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Effects of Ground Strain and Pipeline Orientation on Pipeline Damage during Earthquakes

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ABSTRACT

Pipeline damage correlations are used for risk studies of water distribution systems. One of the parameters correlated with pipeline damage in permanent ground deformation zones is horizontal (lateral) ground strain. Some damage correlations use the maximum absolute value of the two principal strains around the pipelines as the lateral ground strain parameter. However, strains caused by lateral ground movements can be resolved into components such as axial strains in the direction of the pipelines. Performing such a process for a large urban water distribution system is a relatively complicated task and development of damage relationships requires comprehensive ground deformation and pipeline data. The unprecedented database following the Canterbury Earthquake Sequence in New Zealand (NZ) provides an opportunity to explore the effects of ground strain and pipeline orientation on pipeline damage during earthquakes. This study presents the GIS methodology for using pipeline orientation to evaluate pipeline network damage caused by ground deformation during earthquakes. The geospatial analyses results indicate differences in the responses of asbestos cement (AC) and cast iron (CI) segmental pipelines under compressive and tensile axial strains.

INTRODUCTION

The seismic performance of water systems is critical to the resilience of the communities they serve (e.g., Davis, 2014). Ground displacements caused by earthquakes impose strains in pipelines that may result in pipeline damage as well as the disruption of vital services. In general, ground displacements caused by permanent ground deformation (PGD), such as lateral spreading in liquefaction zones, are significantly higher than those caused by transient ground deformation (TGD) associated with seismic waves. PGD damage tends to result in greater pipeline repair numbers and service interruption effects. Loss estimation methodologies frequently use correlations of pipeline repair rates versus a parameter representing seismic demands. Repair rate (RR) is the number of repairs divided by the length of a specific type of pipelines in the same area. The most common parameters representing seismic demands include peak ground velocity (PGV) for TGD and ground strains for PGD.

Recently, some other liquefaction related parameters have been proposed in pipeline damage correlations. Toprak et al. (2019) developed pipeline damage correlations by using liquefaction

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potential index (LPI), liquefaction severity number (LSN), and one-dimensional volumetric reconsolidation settlement (S_{V1D}). Bellagamba et al. (2019) utilizes the peak ground velocity, pipe characteristics, and soil liquefaction susceptibility expressed by the cyclic resistance ratio (CRR). Key pipeline characteristics and different damage correlations can be found in publications by various researchers (e.g., O'Rourke and Toprak, 1997; ALA, 2001; O'Rourke and Deyoe, 2004; Toprak and Taskin, 2007; Ballantyne, 2010; O'Rourke et al., 2014, Toprak et al., 2019; Bellagamba et al., 2019).

In their state of the art review, Pineda-Porras and Najafi (2010) identified pipeline damage estimates, including the effects of pipeline orientation, as one of the challenges, or gaps, for future investigations. Existing methods either do not account for the orientation of the pipeline within the ground strain field (e.g. O'Rourke and Deyoe, 2004; O'Rourke et al., 2014), or provide only for an approximation of orientation (O'Rourke, 2009). Bouziou and O'Rourke (2019) proposed a probabilistic way to account for the relative orientation of pipelines with respect to maximum ground strains. In their approach, the expected value of the ground strain in the axial pipeline direction, ε_e, is calculated assuming that the probability of a given pipeline orientation relative to the direction of principal ground strain is uniformly distributed. Toprak et al. (2016) performed a pilot study to account directly for pipeline orientation with respect to ground strain field in terms of pipeline damages by using the Avonside neighborhood of Christchurch, NZ. In the current study the GIS methodology for using orientation in pipeline damage assessment is presented, and damage correlations are developed by evaluating pipeline orientations in the Christchurch water distribution system. This study focuses on axial ground strains in the direction of the pipelines, which are considered as the main cause of the damage, related primarily to joint failures.

GIS DATABASE

Both ARCGIS and QGIS were used at different stages of the study. ARCGIS is a commercial program by ESRI (2011) and QGIS (2020) is an open source software. All data were assembled in GIS with required attributes and appropriate coordinate systems and projections. The data involved both raster and vector components which could be processed routinely in GIS.

The 2011 Christchurch earthquake caused substantial damage to the Christchurch water distribution system. The data collected following the earthquake are unprecedented in size and detail, involving high resolution light detection and ranging (LiDAR) measurements of ground movements and detailed repair records for thousands of km of underground pipelines with coordinates for the location of each repair as well as seismic, geological and geotechnical information. For the water distribution system, this study focuses on damage to water mains, it does not include repairs to smaller diameter submains and customer service laterals. There were 1502 repairs to 1730 km of water mains, which are pipelines with diameters typically between 75 and 600 mm, conveying the largest flows in the system. The present study uses the most recent and improved water distribution network repair records provided by the Stronger Christchurch Infrastructure Rebuild Team (SCIRT). A comprehensive description of the databases used herein can be found in CGD (2012), Bray, et al., (2013), O'Rourke, et al. (2014), Cubrinovski, et al. (2014), Bouziou and O'Rourke (2017), and Toprak, et al. (2019).

Figure 1 shows the city of Christchurch water distribution system and repairs after the 2011 Christchurch earthquake superimposed on areas of liquefaction and PGD areas as characterized by LiDAR measurement. The majority of the pipelines and repairs belongs to asbestos cement (AC), cast iron (CI), and PVC pipelines.

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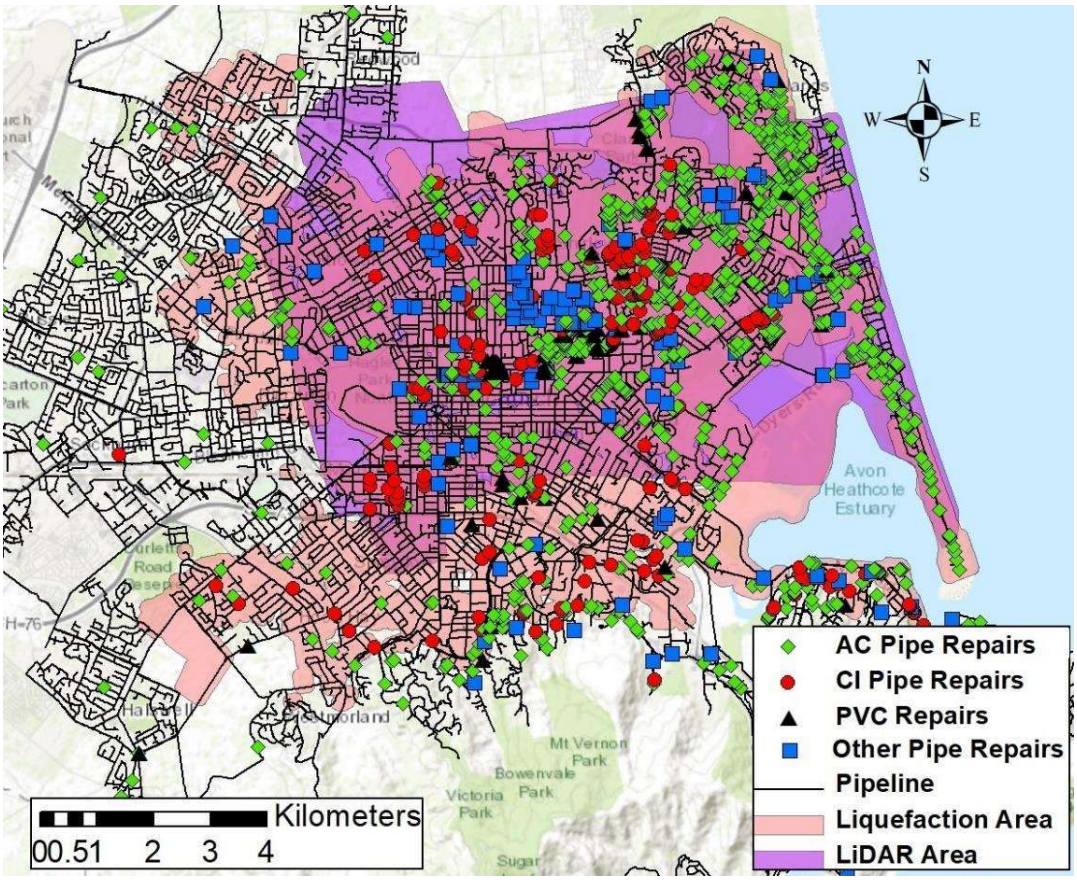

Figure 1. Water distribution pipelines in Christchurch and pipe repairs for the 22 Feb. 2011 earthquake.

METHODOLOGY

Figure 2 provides the flowchart of the procedure used herein for evaluating pipeline orientation combined with lateral permanent ground deformations (PGD). It is a modified version of the methodology used by various researchers (e.g., Bouziou and O'Rourke, 2017; Nacaroglu, 2017) to incorporate pipeline orientation in pipeline damage correlations. The procedure works with three different sets of data, namely ground displacements, pipeline, and pipe repairs following the process described below. Some of the elements of the flowchart are presented and discussed in detail in the following sections. Lateral strains, which characterize the effect of observed PGD on pipelines, are calculated from ground displacements. The RRs corresponding to various strain levels are determined via GIS analyses performed on pipelines and repairs.

This study uses LiDAR data of 4-m spacing as it is more compatible with typical pipe segments ranging between 4 to 6-m in Christchurch. As discussed in Toprak et al. (1999) the scaling effect is important in pipeline damage assessment. The overall area of the resulting GIS lattice points and 4-m polygons is about 74 km^2 (Figure 3a). Considering the dimensions of LiDAR coverage area is approximately 12 x 9 km, these data create an enormous database with 4270841 data points with no data points on lakes, sea, rivers, etc. Each data point in the grid is characterized by coordinates and horizontal displacements east-west and north-south directions.

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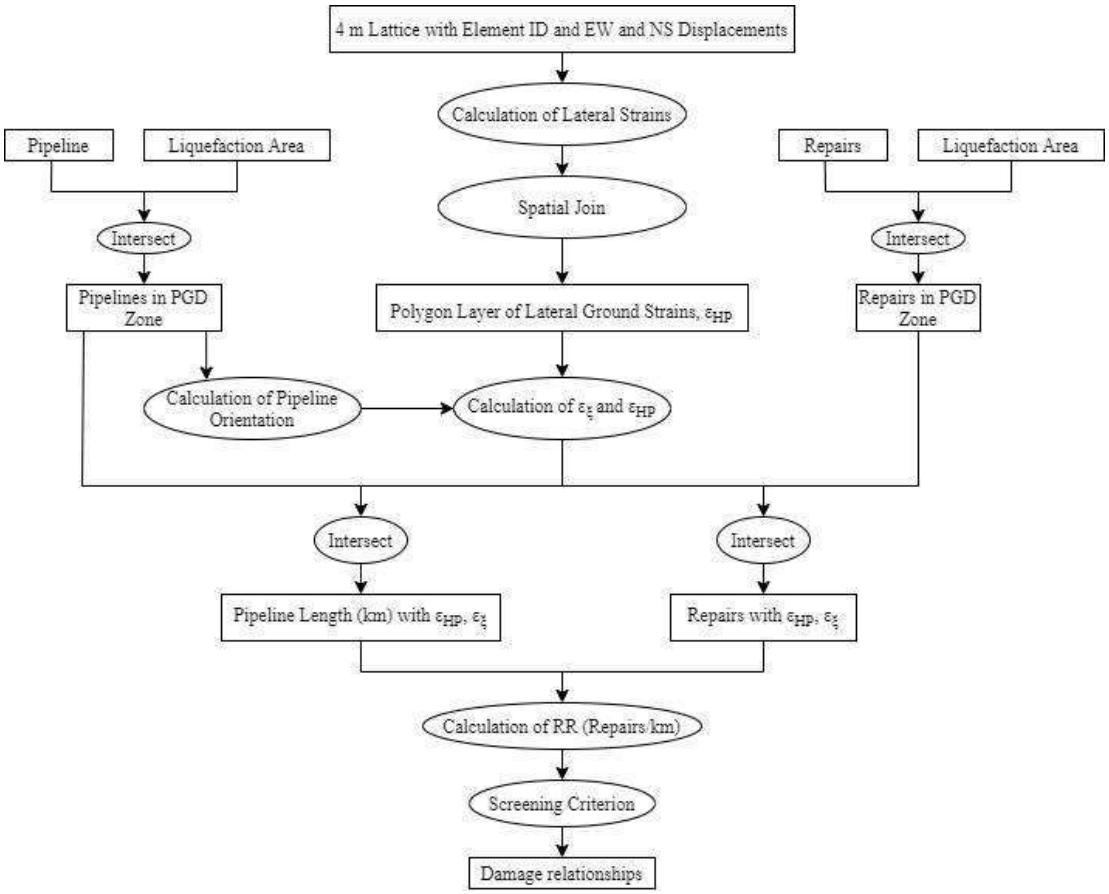
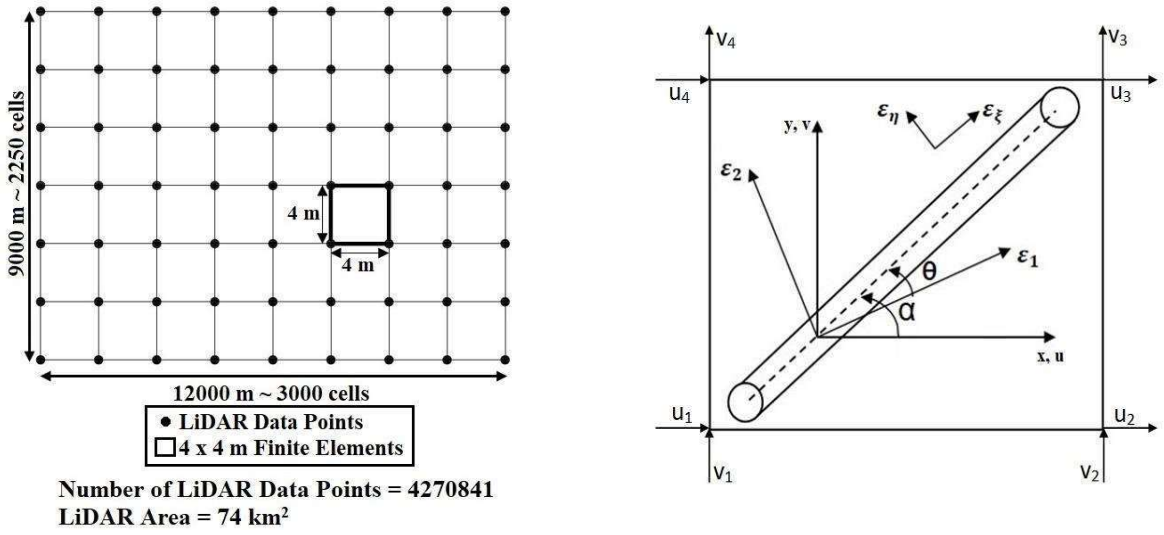


Figure 2. Flowchart of the GIS Methodology for Lateral Permanent Ground Deformations Considering Pipeline Orientations.



a) LiDAR coverage area and FEM mesh (b) Pipeline orientation and strain definitions

Figure 3. Calculation of strains in different directions with respect to pipeline.

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To calculate the ground strains numerically, the Finite Elements Method (FEM) was used with GIS and spreadsheets. In this method, a continuum is decomposed into finite number of elements and a systematic approximate solution is obtained via interpolation functions in terms of the field variables defined at the nodes. Each element is connected to neighboring elements at common nodes. As shown in Figure 3a, the LiDAR data points form a square pattern and the square elements (4x4 m) that compose the obtained data set can be considered as a finite element network consisting of known rectangular elements in finite element analyses (FEA). Figure 3b shows an enlarged square element from Figure 3a with displacements in east-west direction (u_i) and north-south direction (v_i) shown at corners of such an element. In essence, the LiDAR data points are taken as the nodes of the ground element. Also shown in Figure 3b is a pipe oriented with an angle α with respect to x (East) axis. Because of uneven displacements at corners of elements, some deformations occur in each element. Strains corresponding to these deformations at the centers of elements have been obtained with FEA formulas corresponding to plain strain conditions for quadrilateral elements, which are frequently used in the literature and given by Cook (1995) (Eqn 1).

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \frac{1}{(2a)^2} \begin{bmatrix} -(a-y) & 0 & (a-y) & 0 & \dots. \\ 0 & -(a-x) & 0 & -(a+x) & \dots. \\ -(a-x) & -(a-y) & -(a+x) & (a-y) & \dots. \end{bmatrix} \begin{Bmatrix} u_1 \\ v_1 \\ u_2 \\ v_2 \\ \vdots \\ v_4 \end{Bmatrix} \quad (1)$$

Here, u_1, v_1, u_2, v_2… v_4 represent the corner displacements, x and y coordinates represent two-dimensional space, and a represents the edge length of the square element. As a result of the analyses, strains in the east-west and north-south (ε_x and ε_y, respectively) directions and shear strains in xy plane (γ_{xy}) can be calculated for each element. The principal strains in the ground element can be determined by using Eqn. 2:

$$\varepsilon_{1,2} = \frac{\varepsilon_x + \varepsilon_y}{2} \pm \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma_{xy}}{2}\right)^2} \quad (2)$$

The strain in the ground element in the longitudinal direction of a pipe (ε_ξ) can be obtained from Eqn. 3:

$$\varepsilon_\xi = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2} cos\, 2\,\alpha + \frac{1}{2}\gamma_{xy}\, sin\, 2\,\alpha \quad (3)$$

Similarly, the strain in transverse direction (ε_η) can be calculated by using Eqn. 4, which is not the primary topic of this paper.

$$\varepsilon_\eta = \frac{\varepsilon_x + \varepsilon_y}{2} - \frac{\varepsilon_x - \varepsilon_y}{2} cos\, 2\,\alpha - \frac{1}{2}\gamma_{xy}\, sin\, 2\,\alpha \quad (4)$$

Figure 3b shows the orientation of a pipe and relevant angles used in the equations with respect to EW directions and relative to different strains described herein.

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The evaluation can be performed of strains conforming to the pipeline axial orientation. The first step in such a process is to determine the orientation of each individual pipe segment with respect to a defined Cartesian coordinate system. The second step is to calculate strains for each pipe corresponding to its longitudinal direction. The next step is to calculate RR corresponding to different strain levels and regressing the data to obtain pipeline damage correlations. It is assumed that the pipelines conform to the ground movements and experience similar strains as the ground.

ANALYSES

The GIS methodology described in the previous section was used to calculate the strain values, prepare a strain distribution map, and develop correlations. In the calculation of maximum absolute principal strains and strains in the longitudinal direction of pipelines, respectively Eqn. 2 and 3 were used. Since the inclination of the pipeline with respect to the horizontal axis (α, see Fig. 3b) is required in Eqn. 3, the first step was to calculate the orientation angles of all pipelines in the liquefaction zone by using GIS. Then, the strains in the axial direction of pipelines could be obtained.

Orientation of the pipelines in an urban water distribution system naturally follows the layout of the streets and buildings. Figure 4 shows on the same plot the orientations of all pipelines in the Christchurch water distribution system as well as orientation of the pipelines in the liquefaction zone which is a subset of whole city. The pipeline orientation is defined by angle α which is the angle between x axis and pipe axis direction, changing counterclockwise between 0 and 180^0 as shown in Figure 3b. The orientation of pipelines were determined in GIS. The histogram illustrates that the number of pipes in the east-west and north-south direction (within $\pm 10^0$) are approximately equal and make up about forty percent of all pipes. Similarly, number of pipes in the northeast-southwest and northwest-southeast direction (within $\pm 10^0$) are approximately equal and make up about thirty percent of all pipes. The rest of the pipes are equally divided in other orientations. The same trend is observed for pipelines in liquefaction area and all Christchurch.

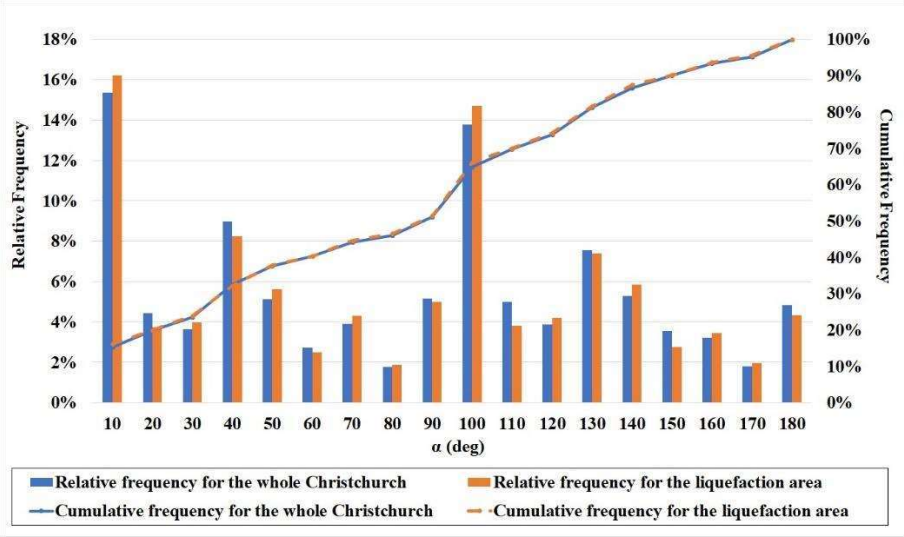

Figure 4. Pipeline Orientations in the whole Christchurch and liquefaction area.

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Calculating strain for the whole area at once was not possible due to GIS software constraints. To solve this problem, LiDAR coverage area of the liquefaction zone was divided into 31 smaller sub-regions. Figure 5 shows these 31 zones superimposed on pipelines and pipe repairs. Separate ground strain analyses were performed for all regions and then were combined. The areas of the sub-regions were created as equal as possible such that they will have about the same area. Overall, 26 of the 31 regions have nearly the same area and are somewhat larger than the other five regions. These five regions are on the border resulting in smaller areas. Each of the 26 regions was created as a region with dimensions of 2188 m in the X direction and 1596 m in the Y direction with a total area of 3492048 m^2. As a result, each of these sub-regions consists of a total of 218253 square elements of 4x4 m. The GIS shapefile file, which is created in order to overlap this region with LiDAR 4m displacements and to obtain displacements in the corner of each square, consists of approximately 1,000,000 points. This data set required a relatively long time for analysis.

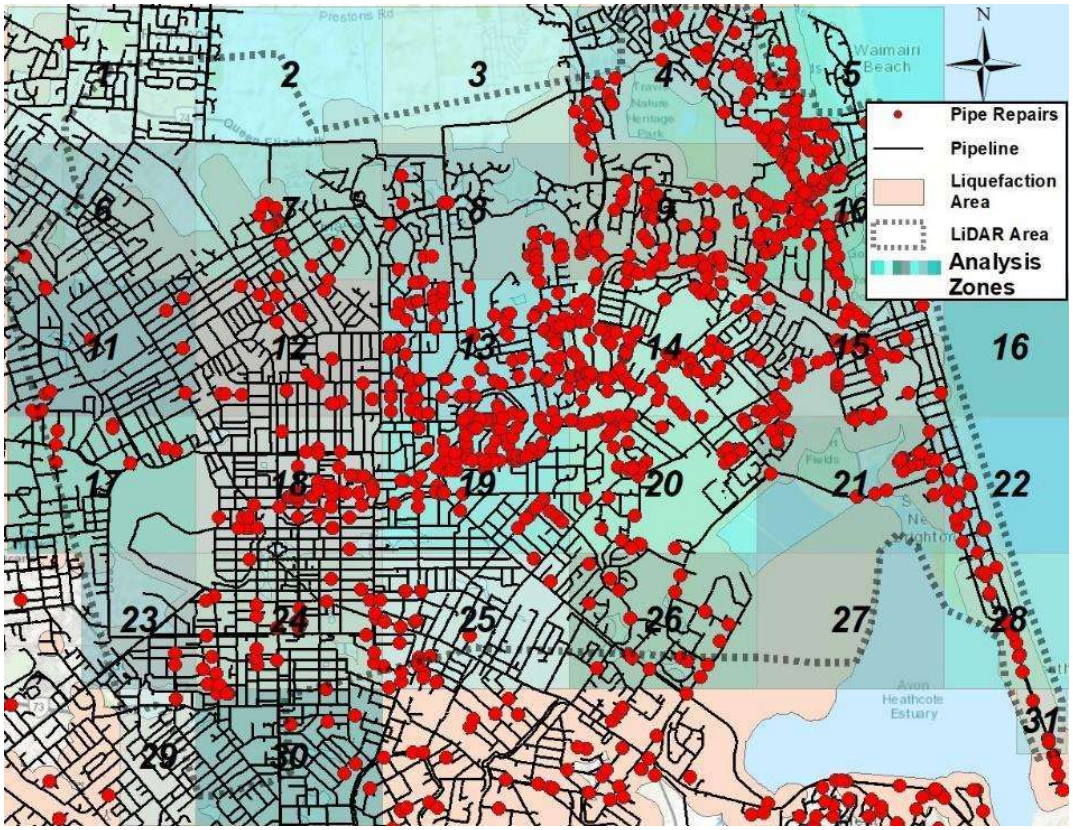

Figure 5. Map of 31 zones used to calculate strains.

To develop pipeline damage correlations, first, the strain map was combined with both pipeline and pipeline repairs data to determine the length of the pipelines and number of repairs corresponding to certain strain levels. Afterwards, the RR values with respect to strain values were calculated from the pipeline length and repair data. During the process, the screening criteria was used to determine appropriate strain intervals which includes sufficient pipe length to produce meaningful correlations (e.g., O'Rourke et al., 2014). The data which satisfy the screening criteria were used to obtain the pipeline damage regressions. It should be noted that

this process was performed on the assembled data from all 31 sub-regions not on individual sub-regions. Like the process followed for the pipeline damage correlations for maximum absolute strains, similar screening criteria were used for the development of pipeline damage correlations with respect to axial strains. Previous studies showed that pipe material is an important parameter in the seismic performance of water distribution systems. Therefore, the analyses herein were carried out separately with respect to pipe material. Because of the space limitations only the correlations related to CI and AC pipelines are presented herein.

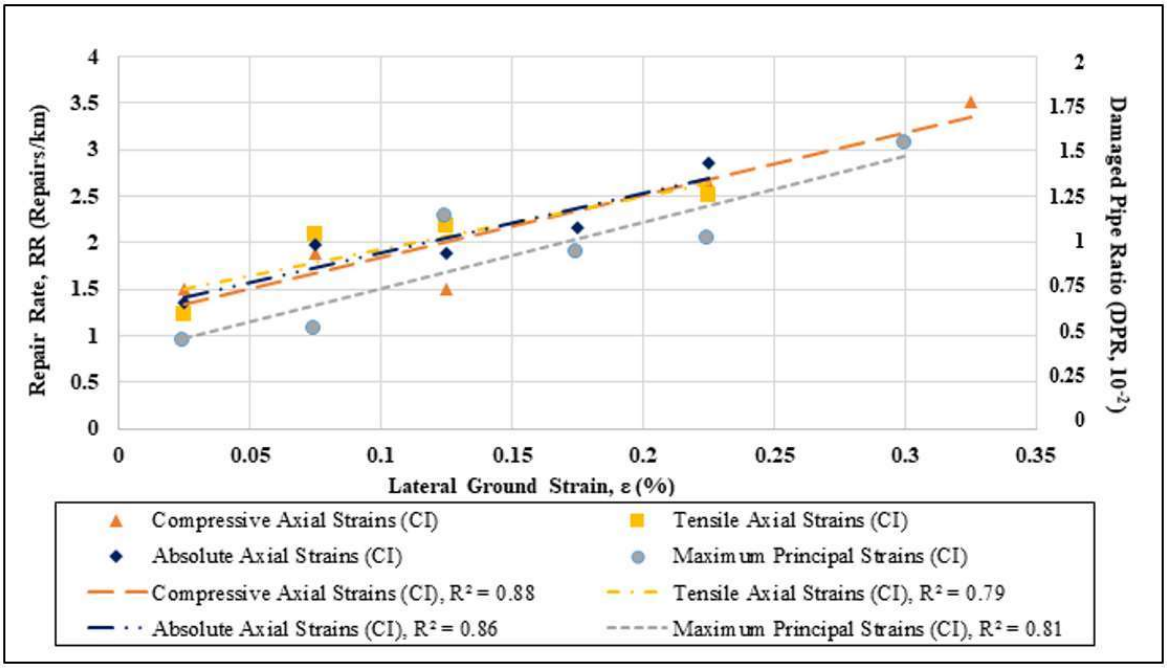

Figure 6. Repair rates for CI pipelines considering pipeline orientations and strains.

Figures 6 and 7 show repair rates and damage correlations with respect to strains for CI and AC pipelines, respectively. In addition to RR, pipeline damage was correlated with the damaged pipe ratio (DPR), which is a dimensionless parameter (e.g., Toprak et al., 2018; 2019). obtained by dividing the total number of pipe segments needing repairs by the total number of all pipe segments in each strain bin. The linear regressions for the correlations provide a comparable and good fit of the data with relatively high r^2 values. Four different strains are used in the figures, namely absolute maximum principal strain (ε_{HP}), compressive axial strain (ε_{CA}), tensile axial strain (ε_{TA}), and absolute axial strain (ε_{AA}). The absolute axial strain corresponds to the maximum of the absolute of tensile and compressive axial strain. The range of the strains for which damage relationships could be developed varied as a result of the availability of existing data in these ranges and screening criteria. Figure 6 shows that the RRs and regression lines for the tensile and compressive strains plot very close, indicating that the response of CI pipelines under tensile and compressive axial strains is quite similar. Figure 7 shows that AC pipelines have higher repair rates when exposed to tensile axial strain than the compressive axial strains. This can be explained by the weakness of AC pipelines especially at the joints with lower resistance against pullout when affected by tensile strains than compression when affected by compressive ground strains.

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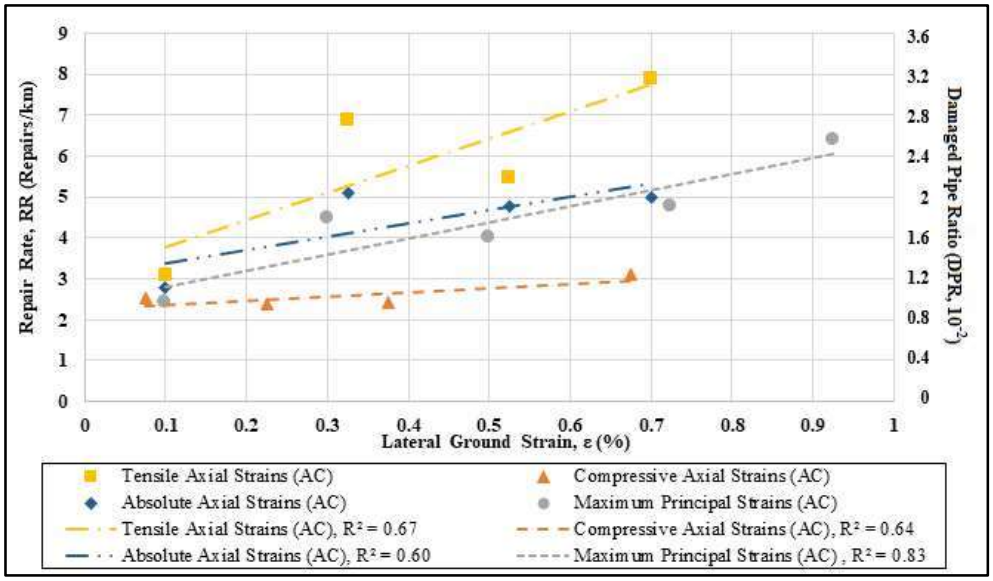

Figure 7. Repair rates for AC pipelines considering pipeline orientations and strains.

CONCLUSIONS

Research work performed in the current study presents a GIS methodology that considers pipeline orientation whenevaluating damage in large pipeline networks caused by ground deformation during earthquakes. Damage correlations were developed in this study by taking into consideration the pipeline orientations in the Christchurch water distribution system. The pipeline network, its damage and ground deformation data from the 22 February 2011 earthquake were used. The process involved the calculations of the orientation of each pipe in the network and ground strains in the axial directions of the pipe. Such an analyses for a large pipeline network could not be achieved in the past partly because of some software limitations but more importantly the absence of ground deformation information at the required resolution.

In this study, high resolution Light Detection and Ranging (LiDAR) measurements of lateral movements on 4-m spacing which is compatible with typical pipe segments ranging between 4 to 6-m in Christchurch were utilized. The primary focus of the study is axial strains in the direction of the pipelines because they are considered as the main cause of the damage, related primarily to joint failures. The geospatial analyses results revealed differences in the responses of asbestos cement (AC) and cast iron (CI) segmental pipelines under compressive and tensile axial strains. The results showed that the response of CI pipelines under tensile and compressive axial strains is quite similar. However, AC pipelines have higher repair rates when exposed to tensile axial strain than compressive axial strain. This can be explained by the weakness of AC pipelines especially at the joints with lower resistance against pullout when affected by tensile strains than compression when affected by compressive ground strains.

Accounting explicitly for pipeline orientation effects with respect to axial strain results in about the same statistical significance (using r^2 and residuals) as previous studies focused on maximum principal strains. During ground movements caused by seismic excitation, pipelines may be influenced by axial strains as well as angular distortion. The combined effects of both these deformation parameters are under investigation as a continuation of the research presented herein.

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