Response of the Christchurch Water Distribution System to the 22 February 2011 Earthquake

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ABSTRACT

The effects of transient and permanent ground deformations during the 22 February 2011 earthquake on the Christchurch water distribution system are investigated through geospatial analysis with the most detailed and accurate databases currently available. Using the most recent repair records, ground motion records, high resolution Light Detection and Ranging (LiDAR) data collected before and after the earthquake, and improved screening criteria, repair rates, expressed as repairs/km, for different types of pipeline are correlated with 1) peak ground velocity outside liquefaction areas, and 2) differential ground surface lateral and vertical movements in liquefaction areas. The substantial influence of LiDAR resolution on the relationship between pipeline damage and lateral ground strain indicates sensitivity of repair regressions to the degree of data resolution. Repair regressions of different pipelines show that polyvinyl chloride pipelines are markedly more resilient to earthquake effects than other types of segmental pipelines in the Christchurch system. The analytical process is described in detail for assistance in future investigations with data sets of similar size and complexity.

KEY WORDS: geospatial analysis; pipelines; earthquake; Christchurch; LiDAR; repair regressions

1. INTRODUCTION

The 22 February 2011 earthquake (Moment Magnitude, $M_w=6.2$) was the most severe seismic event during the 2010-2011 Canterbury Earthquake Sequence (CES) that caused unprecedented damage in the city of Christchurch and the largest number of fatalities since the 1931 Hawkes Bay (Napier) earthquake. The 22 February 2011 earthquake was caused by a local fault approximately 5 km south-east of the Christchurch Central Business District (CBD) which

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Abbreviations:

LiDAR: Light Detection and Ranging

GMPGV: Geometric Mean Peak Ground Velocity

PGD: Permanent Ground Deformation

TGD: Transient Ground Deformation

produced strong to very strong ground shaking within Christchurch [1]. The water distribution system in Christchurch was severely affected by ground shaking and widespread liquefaction that took place over 96 km² (66%) of the Christchurch area.

Systematic mapping and recording of damage in the water distribution system, as well as observations and measurements of transient ground motion and permanent ground surface movements, resulted in data sets associated with the CES that are unique in size and detail. The geospatial data sets that are used in this study include high resolution Light Detection and Ranging (LiDAR) surveys before and after the 22 February earthquake, maps of areas of liquefaction interpreted from aerial photography and lateral spreading observations, ground motion records from 40 stations, and detailed repair records of thousands of km of underground pipelines in the water distribution system.

This paper provides significant updates to and expansion of investigations by O'Rourke et al. [2] for analysis of underground pipeline performance during the CES. The present study uses the most recent and improved water distribution network repair records provided by the Stronger Christchurch Infrastructure Rebuild Team (SCIRT). High resolution LiDAR lateral movements on 4-m spacing were acquired for this study and represent a significantly higher degree of resolution than those associated with 56-m spacing, which originally were released by the Canterbury Earthquake Recovery Authority (CERA) [3] and were used in the previous study. Moreover, refinements in the geostatistical processing of ground motion data to include the effects of anisotropy are used in this work to develop correlations between pipeline damage and peak ground velocity (PGV).

2. GIS DATABASE

Figure 1 shows the water distribution system in Christchurch City and Lyttelton Harbor superimposed on areas of liquefaction effects and pipeline repair locations associated with the 22 Feb. 2011 earthquake. Geospatial data for the 22 Feb. 2011 earthquake include approximately 1700 km of water mains and trunk lines, ranging from 75 to 600 mm in diameter, with internal pressure of about 100 kPa. It does not include repairs to smaller diameter submains and customer service laterals. The water distribution system spatial dataset developed by SCIRT, and sourced originally from the Christchurch City Council (CCC), provides the most complete picture of the system as of 4 Sept. 2010 and includes information about the type, diameter, material, length, and year of installation for each individual pipe in the network [4]. It also includes information on continuous daily repair records for re-establishment of services between the period from February 23, 2011 to March 11, 2013, after the occurrence of the 13 June 2011 and 23 December 2011 earthquakes and numerous aftershocks. Similar to the study by O'Rourke et al. [2], water distribution system repair records in the latest data set dating from February 23, 2011 to April 15, 2011 were related to the 22 Feb. 2011 earthquake and were used in this study.

The areas of liquefaction effects presented in Figure 1 were derived from maps of observed liquefaction effects that were documented through aerial photography and site observations, and are available through the Canterbury Geotechnical Database [5]. Observed liquefaction effects include sand ejecta, ground cracking, lateral spreading and differential surface settlement. The

areas of observed liquefaction were only defined by visible surface features and, therefore, they were expanded to account for a zone of influence at their perimeter that affects underground pipelines. The zone of influence of underground pipeline damage was taken as 125 m, which is approximately one-half a typical street length in a residential neighborhood and is consistent with the distance that significant pullout forces can be transmitted longitudinally along underground pipelines [6]. These areas are described in this paper as the areas of liquefaction effects.

Figure 1. Map of Christchurch water distribution system during the 22 Feb. 2011 earthquake.

Ground motion records related to the 22 Feb. 2011 earthquake from 40 stations in the Christchurch area were selected for spatial analysis [7]. The selected records were fully processed by GNS Science [8] to provide acceleration, velocity, and displacement time histories and response spectra. The processed data from GNS Science are derived using a filter with corner frequencies of 25 Hz and 0.25 Hz, meaning that the ground motions are screened to focus on periods between 0.04 and 4 sec. The geometric mean peak ground velocity (GMPGV) was used as a metric in pipeline repair regressions in areas affected by transient ground deformations (TGD). Peak ground velocity has been shown in previous studies to provide the most robust regressions related to pipeline damage (e.g., [9]). GMPGV was calculated for each station as the mean of the natural logs of the two horizontal orthogonal PGV components recorded at the station and obtained through GNS Science.

Airborne Light Detection and Ranging (LiDAR) data were obtained by AAM Brisbane (AAM) and New Zealand Aerial Mapping (NZAM) before and after each of the main seismic events

during the CES, and pairs of these data were combined by GNS Science (accessed June 2013), under contract with Tonkin & Taylor Pty Ltd (T&T), Christchurch, New Zealand, to determine horizontal and vertical ground movements. Vertical ground movements were developed at 5-m spacing, whereas horizontal movements at 4-m and 56-m spacing. The NZAM LiDAR give a fundamental vertical accuracy of ± 10 cm for areas of open ground with hard surfaces, and the AAM LiDAR give a fundamental vertical accuracy of ± 7 to ± 15 cm [10]. The AAM LiDAR horizontal accuracy, compared to land survey measurements supplied by the Christchurch City Council (CCC), Land Information New Zealand (LINZ) and Environment Canterbury, is 40 to 55 cm [10]. The vertical and horizontal ground surface movements developed by pairs of LiDAR data sets collected before and after the 22 February 2011 earthquake were used to develop grids of differential vertical and horizontal ground movement.

3. SPATIAL ANALYSIS OF PIPELINE DAMAGE

Pipeline repair rates (RRs), expressed as repairs/km, were evaluated through spatial analysis with respect to 1) areas unaffected by liquefaction effects where TGD is likely to be the primary cause of damage, and 2) areas affected by liquefaction effects, where PGD is likely to be the primary cause of damage. Using the data sets described above, the spatial distribution of damage in the water distribution system during the 22 Feb. 2011 earthquake was quantified and is summarized in Table 1. The table provides information pertaining to pipeline length, repairs, and RRs for asbestos cement (AC), cast iron (CI), polyvinyl chloride (PVC), and modified polyvinyl chloride (MPVC) pipelines in the water distribution system, including locations inside and outside areas of liquefaction effects. The category of “other” includes pipe types that were individually present in the network in quantities too small to provide statistically robust correlations. The information provided in Table 1 is derived using the most accurate and complete data set of pipeline repairs that were obtained through SCIRT in March, 2013.

Column 4 in Table 1 shows the RRs for each pipe type as the ratio of the total number of repairs for each pipe type to the total length of each pipe type. The percentage of repairs within the areas of liquefaction effects for each pipe type with respect to the total number of repairs recorded for each pipe type is presented in column 5. Similarly, the percentage pipeline within the areas of liquefaction effects for each pipe type with respect to the total length of each pipe type is presented in column 6. Column 7 shows the percentage of pipelines that were damaged within the areas of liquefaction effects for each pipe type with respect to the total length of each pipe type. In a similar manner, column 8 shows the percentage of pipelines that were damaged outside the areas of liquefaction effects for each pipe type with respect to the total length of each pipe type. Finally, column 9 shows the average RR for each pipe type as the ratio of repairs of each pipe type within the areas of liquefaction effects to pipeline length of each pipe type within the areas of liquefaction effects, and, similarly, column 10 shows the average RR for each pipe type as the ratio of repairs of each pipe type outside the areas of liquefaction effects to pipeline length of each pipe type outside the areas of liquefaction effects.

The use of RR as a normalized indicator of pipeline damage allows for comparison of the vulnerability of different pipe types relative to their total length in the water distribution network. As shown in Table 1, the RRs for AC and CI pipes are similar and approximately 3 to 4 times

greater than PVC pipe RRs, and 6 to 15 times greater than MPVC pipe RRs. The average RRs inside the liquefied areas are at least 4 times greater than RRs in areas without liquefaction effects for all pipe types. Table 1 also provides information about the distribution of repairs and pipelines inside and outside the areas of liquefaction effects. More than 80% of repairs for each pipe type are located inside the areas of liquefaction effects, whereas the percentage of pipelines within the areas of liquefaction effects for each pipe type ranges between 33% and 83%. The aforementioned remarks verify that pipeline damage during the 22 February 2011 earthquake was associated primarily with PGD effects caused by liquefaction. The percentage of damaged pipelines inside and outside the areas of liquefaction effects is also used in Table 1 as an indicator of damage and shows that pipeline damage was mostly concentrated inside the liquefied zone. As shown in Table 1, AC and CI pipes were most severely affected by the 22 Feb. 2011 earthquake, whereas PVC and MPVC pipes performed significantly better.

Table 1. Statistics of water main and trunk line pipeline repairs and repair rates in both liquefaction and non-liquefaction areas for different water pipe types.

	1	2	3	4	5	6	7	8	9	10
	Pipe Material	Pipe Length (km)	Repairs	Overall Average RR ²	% Repairs in LIQ ¹ areas	% Pipeline in LIQ ¹ areas	% Damaged Pipeline in LIQ ¹ areas	% Damaged Pipeline in Non LIQ ¹ areas	Average RR ² in LIQ ¹ areas	Average RR ² in Non LIQ ¹ areas
22 February 2011	AC	867.2	1024	1.18	85%	47%	16%	3%	2.15	0.33
	CI	194.4	255	1.31	89%	67%	14%	3%	1.73	0.44
	PVC	213.6	68	0.32	93%	52%	5%	1%	0.56	0.05
	MPVC	149.7	13	0.09	100%	33%	2%	0%	0.27	0.00
	Other	305.4	142	0.47	83%	83%	4%	4%	0.46	0.47
	Total	1730.3	1502	0.87	86%	55%	11%	2%	1.36	0.27

¹ LIQ: Areas of liquefaction effects

² RR: Repair Rate

4. SCREENING CRITERIA

The screening criteria developed by O'Rourke et al. [2] were used during the regression analysis of pipeline damage to ensure fidelity of the RR correlations. As recommended by previous researchers [11], it was assumed that pipeline damage follows a Poisson distribution where

$$(1-\alpha) p \leq (RR) x \leq (1+\alpha) p \quad (1)$$

in which p is the actual number of repairs, RR is repair rate, α is a fraction of the actual number of repairs, and x is the sampling length. For a Poisson distribution the mean is $\mu=(RR)x$ and the standard deviation is $\sigma=[(RR)x]^{1/2}$.

The confidence level corresponding to the sampled number of repairs falling within $\pm\alpha$ of the actual repairs can be estimated by recognizing that the sampled repairs follow a normal distribution in accordance with the central limit theorem. For a confidence level interval, β_c , and standard normal deviate, $\phi^{-1}(\beta_c)$, the lower and upper bounds of Equation 1 are

$$\mu \pm \phi^{-1}(\beta_c)\sigma = (1\pm\alpha)p \quad (2)$$

Combining Equations 1 and 2 with $p = (RR)x$ results in

$$x \geq [\phi^{-1}(\beta_c)]^2 / \alpha^2(RR) \quad (3)$$

Equation 3 provides the minimum sampling length, x , needed for a confidence level, β_c , that the actual number of repairs falls within $\pm \alpha$ of the mean value $(RR)x$. The screening criterion presented in Equation 3 allows for sampling and data selection to be administered by choosing β_c and α . In the present study, α was equal to 50% and a relatively high confidence interval of $\geq 90\%$ was applied in most cases. As presented in the following sections, in some cases the confidence interval was reduced to produce additional RR data and extend ground deformation levels in RR correlations over a broader range.

5. RR CORRELATIONS WITH GMPGV

The performance of the Christchurch water distribution system in areas affected by TGD during the 22 February 2011 earthquake was evaluated through correlations of pipeline damage with earthquake ground motions. Figure 2 presents the flow chart of the spatial analysis steps that were followed in developing RR correlations with GMPGV. The spatial distribution of GMPGV was interpolated using ground motions recorded at 40 stations during the 22 February 2011 earthquake. The peak ground velocity (PGV) horizontal orthogonal components that were processed by GNS Science [3] were used to calculate the GMPGV sample values that were introduced in the geostatistical model. The spatial interpolation technique employs an ordinary kriging model with a spherical variogram similar to the study by Jeon and O'Rourke [9]. The spherical variogram used in this study accounts for anisotropy to incorporate the influence of direction dependency as a result of forward directivity and strong basin edge effects that have been reported by Bradley and Cubrinovski [12] for the 22 February 2011 earthquake.

The areas of observed liquefaction were imported in ArcMap 10.1 [13] and were subsequently expanded by 125 m using the “buffer” tool to account for a zone of influence at the perimeter of the liquefaction areas that affects underground pipelines. Pipelines and repairs that were projected in ArcMap 10.1 [13] and were located inside the expanded liquefaction areas were excluded from the analytical process for PGV using the “erase” tool based on the assumption that they were associated with PGD effects. Pipelines affected by landslides and rock falls during the 22 February 2011 earthquake were also removed in a similar manner assuming that pipelines

at elevation above 50 m in the Port Hills were primarily affected by landslide- and rockfall-

Figure 2. Flow chart for RR correlations with GMPGV (Rectangles represent input/output data sets and ovals represent processes/tools).

related PGD. Pipelines and repairs outside the expanded areas of observed liquefaction and at elevations below 50 m were spatially intersected by the geostatistically-determined GMPGV surface layer using the “intersect” tool in ArcMap 10.1 [13]. Using the spatially located pipelines and repairs, the repair rate (RR) for a given interval of GMPGV was calculated by dividing the number of repairs for a particular type of pipeline by the kilometers of that pipeline type within a contour interval of 10 cm/s. The resulting RR was then associated with a value of GMPGV and was used as a single data point in RR correlations. The screening criteria previously discussed were applied to produce RR vs GMPGV correlations using appropriate confidence intervals.

Figures 3a and 3b show the areas of liquefaction effects, water distribution pipelines, repairs outside liquefied areas, and 10 cm/sec contours of GMPGV for the 22 Feb. 2011 earthquake, pertaining to AC and CI distribution mains, respectively. Correlations of RR vs GMPGV were not developed for PVC pipelines due to insufficient number of PVC pipeline repairs even after considering lower confidence levels in the screening process. Ground motion directionality in the northwest direction is reflected in the contours of GMPGV and is in good agreement with the remarks made by Bradley and Cubrinovski [12] for forward directivity effects in the fault normal component that are manifested as large ground velocities.

The results of regression analysis for RR vs GMPGV for AC and CI pipelines are presented in Figures 4a and 4b, respectively. The RRs for AC pipelines and various GMPGV values for the 22 February 2011 earthquake were combined with similar data reported by Jeon [14] for AC pipelines damaged during the 1994 Northridge earthquake. Similarly, the RR vs GMPGV data

points for CI pipelines for the 22 February 2011 earthquake were combined with historical data

Figure 3. a) 22 Feb. 2011 earthquake map of GMPGV and liquefaction with AC pipelines and repairs, and b) 22 Feb. 2011 earthquake CI pipeline layout, repairs, and map of GMPGV.

Figure 4. Repair rate vs. GMPGV for a) AC pipelines and b) CI pipelines.

reported by Jeon and O'Rourke [9] to develop the linear regression shown in Figure 4b. The linear regressions shown in Figures 4a and 4b combine data points from all earthquakes and provide good fit for the data with relatively high r^2 values. Comparison between the regression lines for AC and CI pipelines indicates that AC pipelines sustain up to 3 times more damage due to TGD effects than CI pipelines. The new data points combined with historical data shown in Figures 4a and 4b expand the available database and provide improved regressions for future fragility analyses of water distribution pipeline damage during earthquakes.

6. RR CORRELATIONS WITH DIFFERENTIAL VERTICAL GROUND MOVEMENT

Measurements of ground surface elevation before and after each earthquake during the CES were acquired through high resolution Airborne LiDAR surveys by AAM Brisbane (AAM) and New Zealand Aerial Mapping (NZAM) in the Christchurch area. The NZAM LiDAR sets are associated with fundamental vertical accuracy of $\pm 0.10\text{m}$ for areas of open ground with hard surfaces which was estimated with respect to field surveying data. The AAM LiDAR sets are associated with a vertical accuracy of ± 0.07 to $\pm 0.15\text{m}$ [10]. The acquired point clouds were classified and screened to develop bare earth digital elevation models (DEM) at 5m spacing by averaging ground return elevations with 5-m x 5-m cells. Pairs of the DEMs were used to calculate vertical elevation changes at 5-m spacing for each earthquake as well as for sets of consecutive earthquakes. The data set of vertical elevation changes pertaining to the 22 February 2011 earthquake was obtained through the CERA [15] and was corrected for tectonic movements using a dislocation model of vertical tectonic movements provided by GNS Science.

The differential vertical ground surface movements associated with PGD effects during the 22 February 2011 earthquake were used to calculate angular distortion, β , and evaluate the effects of differential vertical ground movement on pipeline damage. As discussed by O'Rourke et al. [2], angular distortion is the gradient of settlement between two adjacent LiDAR points

$$\beta = \frac{\delta z_1 - \delta z_2}{l_{12}} \quad (4)$$

where δz_1 and δz_2 are the vertical movements of points 1 and 2, respectively, and l_{12} is the distance between the two points in the horizontal plane.

Angular distortion, β , is a dimensionless parameter that allows for calculation of relative vertical movement between LiDAR points, eliminating inherent errors in the measurements such as GPS network error and approximations with the reference surface. In this study β was calculated on a 5-m grid with a third order finite difference approach that uses a 3-by-3-cell moving window and weighting factors assigned to each neighboring cell based on their distance from the cell at the center of the window [16]. The LiDAR dataset of vertical movement was large, containing approximately 3 million data points in total, and 2.4 million points in the zone of liquefaction effects. The process that was followed to calculate β using this dataset was performed within the ArcMap 10.1 [13] environment.

The analytical process for RR correlations with β is presented in the flow chart in Figure 5. As

shown in Figure 5, the “slope” tool was used to calculate β using the LiDAR data set of vertical movement in the liquefied zone and the output of the process was a surface of β values. Pipelines and repairs inside the area of liquefaction effects were selected using the “clip” tool. Pipelines affected by landslides and rock falls during the 22 Feb. 2011 earthquake were removed from the data set. The selected sets of pipelines and repairs inside the areas of liquefaction effects and at elevation below 50 m were spatially intersected with the layer of β values using the “intersect” tool. RR for a given interval of β was calculated by dividing the number of repairs for a particular type of pipeline by the kilometers of that pipeline type within the same interval. The interval size for β was 1×10^{-3} . The calculated RR was associated with the geospatially correlated value of β and was used as a single data point in RR correlations.

The screening criteria previously discussed were applied to produce RR vs β correlations using appropriate confidence intervals. The confidence level during the screening process was adjusted to account for the number of repairs, which declines progressively for AC, CI, and PVC pipelines. By relaxing the confidence interval in the screening criteria, more RR values are provided to develop a linear regression for each pipe type over a suitable range of β . Confidence

Figure 5. Flow chart for RR correlations with β (Rectangles represent input/output data sets and ovals represent processes/tools).

levels of 95%, 90%, and 75% were used in the screening criteria for AC, CI, and PVC pipelines, respectively. The results from the regression analysis for β are presented in Figure 6a. The linear regressions for all three pipe types provide a good fit of the data with r^2 values of 0.86, 0.79, and 0.88 for AC, CI, and PVC pipelines, respectively. RRs for AC pipelines plot 1.3 to 2.2 times higher than CI, and 2.1 to 9.9 times higher than PVC. The results indicate that the best performance with respect to β is shown by PVC pipelines. Figure 6b compares the results of the current investigation, using the most recent and complete repair records, with the results of previous work (O'Rourke et al., 2014). With the exception of a decreased RR for AC pipelines using the new data, the regressions for each pipe type compare favorably with each other.

Figure 6. Repair rate vs. angular distortion for AC, CI, and PVC pipelines: a) Results with updated measurements, b) Comparison of current and previous results.

7. RR CORRELATIONS WITH LATERAL GROUND STRAIN

Similar to vertical ground movements, lateral ground surface movements were calculated both for individual seismic events as well as for sets of consecutive earthquakes using pairs of LiDAR point clouds. The AAM LiDAR horizontal accuracy, compared to land survey measurements supplied by the Christchurch City Council (CCC), Land Information New Zealand (LINZ) and Environment Canterbury, is 40 to 55 cm [10]. The lateral ground surface movements were calculated using a sub-pixel correlation method developed by Imagin' Labs Corporation, Pasadena, CA, and California Institute of Technology on 4-m spacing (8-m for the pre-earthquake LiDAR sets) from both ground and non-ground LiDAR points and were subsequently averaged to provide movements in the east-west (EW) and north-south (NS) directions on 56-m spacing. The 4-m and 56-m grids of lateral ground surface movements pertaining to the 22 February 2011 earthquake were provided by Tonkin & Taylor, New Zealand, and CERA [17],

respectively, and were corrected for tectonic movements using a dislocation model of horizontal tectonic movements during the 22 February 2011 earthquake provided by GNS Science.

The methodology for calculation of lateral ground strains was based on plane strain conditions for quadrilateral elements and is described in detail by O'Rourke et al. [2]. The lateral ground movement data points were used as corners of square elements, and finite element formulations were used to determine horizontal ground strains in the center of the elements, according to the method described by Cook [18]. Pipeline damage on segmented pipelines, expressed as RR, is assumed to be caused by axial ground strains and related primarily to failure of the joints [19]. The absolute maximum value of lateral ground strain, ϵ_{HP} , in each elemental area of ground was used as a metric for RR correlations with lateral ground strain. Lateral ground strain ϵ_{HP} is equal to the absolute maximum value of principal strains given by

$$\epsilon_{1,2} = \frac{\epsilon_x + \epsilon_y}{2} \pm \sqrt{\left(\frac{\epsilon_x - \epsilon_y}{2}\right)^2 + \left(\frac{\gamma_{xy}}{2}\right)^2} \quad (5)$$

Figure 7. Flow Chart for RR Correlations with ϵ_{HP} (Rectangles represent input/output data sets and ovals represent processes/tools).

The analytical process for RR correlations with ϵ_{HP} is presented in the flow chart in Figure 7. Lateral ground movements in the EW and NS directions at 4-m and 56-m grid spacing were imported in ArcMap 10.1 [13] and were subsequently converted to point layers using the conversion tool. The LiDAR datasets with lateral movements in the EW and NS directions at 4-m grid spacing were large, containing approximately 4.7 million data points in total and 3.7 million points in the zone of observed liquefaction effects. The manipulation of the datasets for calculating lateral ground strains was performed using the Manifold System Release 8 GIS package [20] to overcome memory usage constraints in ArcMap 10.1 [13]. The Matlab and Statistics Toolbox Release 2012a [21] software was used for the calculation of lateral strains.

As previously discussed, the data points of lateral displacement at 4-m and 56-m spacing were considered as corner points of two sets of square quadrilateral elements, and were used to create the 4-m and 56-m grids of quadrilateral elements through the “create fishnet” tool in ArcMap 10.1 [13]. Each element was uniquely identified with an ID in ArcMap 10.1 [13]. The Manifold package [20] was used to correlate each element center point to the appropriate set of four corner points using a structured query language (SQL) statement for each grid size. Spreadsheets of the resulting intersection at 4-m and 56-m spacing were exported to Matlab [21] for calculation of lateral strains. The calculated lateral strains were imported in ArcMap 10.1 [13] in 4 m x 4 m and 56 m x 56 m polygons to allow for spatial correlation with the pipeline network and pipe repairs.

Similar to RR correlations with β , pipelines and repairs inside the areas of liquefaction influence and excluding those above 50 m in elevation subject to landslides in the Port Hills were used for RR correlations with lateral ground strains at 4-m and 56-m spacing. RR for a given interval of ϵ_{HP} was calculated by dividing the number of repairs for a particular type of pipeline by the kilometers of that pipeline type within the same interval. Pipelines and repairs were initially binned at intervals of ϵ_{HP} equal to 0.05%, and the interval size of ϵ_{HP} was adjusted during the screening process to develop meaningful correlations. The calculated RR was associated with the geospatially corresponding value of ϵ_{HP} and was used as a single data point in RR correlations.

The results for RR correlations with ϵ_{HP} for AC, CI, and PVC pipelines are presented in Figure 8a through Figure 8c. The screening criteria were applied using a confidence level, β_c , of 95%, 85%, and 75% for AC, CI, and PVC pipelines, respectively. Procedures similar to those for correlations with angular distortion were used, in which the confidence interval is relaxed for the progressively smaller number of repairs for AC, CI, and PVC. The linear regressions for all three pipe types provide a good fit of the data with relatively high r^2 values.

Comparison between RR correlations derived from 4-m and 56-m spacing of lateral strain shows significant differences for AC and PVC pipelines. For AC pipelines lateral strains at 56-m spacing in Figure 8a correlate with RRs that are 2 to 3 times higher than the RRs for lateral strains at 4-m spacing. Similarly, the PVC pipeline RRs for lateral strains at 56-m spacing in Figure 8c are up to 2.3 times higher than RRs for lateral strains at 4-m spacing in Figure 8c for the same levels of ϵ_{HP} . These differences in RR correlations with ϵ_{HP} between lateral ground strains at 4-m and 56-m spacing reveal the sensitivity of RR correlations to the scale used for discretization of the ground parameters used in the analysis. Lateral movements at 56-m spacing result in a relatively coarse lattice of lateral ground strains that does not capture local effects with high values of horizontal strain.

Figure 8. Correlations of repair rate with lateral ground strain at 4-m and 56-m spacing for a) AC, b) CI, and c) PVC pipe materials for the 22 Feb. 2011 earthquake, and d) comparison of repair rate with lateral ground strain at 4-m spacing with previous work by O'Rourke et al. (2014).

In contrast to AC and PVC pipelines, Figure 8b shows that RR correlations for CI pipelines with lateral strains at 56-m and 4-m spacing are in good agreement. CI pipeline repairs are located in areas where more uniform strain patterns take place, whereas AC and PVC pipeline repairs are

located in areas of variable and locally high strains. As a result, higher levels of repair in AC and PVC pipelines are correlated with lower strains using a 56-m spacing which does not capture strain field variability in as much detail as a 4-m spacing. This scaling effect is reflected in the higher regression slopes of RR vs ϵ_{HP} for AC and PVC pipelines. The higher slope occurs because RRs are correlated with ϵ_{HP} that is often too low with a 56-m spacing. In contrast, more uniform strain fields associated with CI pipelines reduce the effects of grid size on the resulting RR vs ϵ_{HP} correlations.

Using the correlations of RR with ϵ_{HP} at 4-m spacing in Figure 8a through Figure 8c, comparison among the results for AC, CI, and PVC pipelines indicates that AC pipelines sustained 1.4 to 2.1 times greater damage than the damage observed for CI pipelines. AC pipelines sustained repair rates 2.7 to 10.5 times greater than those of PVC pipelines.

Figure 8d compares the results of the current study with the results of previous work by O'Rourke et al. [2] which was performed using a 56-m grid, an earlier formulation of the screening criteria, and an earlier version of the water pipeline repair data set for the 22 February 2011 earthquake. The regressions for AC and PVC pipelines based on 4-m LiDAR spacing plot lower with a reduced regression slope compared to those developed in previous work by O'Rourke et al. [2] with 56-m LiDAR spacing. The regressions for CI pipelines compare favorably because the pipelines were located in relatively uniform strain fields for which the higher resolution at 4-m spacing does not show significant difference compared to 56-m spacing.

8. COMBINED EFFECTS OF DIFFERENTIAL VERTICAL GROUND MOVEMENT AND LATERAL GROUND STRAIN

The combined effects of lateral ground strain and vertical differential ground movement on pipeline damage were evaluated using an approach similar to that developed by Boscardin and Cording [22] for ground movement effects on buildings. Pipeline RRs were correlated with both β and ϵ_{HP} calculated from vertical and horizontal LiDAR movements at 5-m and 4-m spacing, respectively. Similar correlations were developed by O'Rourke et al. [2] using a 56-m grid, an earlier formulation of the screening criteria, and an earlier version of the water pipeline repair data set for the 22 February 2011 earthquake. It should be pointed out the LiDAR measurements on 5-m and 4-m spacing are well matched with the average length of a jointed pipeline, which is typically 6 m.

Lateral ground strains at 4-m spacing were used to correlate RR with ϵ_{HP} . Pipelines and repairs were spatially intersected with β and ϵ_{HP} , and RR was calculated for a given pair of β and ϵ_{HP} intervals by dividing the number of repairs for a particular type of pipeline by the kilometers of that pipeline type within the same pair of intervals. The interval for β was 1×10^{-3} , and for ϵ_{HP} was 0.2%. The RRs were associated with the appropriate pair of β and ϵ_{HP} and were used as data points for RR correlations.

The screening criteria in Equation 3 were applied in the data points and resulted in sufficient number of repairs for correlations among RR, β , and ϵ_{HP} for AC and CI pipelines. There is insufficient number of repairs, however, to develop correlations with PVC pipelines even if the

confidence interval is relaxed to a relatively low value when screening the data. The confidence level when screening the data for AC and CI pipelines was adjusted to 75% and 60%, respectively, to attain a broad distribution of data within the β vs ϵ_{HP} space. Correlations among RR, β , and ϵ_{HP} for AC and CI pipelines were developed, using the global polynomial interpolation method in ArcMap 10.1 with a first-order polynomial model.

The resulting contour surfaces are presented in Figure 9a and 9b for AC and CI pipelines, respectively. The extent of the data for CI pipelines is smaller than the extent of data for AC pipelines due to the higher number of AC pipeline repairs that provide a more extensive database for sampling with respect to combined ϵ_{HP} and β . Similar to Figure 6 and Figure 8, the results for AC and CI pipelines in Figure 9 show that AC pipelines sustained more damage compared to CI pipelines.

The correlations in Figure 9 represent a marked improvement over those presented previously by O'Rourke et al. [2], where the interval chosen for ϵ_{HP} was too large. The selection of ϵ_{HP} intervals in Figure 9 was guided by a study of the statistical distribution of lateral ground strains associated with the water pipeline network that is described by Bouziou and O'Rourke [23]. The study shows that approximately 90% of the 4m x 4m cells of ϵ_{HP} overlying the pipeline network is associated with values of $\epsilon_{HP} \leq 1\%$. Similarly, 90% of the 5m x 5m cells of β overlying the pipeline network is associated with values of $\beta \leq 1 \times 10^{-2}$. Based on these observations, the ϵ_{HP} and β intervals in the sampling process were selected to reflect combined ϵ_{HP} and β effects at a scale that is consistent with the actual ground deformations experienced by the majority of pipelines.

Figure 9. Repair rate vs. lateral ground strain and ground angular distortion for a) AC and b) CI pipelines.

9. CONCLUSIONS

The performance of the Christchurch water distribution system is evaluated through spatial

analysis in this study. This paper expands on work by O'Rourke et al. [2] by using the most recent and complete repair records, incorporating high resolution Light Detection and Ranging (LiDAR) measurements of lateral movements on 4-m spacing, applying refinements for anisotropy in the geo-statistical interpolation of geometric mean peak ground velocity (GMPGV), and using the higher resolution data and improved screening criteria to provide better correlations among pipeline damage and liquefaction-induced lateral ground strains and differential vertical ground movements. The principal findings are:

- The Christchurch data for repair rate (RR) vs GMPGV provide improved regressions for future fragility analyses of water distribution pipeline performance during earthquakes and expand the database of historical data. The regressions in this study compare favorably with those previously reported by O'Rourke et al. [2].
- In this study, the regressions between RR and ground angular distortion, β , show a slightly lower level of damage for AC pipelines at relatively small β compared to the regressions reported by O'Rourke et al. [2], but otherwise for AC, CI, and PVC pipelines compare favorably with the previous work. In the present study, RRs vs β for AC pipelines plot approximately two times higher than those for CI pipelines, and 5 to 10 times higher than those for PVC pipelines.
- The regressions between RR and lateral ground strain, ϵ_{HP} , using the 4-m LiDAR measurement spacing are significantly different for AC and PVC pipelines than those previously reported for LiDAR measurements on 56-m spacing. The RR vs ϵ_{HP} regressions for CI pipelines compare favorably because the pipelines were located in relatively uniform strain fields for which there is no significant difference between 4-m and 56-m resolution. RRs vs ϵ_{HP} for AC pipelines are approximately 50% to 100% higher than those for CI pipelines, and approximately 3 to 11 times higher than those for PVC pipelines.
- The correlations among RR, ϵ_{HP} , and β for AC and CI pipelines in this work are a significant improvement over those previously presented by O'Rourke et al. [2]. These correlations provide the means to predict RR with respect to the combined effects of lateral ground strain and differential vertical ground movement.

The segmented pipelines most resilient to permanent and transient (PGD and TGD, respectively) ground deformation effects are PVC pipelines, for which substantial improvements in earthquake performance are quantified in this work with respect to AC and CI pipelines.

Scale effects have a substantial impact on the inferred relationship between pipeline damage and lateral ground strain, and depend on local variations in the strain field. High resolution data are needed to capture the influence of localized ground deformation. Computational modeling that utilizes regressions, such as those of RR vs ϵ_{HP} , need to account for scale effects, and should strive for the highest resolution possible at a scale equivalent to that of the structure being investigated.

Correlations among pipeline repair rates (RR), lateral ground strains, and differential vertical ground surface movements provide the means to predict pipeline damage on the basis of the combined effects of lateral ground strain and differential vertical ground movement. These correlations may be used in future planning, design, and loss estimation to assess limiting deformations for pipelines subjected to both PGD-induced lateral and vertical differential

displacements.

The flow charts with detailed steps in the geospatial analysis that were presented in this paper provide detailed documentation of the methods used for analyzing the data for clarity of process and to assist in future investigations with data of similar size and complexity.

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