. Pipelines are spatially correlated with GMPGV using the contour map of GMPGV by Bouziou (2015). For each bin of GMPGV (each bin has a 10 cm/s interval of values), the expected value of the repair rate is estimated for AC and CI pipes using the RR vs GMPGV correlations. Having calculated the total length of pipelines within each GMPGV interval, and having an estimate of the repair rate for the same GMPGV interval, the expected number of repairs related to the specific GMPGV interval is calculated. These repairs and their respective repair rate represent pipeline damage that would likely have occurred during the 22 Feb. 2011 earthquake if liquefaction had not occurred in the LIQ Zone. The additional number of repairs caused by liquefaction effects during the 22 Feb. 2011 earthquake is calculated as the difference of the total number of repairs that were recorded minus the estimated number of repairs attributed to GMPGV. The additional repair rate, i.e. RR_{add}, represents the number of the additional repairs caused by liquefaction and the respective pipe length.

3.2 *Repair rate correlations with the combined effects of liquefaction-induced lateral displacement and settlement*

Similar to the correlations of repair rate with the combined effects of lateral ground surface strain and differential ground surface movement by Bouziou (2015), the simultaneous effects of liquefaction-induced settlement and lateral displacement during the 22 Feb. 2011 earthquake are combined in correlations of RR_{add} in this study.

The additional number of repairs caused by liquefaction is estimated with the methodology described in Section 3.1, and the dataset is geospatially correlated with the lateral displacements and settlements described in Section 2.4. The pipeline network is also correlated geospatially with liquefaction-induced lateral displacements and settlements. Similar to the methodology described by Bouziou (2015), RR_{add} is calculated for a given pair of lateral displacement and settlement intervals by dividing the number of the estimated additional repairs due to liquefaction for a particular type of pipeline by the kilometers of that pipeline type within the same pair of intervals. The intervals for lateral displacement and settlement are 0.2m and 0.1m, respectively, and their selection is guided by a study of the statistical distribution of lateral and vertical ground movements by Bouziou (2015).

Each RR_{add} value is associated with the respective pair of lateral displacement and settlement and is used as a single data point in RR_{add} correlations. The screening criterion described by Bouziou (2015) is applied for each set of data points to ensure fidelity of RR_{add} correlations. The confidence interval is relaxed at 80% and 70% for AC and CI pipelines, respectively, in order to produce as many reliable data points as possible and cover a broader range of ground movements in the correlations. Correlation of RR_{add} with lateral displacement and settlement for PVC pipelines is not possible due to the insufficient number of repairs that does not allow for meaningful results to be derived.

The global polynomial interpolation method with a first-order polynomial model in ArcMap 10.1 (2018) is used to fit a smooth surface of RR_{add} contours. The resulting RR_{add} correlations for AC and CI pipes are presented as contour plots in the 2-D space defined by lateral displacement and settlement in Figure 4. The contours space for CI pipelines (Figure 4b) is smaller than the contours space for AC pipelines (Figure 4a) due to the significantly higher number of AC repairs and their wider geographical distribution throughout Christchurch which provides for correlations to be achieved using a wider range of lateral displacement and settlement. Results in Figure 4 show that AC pipelines sustained more damage during the 22 Feb. 2011 earthquake compared to CI pipelines.

3.3 *Repair rate correlations with LSN*

Correlations of pipeline damage with LSN are developed for the three major pipe types, i.e. AC, CI, and PVC pipes using the estimated RR_{add}. The LSN wide area model, and specifically the maps of the 50th and 75th percentile values of LSN across Christchurch are used in correlations with the additional number of pipe repairs due to liquefaction and the pipeline network pertaining to the 22 Feb. 2011 earthquake. Using the spatially located pipelines and repairs, RR_{add} for a given range of LSN values is calculated by dividing the number of repairs for a particular type

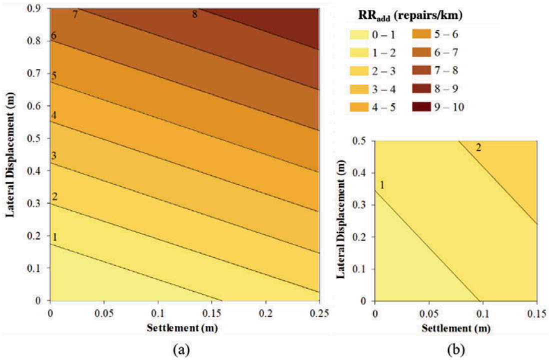


Figure 4. Correlations of RR_{add} with lateral displacement and settlement: a) AC and b) CI pipelines.

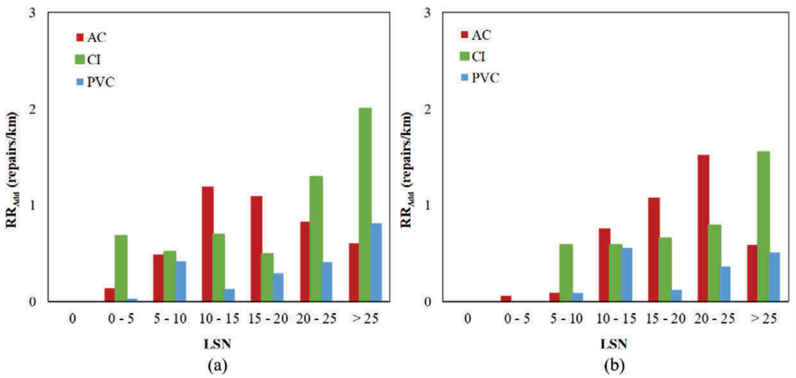


Figure 5. Histograms of RR_{add} vs LSN for: a) AC, CI and PVC pipelines using the 50^{th} percentile, and b) AC, CI and PVC pipelines using the 75^{th} percentile.

of pipeline by the kilometers of that pipeline type within an LSN interval. The interval of LSN values is 10, and the resulting RR_{add} is associated with the average value of LSN within each bin. Each pair of RR_{add} and LSN is used a single data point in the correlations.

The resulting correlations of RR_{add} with respect to the 50^{th} and 75^{th} percentile LSN values for AC, CI, and PVC pipelines are presented in Figure 5. The histograms of RR_{add} with respect to the 75^{th} percentile LSN values (Figure 5b) provide stronger increasing trends and indicate stronger correlations between pipeline damage and LSN than the histograms of the 50^{th} percentile LSN values (Figure 5a). The 75^{th} percentile LSN is related with higher LSN values than the 50^{th} percentile LSN, and, thus, it is expected to control pipeline damage to a higher degree than the 50^{th} percentile LSN. As shown in Figure 5b, LSN values correlate overall with higher values of RR_{add} for AC than CI pipes, followed by PVC pipes, indicating that AC pipes are more susceptible to liquefaction-related effects than CI pipes, and CI pipes are in turn more susceptible to liquefaction-related effects than PVC pipes.

4 FRAMEWORK FOR APPLICATION IN PRE- AND POST- EARTHQUAKE EVENT SITUATIONS

The findings of the present study are organized into the framework in Figure 6 to be applied in pre-earthquake situations. Pipeline damage in future earthquake events may be predicted in areas affected by the combined effects of liquefaction and seismic ground shaking using generic input parameters such as LSN, combined with seismic ground motion prediction models.

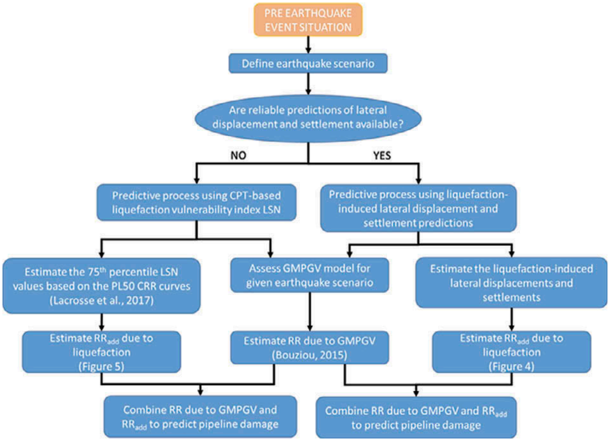


Figure 6. Flow chart of recommended framework to be used in pre-earthquake situations. (Note: The predictive process for pipeline damage using CPT-based liquefaction vulnerability index parameter LSN may be used even when reliable predictions of liquefaction-induced lateral displacements and settlement are available.)

These correlations can be incorporated into design procedures or earthquake catastrophe loss models that account for liquefaction and seismic ground shaking effects on pipelines to evaluate the performance of the pipeline network. The framework will improve asset management planning for targeted pipeline rehabilitations and replacement schemes with materials and technologies that are more resistant to earthquakes.

In addition to pre-earthquake situations, the present study may be applied in post-earthquake situations to improve decision-making, emergency response and recovery planning after an earthquake by use of the framework in Figure 7. Within this framework, pipeline damage may be estimated immediately after an earthquake through remote sensing technologies that provide information on earthquake-induced ground surface movements. Similar to a study by van Ballegooy et al. (2014), high levels of such ground surface movements (i.e. horizontal displacements greater than 30cm and/or vertical displacements greater than 10 cm) in areas with visual observation of liquefaction effects (e.g. sand ejecta, ground cracking etc.) may be related to high levels of liquefaction occurrence. Correlations presented in Figure 4 suggest that the locations with high

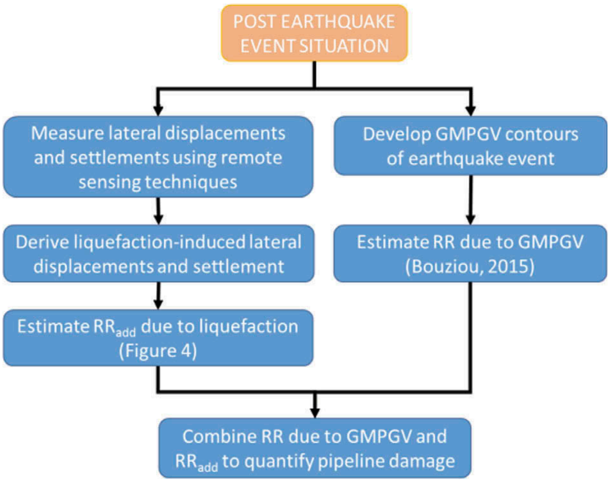


Figure 7. Flow chart of recommended framework to be used in post-earthquake situations.

concentrations in pipe failure due to liquefaction effects may be identified by the locations with high levels of liquefaction-induced ground movements that are derived from remote sensing surveys. Decision making for rapid reestablishment of service in the pipe network may then become more targeted towards these areas, thus, leading to more cost-effective decisions. This methodology may be included as part of a general rapid impact response scheme after an earthquake.

5 CONCLUSIONS

This paper evaluates pipeline damage, expressed as repair rate, with respect to liquefaction-induced ground movements and CPT-based liquefaction vulnerability metrics using the most detailed and accurate geospatial data pertaining to the 22 Feb. 2011 earthquake in Christchurch, NZ. The dataset of repairs was improved by means of relocating and/or de-clustering mislocated repairs as well as multiple registrations. A methodology was developed for assessing liquefaction-induced pipeline damage in addition to that predicted from seismic ground waves. The resulting correlations were incorporated into two frameworks for predicting and assessing pipeline performance in pre- and post- earthquake situations, respectively. The main findings of this paper are:

- Correlations between RR_{add}, liquefaction-induced settlement and lateral displacement provide for the first time the means to evaluate pipeline damage on the basis of the combined effects of such ground movements.
- AC pipes sustained more damage compared to CI pipes with respect to liquefaction-induced ground movements during the 22 Feb. 2011 earthquake.
- RR_{add} for the three major pipe types in Christchurch correlates favorably with LSN.
- RR_{add} correlations with the 50^{th} and 75^{th} percentile values of LSN show that AC pipelines are more susceptible to liquefaction vulnerability than CI pipes, and CI pipes are in turn more susceptible than PVC pipes.
- The 75^{th} percentile LSN values provide stronger correlations with RR_{add} than the 50^{th} percentile LSN values.

The resulting correlations were incorporated in two frameworks that may be used in the design, planning and risk management of infrastructure in pre-earthquake situations, and may improve decision-making, emergency response and recovery planning in post-earthquake situations. CPT provide liquefaction vulnerability indices, and, combined with seismic ground motion prediction models and the resulting pipeline damage correlations, allow for pipeline damage in future earthquake events to be predicted in areas affected by the combined effects of liquefaction and seismic ground shaking. Liquefaction-induced ground movements can be measured directly after an earthquake using remote sensing techniques, and, in combination with seismic ground motion prediction models and the resulting pipeline damage correlations, provide a useful tool for post-earthquake rapid identification of areas where pipeline damage is more likely to have occurred.

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