Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 196

RESILIENCE OF WASTEWATER PIPELINES IN EARTHQUAKES

M. R. Zare[1] and S. Wilkinson[2]

ABSTRACT

Breakages and leakages in wastewater pipelines after devastating earthquakes are of great concern to every municipal region. Wastewater pipeline failure caused by an earthquake significantly affects communities in urban areas, particularly densely populated ones. The numbers of defects caused by any particular earthquake significantly affect post earthquake rehabilitation. Good estimation of the number of defects can decrease recovery. Good estimation of the number of defects is fundamental to wastewater reticulation resilience to earthquakes. There are various types of formulae for estimating wave propagation effects on pipelines. Selecting and applying adequate formula according to available data is of concern to resilience in wastewater reticulation.

Introduction

Pipelines in urban areas carry essential fluids into the city or out. Densely populated areas not only require essential fluid such as potable water but also they need wastewater transmit outward. Wastewater pipelines failure significantly endangers human health as well as environmental pollution.

Considering the past earthquakes damage in pipelines reveals the significance of earthquake effects on pipelines. Significant number of defects in pipelines after an earthquake attracted earthquake engineers and researcher to find the appropriate estimation of damage. Earthquakes affect wastewater pipelines in two different ways: pipe breakages and pipe leakages (Wang, Wang et al. 1991; Lund, Cornell et al. 1998; Chen, Shih et al. 2002).

Earthquake damage in pipelines

Katayama was the first to illustrate the earthquake effects on water and gas pipelines in some earthquake affected cities in Japan (Katayama, Kubo et al. 1975). The 1906 earthquake affected all of the transmission pipes (Eidinger, de Castro et al. 2006). Lund's work (1998) showed the wastewater system was significantly affected by the earthquake during the 1989 Loma Prieta earthquake. Lund (1998) also mentioned that the earthquake in San Francisco Bay caused 350 main repairs to be made mostly on 4, 6, and 8 inch diameter Cast Iron (CI) water pipes.

[1] PhD student, Dept. of Civil Engineering, University of Auckland, Auckland, NZ
[2] Associate professor, Dept. of Civil Engineering, University of Auckland, Auckland, NZ

The 1994 Northridge earthquake caused significant damage to the US water supply. The Northridge earthquake caused about 1100 repairs in the water pipelines, 93 % of which belonged to pipes with diameter less than 24 inches (Jeon 2005). Jeon (2005) concluded damage to wastewater pipelines seems to be the same as in water pipelines. Severe damage was reported to pipelines particularly water pipelines after the 1995 Hyogo-ken Nanbu earthquake (Kuraoka and Rainer 1996). Kuraoka (1996) reported a total number of 3300 breakages in water pipes after the earthquakes and also mentioned how pipe breakages caused serious difficulties for the whole region. The 1999 Ji-Ji earthquake in Taiwan severely damaged the gas pipeline network. Schiff et al (2000) reported in some regions the earthquake severely damaged water pipelines, such as 50 breakages in just 3 km of the water pipeline. (Schiff, Abrahamson et al. 2000)

In the 2004 Niigata Ken Chuetsu earthquake in Japan, the wastewater reticulation suffered serious damage. Scawthorn et al (2006) showed that 187 pipe breakages occurred in sewers, whereas just 22 water invasions had been reported in wastewater pipelines. Scawthorn et al (2006) also showed that the immediate effect of the earthquake on the wastewater pipelines represented about 12% of the total real damage.

Pender's work (1987) showed during the Edgecombe earthquake in 1987 sewage pipelines suffered serious damage. The most number of damages was reported in 150 and 200 mm-diameter asbestos pipes. Pender (1987) mentioned that almost every individual earthenware pipe was damaged severely and hundreds of meters of this pipe type had to be completely replaced with new pipes (Pender 1987). The last notable earthquake in New Zealand (Gisborne 2007) caused damage to the two main wastewater pipelines underneath bridges, although some other pipe damage was reported later (Rentoul 2008). Read and Sritharan (1993) reported no major damage to the wastewater pipe network or the wastewater system in the 1993 Ormond earthquake. The most immediate damage to the sewer reticulation was the pipe breakage at a bridge in the 1993 Ormond earthquake (Read and Sritharan 1993). The 2003 Bam earthquake in Iran damaged 70 to 80 % of water pipeline along the 49 km of water distribution network. It should be noted that the pipelines in this network aged from 2 months up to 40 years. When the earthquake struck Bam no wastewater reticulation was operating there (EERI 2004).

The above case studies show that earthquakes could have significant effects on wastewater pipelines, especially in brittle pipes. Depending upon the magnitude of the earthquake and pipelines characteristics, the number of breakages and leakages can vary from minor to significant. Most of the cases concentrated on water pipeline defects, due to instant and visible defects caused by earthquakes in pressure pipes compared with gravity pipelines (sewer). The pipe material used in both water and wastewater reticulation are approximately the same but reported damage to some sewers in some cases were less than those of pressured pipelines. If wastewater pipes do not obstruct the flow, wastewater will continue to flow and the damage will not appear until later (Schiff 1995).

Wave propagation effect of earthquake calculation method

Correlation between earthquake characteristics and pipeline damage is the main concern of researchers for evaluating earthquake effects on pipelines. Various types of pipe parameters and earthquake characteristics were taken into account to demonstrate pipelines vulnerability to earthquakes in the available formulae. Peak Ground Acceleration (PGA) and Modified Mercalli Intensity (MMI) provide the basis of the preliminary damage formulae. For instance, Katayama (1975) first correlated PGA to damage rate in pipelines according to his work in the different cities in Japan (Katayama, Kubo et al. 1975). Wang (1991) based on historical data from the past 7 earthquakes around the world recommended some formulae for different soil types by applying PGA and MMI. Spectral Acceleration (SI) also was used as an indicator of the earthquake magnitude or estimator of Peak Ground Velocity (PGV) (for instance, see (Chen 2002; FEMA 2003; Jeon 2005)).

Preliminary formulae apply PGA and MMI as the earthquake parameters and normally the difference between two distinct effects of earthquakes are not considered. Wave propagation and permanent ground deformation are two main types of earthquake effects on pipelines. Most researchers after Eguchi (1983), who derived damage rate and earthquake parameters correlation usually consider both earthquake effects distinctively.

PGA and MMI are the two well-known parameters that show earthquake magnitude and are still used to illustrate a number of defects after an earthquake. Severe damage to the pipelines in the Kobe earthquake was the bases for Isoyama and et al (2000) to recommend empirical correlation to calculate damage rate. PGA multiplied with some correction factors have been applied to show pipe damage (Isoyama 2000). Chen et al 2002 emphasised that the PGA compared with Spectral Acceleration (S) and Peak Ground Velocity (PGV) is the most proper earthquake indicator to calculate number of defects after an earthquake. MMI is the most comprehensible earthquake indicator which is still being used to calculate the number of defects (Zhao 2008).

Eguchi (1983) was the first person who divided earthquake effects on pipelines into two main groups; ground shaking and ground displacement. After Eguchi, studies followed his approach and divided earthquake effects on pipelines into two distinct groups. Eguchi suggested the correlation between MMI and repair rate in 5 types of pipe(1983), and then in 1991 he expanded his graphs for 10 types of pipes (O'Rourke and Ayala 1993). The advantage of Eguchi graph is applying the simple earthquake parameters and finding earthquake effects on different pipe types. O’Rourke and Ayala (1993) extend Barenberg (1988) graph for more pipe types. Barenberg only had illustrated the correlation between PGV and damage rate in Cast Iron (CI) pipes. Damage rates in the 11 earthquakes with various types of pipe material were applied to confirm the similarity between damage trend in CI and other pipe types, such as asbestos cement pipes and concrete pipes(O'Rourke and Ayala 1993). All the graphs suggested by Eguchi (1983 and 1991), Barenberg (1988) and O’Rourke (1993) followed a linear trend for each pipe material.

Eidinger (1998), used collected data (135 repairs) from the 1989 Loma Prieta earthquake to reveal the correlation between damage rate in pipes with two earthquake parameters and four pipe characters. As he mentioned, damage rate in pipelines has a direct correlation to soil types, soil corrosivity, pipe diameter, pipe age and seismic parameters, such as PGV and peak ground deformation (Eidinger 1998). After The 1989 Loma Prieta earthquake, Eidinger added damage rates for three different pipe types into the O’Rourke’s work (1993). O’Rourke (1998) found PGV as the most statistically relevant parameter to repair rate caused by an earthquake

(O’Rourke 1998). Eidinger (1999) recommended exponential equation to calculate damage rates caused by wave propagation effects. Considering pipe types, pipe joints and pipe diameters, he recommended coefficients with which to multiply the original equation to calculate damage rate in various pipe types(Eidinger and Avila 1999).

The Federal Emergency Management Agency of US used the O’Rourke and Ayala’s (1993) work to establish the PGV based damage rate equation to calculate wave propagation effects of earthquake in pipelines (FEMA 2003). Pipe material was mentioned as the most significant factor to affect vulnerability of pipelines in an earthquake. All types of pipe were divided into two distinct types: fragile and ductile. Damage rate in the ductile pipes was considered to be 70% less than damage rate in the fragile pipe types.

American Lifeline Alliance (ALA) recommended the PGV base equation to calculate the wave propagation effect of an earthquake. Pipe types and pipe joints were both used to define a coefficient factor, and an uncertainty factor was also added to the base equation in contrast with HAZUS equation(American Lifelines Alliance June 2004). According to the Northridge pipelines’ damage, Jeon (2005) derived several equations to show damage rate caused by earthquakes. Various types of PGV including maximum PGV, geometric mean of PGV and maximum vector magnitude of PGV were applied to illustrate the best suitable equation. Jeon’s work revealed maximum PGV has the best correlation with a pipe damage rate (Jeon 2005). Topark and Taskin (2007) classified some types of empirical formulae, which were derived after the Northridge earthquake. These formulae show much more variation between calculated damage rate in ductile pipes compared with estimated damage rate in fragile pipes (Toprak and Taskin 2007). Zhao et al (2008) recommended logarithmic formula based on the MMI, pipe material and soil type and estimate number of defects caused by both earthquake effects (Zhao 2008).

Critical parameters affecting pipeline damage rate

Earthquake magnitude has great impacts on earthquake damage in pipelines. Various types of parameters are applied in available empirical formulae as earthquake indicators although PGV and Permanent Ground Deformation (PGD) are the most popular parameters used to calculate earthquake effects on pipelines (Eguchi 1983; Toprak and Taskin 2007).

Beside earthquake parameters, pipe characteristics are significant factors, which affect severity of earthquake damage. Pipe type, pipe age, corrosion, pipe joints, and pipe diameter are more significant factors which affect earthquake vulnerability of pipelines. Usually flexible pipe types tolerate earthquake shaking better than brittle types. Flexible joints compared with rigid joints suffer less damage in earthquakes as recorded in work by O’Rourke and Ayala (1993), Lund et al (1998), Miyajima et al (2006) among others (O'Rourke and Ayala 1993; Lund, Cornell et al. 1998; Scawthorn, Miyajima et al. 2006). Corrosion rate in pipelines particularly in sewer pipes decrease pipe wall thickness and make pipe more vulnerable to ground shaking (Isenberg and Taylor 1984; Lund, Cornell et al. 1998; Schiff, Abrahamson et al. 2000). Pipe age has direct correlation with pipe corrosion and usually recently installed pipes are more resistant to ground shaking compared with the same pipe types installed before(Wang, Wang et al. 1991; Lund, Cornell et al. 1998; Allouche and Bowman 2006). Pipelines with small pipe diameters are more vulnerable to earthquake effects compared with large diameter pipes (Wang, Wang et al. 1991; Kuraoka and Rainer 1996; Eidinger 1998).

All above case studies show earthquake pipe vulnerability can be affected by the variety of parameters. There are many formulae to calculate damage caused by specific earthquakes in pipelines but there are some differences between calculation methods, applied parameters and estimated damage. Some equations require accurate earthquake parameters, which may not be available for many earthquake prone areas. Many parameters influence a damage rate caused by an earthquake. Considering and participating in all effective parameters in each formula is almost impossible because of complicated correlations exist between damage rate and each parameter. On the other hand, appropriate estimation of damage after each particular earthquake not only will facilitate post earthquake reconstruction, but also can be used to provide an appropriate mitigation plan.

Data analysis:

In order to show how the application of different formulae can affect the number of expected defects in New Zealand's wastewater reticulation, earthquake damage calculated by appropriate formulae was taken into account. Hutt City as the earthquake prone city was selected and damage caused by the earthquake (1000 years return period) on its wastewater reticulation system was taken into consideration.

Wastewater reticulation in Hutt City

Capacity Company on behalf of the Hutt City council is responsible to manage and run the Hutt City reticulation system. According to their work, the Hutt City wastewater reticulation system is composed of two different parts: wastewater reticulation and trunk wastewater system. The Hutt City wastewater reticulation system has 672 kilometres of wastewater pipelines of which 84.5 % of the total length belongs to wastewater reticulation and the remainder is a part of the trunk wastewater system. (Capacity company 2008).

In order to illustrate the wastewater pipelines' characteristics in the Hutt City wastewater system, the wastewater pipelines were classified into different categories. The main wastewater pipeline characteristic which has a significant effect on pipe resistance to an external force, such as an earthquake, is piping material. Hutt City sewer reticulation comprises of different types of pipes, which have been installed during the past century. Reinforced Concrete (RC) pipes, Asbestos Cement (AC) pipes, Earthenware (EW) pipes and Poly Vinyl Chloride (PVC) pipes are the main types of pipe used in the Hutt City wastewater system. The Hutt City wastewater network is built with 30.3 % of RC pipes, which are followed by AC pipes at 21.6%, EC pipes at 16.6% and PVC pipes at 13.1%.

Hutt City geology and earthquake hazard

Hutt City geologically is known as Lower Hutt city and is located at the southern part of the North Island in New Zealand. Hutt City is the second major city in the Wellington region and is located between Wellington (capital) in the south east and Upper Hutt city in the north. The

Hutt City area is 7988 hectares and is located in Hutt river valley (Hutt City council 2006). There are 34662 households in Hutt City 20% of which are located in the central Hutt City region (Statistics 2009).

According to Dellow's work (1992), Hutt City is located on variable Quaternary-age sediments which can be classified by their strength into two main groups: soft sediments and loose to compact coarser-grained materials. Normally consolidated and fine-grained substances (clay, silt and sand) are the main constituents of soft sediments. On the other hand, sand and gravels are the main materials in loose to compact sediments (G. D. Dellow 1992).

Hutt City was divided into five different geological zones, where zone 1 is underlain by bedrock and zone 5 is underlain by more than 10 m of the flexible sediment with a maximum shear wave velocity of 200 m/s. Compact alluvial and fan gravel are predominant in Zone 2, and zones 3-4 lie on 20 m sediment with a layer of small thickness of the soft sediment and compact gravel and sand (Dellow 1992). According to the earthquake hazard classification, ground shaking hazard varies from zone 1 to the worst hazard case in zone 5 including Petone, the southern part of Hutt City central and Wainuimata (R. J. Van Dissen 1992). The earthquake hazard caused by the Wellington fault has a significant effect on the MMI and PGA of the different zones in Hutt City. For instance, MMI varies from IX in zone 1 to XI in zone 5 and PGA varies from 0.5 to 0.8g (Van Dissen 1992). Table 1 shows the characteristics of the Hutt City wastewater reticulations zones(Capacity company 2007).

Table 1: Hutt City wastewater reticulation zones

City zones	Zone1	Zone2	Zone3	Zone4	Zone5	Zone 6	Zone7	Zone8
Region	Stokes Valley	Taita-Naenae	Western Hills	Peton	Hutt Central	Seaview	Eastbourne	Wainuiomata
Hazard zones	2	5&2	2&5	5	5,2&3-4	3--4	2	5
Fragile pipes (km)	53.27	52.62	76.10	36.65	124.38	5.49	23.23	79.92
Ductile pipes (km)	4.01	7.10	15.81	9.74	58.35	3.92	9.11	4.56
% of total	10.15	10.58	16.29	8.22	32.38	1.67	5.73	14.97

Comparison

Nine different formulae were applied in the Hutt City wastewater reticulation system to show the differences between estimated numbers of defects in the wastewater pipelines. Hutt City was divided into 8 municipal zones and wastewater reticulation in each zone was classified by its wastewater pipelines' characteristics (Capacity company 2007). Wastewater pipelines' characteristics in each zone were classified by pipe types, diameter, length and overall pipe physical condition(Capacity company 2007). Earthquake related parameters such as soil types and calculated PGV for each geological zone transferred to municipal zones.

Eguchi (Eguchi 1991), Eidinger (1998), HAZUS (2003), O'Rourke and Jeon (1999), Topark(1998) (Topark 1998), O'Rourke and Deyoe (2004, two formulae), ALA (2001), Jeon and O'Rourke(2005) equations were applied to calculate the wave propagation effect of earthquake on the Hutt City wastewater reticulation. In order to better illustrate their appropriateness, the applied formulae were divided into two main groups: group one and group two. Group one includes Eguchi (1991), HAZUS (2003), Eidinger (1998) and O'Rourke (2004, R waves). Jeon(2005), Topark(1998), O'Rourke and Jeon (1999), ALA (2001) and O'Rourke (2004, S waves) were classified as group two. Eguchi's, HAZUS's, Eidinger's and O'Rourke's (R wave) equations estimated the greatest numbers of defects compared with the 5 other formulae. Table 2 shows the general characteristics of applied formulae which were used to calculate earthquake damage in the Hutt City wastewater reticulation.

Table 2: Applied formulae to calculate earthquake damage in Hutt City

Formula	Eguchi	HAZUS	Eidinger	O'Rourke (R waves)	Jeon	Topark	O'Rourke and Jeon	ALA	O'Rourke (S waves)
Date of publish	1991	2003	1999	2004	2005	1998	1999	2001	2004
pipe type restriction	10 types	Fragile Brittle	6 pipe types	Brittle MIX	4 pipe types	CI	CI&DI	5 types	Brittle MIX
pipe Diameter restriction	NA	MIX	large and small	MIX	NA	Dp≤600 mm	Dp≤600 mm	NA	MIX
joint type restriction	NA	NA	6 pipe types	NA	NA	NA	NA	6 types	NA

Within the first group, Eguchi's equation showeed the greatest number of defects compared with the other formulae in this group. The Eguchi model (1991) represents the most and the least vulnerable regions, compared with the more accurate and updated formulae. Eguchi illustrated some differences in the sequence of vulnerability in other regions. In group one the total number of defects calculated by the Eidinger (1998) is almost similar to others, although the vulnerability sequence between the regions is different HAZUS and O'Rourke (R waves) approximately illustrated the similar expected defects. The difference between the highest and lowest range of defects among the three highest estimated defects is 7%. Figure 1 shows the disparities between the numbers of expected damage calculated by the formulae in the group one.

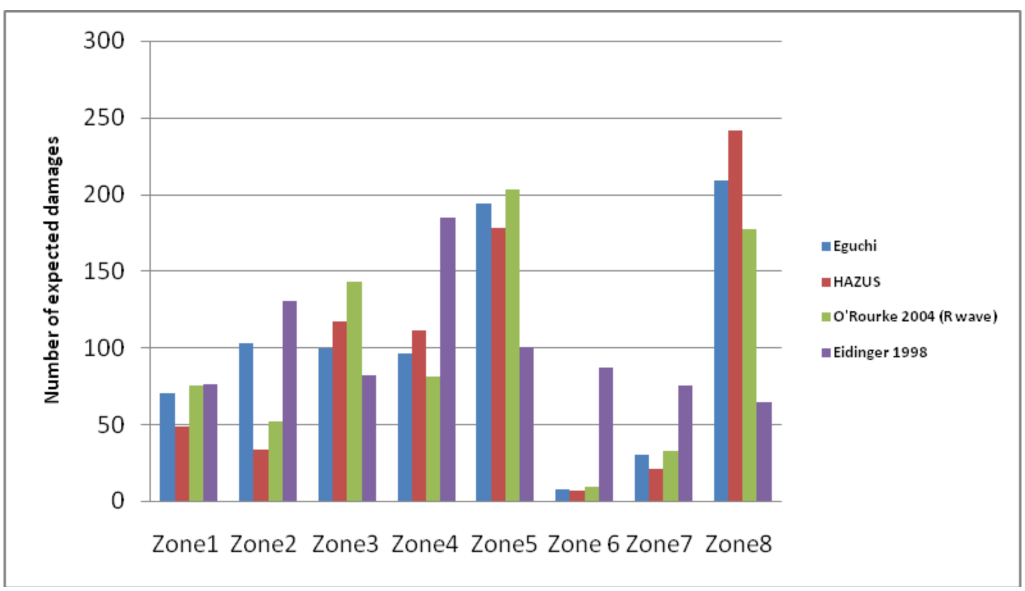

Figure 1: Numbers of defects in the Hutt City wastewater reticulation (group1)

Group two represented the lowest expected repairs in the Hutt City wastewater reticulation. ALA equation presented the lowest number of repairs in the group two. In spite of group one, the differences between estimated defects in the low estimator group (group two) are significant. The total number of defects varies up to 50% of the lowest estimated defects in group two. The total number of defects calculated by ALA is just one-tenth of the total number of defects in HAZUS (the lowest estimated number of defects in group one). Figure two shows the differences between the estimated numbers of defects calculated by group two in the Hutt City wastewater reticulation.

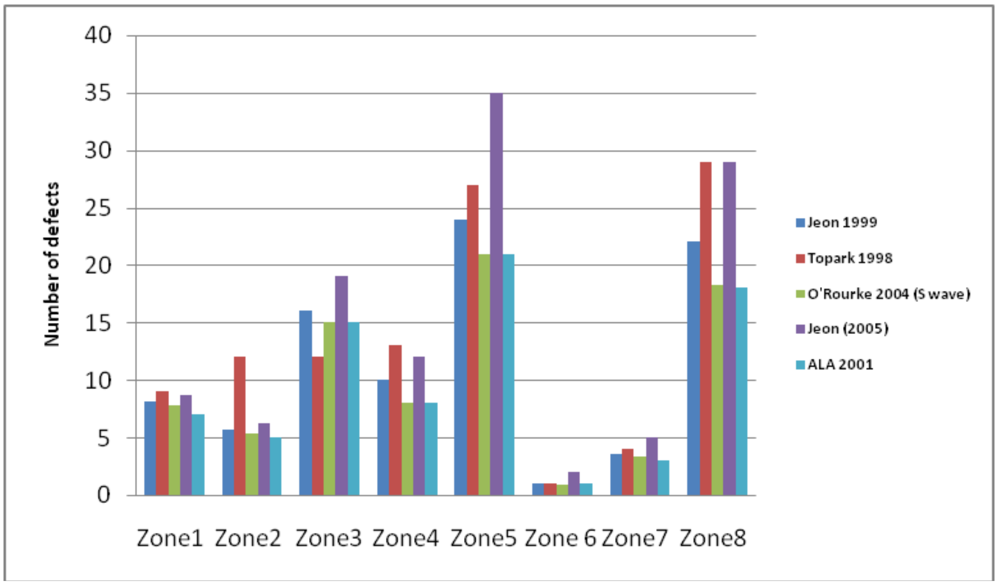

Figure 2: Numbers of defects in the Hutt City wastewater reticulation (group2)

Group one estimates about 12% of the total calculated defects by the group one equations. This reveals the significant difference between the estimated defects.

All applied formulae showed regions 5 and 8 are the most vulnerable regions among all the 8 zones (except Eidinger 1998). Most formulae illustrated the highest and the lowest hazard zones almost the same. For instance, all formulae revealed zone 6 and 7 as the least vulnerable zones and 62% of formulae showed zone 8 as the most vulnerable zone. Most formulae revealed the same vulnerability sequence within the different zones. This study illustrated except significance differences between the results of the two different groups, there are not major differences among each group in the Hutt City wastewater reticulation.

Conclusion:

Pipeline fragility formulae are derived by correlating the earthquake damage in pipelines versus some earthquake parameters. Consequently, pipelines' characteristics beside surrounded soil performance and earthquake characteristics directly affect the number of estimated defects. Other parameters can influence pipe vulnerability such as, pipe quality, pipe thickness, buried depth, applied design and operation standard, age of pipes, number of bends and fittings, pipeline maintenance and numbers of connections are some factors which influence pipe vulnerability. Just few effective parameters are implemented in the available formulae and lots of parameters are neglected. Consequently, there are some intrinsic variances in the estimated numbers of defects. On the other hand, accuracy of estimated earthquake parameters and effects of earthquake parameters on fragility equations affect estimated number of defects.

The main difference between two distinct groups is difference in type of the waves, which may affect the region. If the affected region is far from the earthquake epicentre and earthquake occurs near the surface the number of defects will be following the first group estimation, otherwise number of defects will be following the second group (see (O'Rourke and Deyoe 2004; Toprak and Taskin 2007).

All applied formulae which were used to estimated earthquake damage in pipelines were derived from the earthquake effects in the pressure pipelines. Proper pipe characteristics in pressured pipes and more accurate design and construction of pressured pipes make them more resistant to external excess forces compared with gravity pipelines. Consequently, number of expected defects in gravity pipelines should be greater than the number of defects calculated by the available formulae.

References:

Allouche, E. N. and A. L. Bowman (2006). "Holistic approach for assessing the vulnerability of buried pipelines to earthquake loads." Natural Hazards Review **7**(1): 12-18.

American Lifelines Alliance (June 2004). Wastewater System Performance Assessment guideline part 2 commentary, American Lifelines Alliance.

Capacity company (2007). Wastewater Asset Management plan 2007. Hutt City.

Capacity company (2008). Wastewater Assessment Hutt City. Hutt City Capacity Company and Hutt City Council**:** 137.

Chen, W. W., Shih, B. J., Chen, Y. C., Hung, J. H., Hwang, H. H. (2002). "Seismic response of natural gas and water pipelines in the Ji-Ji earthquake." Soil Dynamics and Earthquake Engineering **22**(9-12): 1209-1214.

Eguchi, R. (1991). Early Post-Earthquake Damage Detection for Underground Lifelines. Final report to Nat. Sci. Foundation, Dames and Moore P.C. Los Angeles, California.

Eguchi, R. T., Taylor, C., Hasselman, T. K. (1983). Seismic component vulnerability models for lifeline risk analysis. Earthquake Performance of Water and Natural Gas Supply System. California.

Eidinger, J., L. de Castro, et al. (2006). "The 1906 earthquake impacts on the San Francisco and Santa Clara water systems - What we learned, and what we are doing about it." Earthquake Spectra **22**(SPEC. ISS. 2): S113-S134.

Eidinger, J. M. (1998). "Water Distribution System." The Loma Prieta, California, Earthquake of October 17, 1989 - Lifelines.

Eidinger, J. M. and E. A. Avila (1999). "Seismic evaluation and upgrade of water transmission facilities." Technical Council on Lifeline Earthquake Engineering Monograph(15): 1-195.

FEMA (2003). Multi-hazard loss estimation methodology earthquake model. HAZUS-MH MR3. Washington , D.C., Department of homeland security emergency preparedness and response directorate FEMA mitigation division.

G. D. Dellow, S. A. L. R., J. G. Begg, R. J. Van Dissen, N. D. Perrin (1992). "Distribution of geological materials in Lower Hutt and Porirua, New Zealand a component of ground shaking hazard assessment." Bulletin of New Zealand National Society for Earthquake Engineering **25**(4): 13.

Isenberg, J. and C. E. Taylor (1984). PERFORMANCE OF WATER AND SEWER LIFELINES IN THE MAY 2, 1983 COALINGA, CALIFORNIA EARTHQUAKE.

Isoyama, R., Ishida, E., Yune, K., Shirozu, T. (2000). "Seismic damage estimation procedure for water supply pipelines." water supply **18**(international water services association and Japan water): 6.

Jeon, S., O'Rourke, T.D. (2005). "Northridge Earthquake Effects on Pipelines and Residential Buildings." Bulletin of the Seismological Society of America, **Vol. 95, No. 1**: 294–318.

Katayama, T., K. Kubo, et al. (1975). "EARTHQUAKE DAMAGE TO WATER AND GAS DISTRIBUTION SYSTEMS." 396-405.

Kuraoka, S. and J. H. Rainer (1996). "Damage to water distribution system caused by the 1995 Hyogo-ken Nanbu earthquake." Canadian Journal of Civil Engineering **23**(3): 665-677.

Lund, L., McLaughlin, J., Edwards, C., Laverty, G.,, H. Cornell, Guerrero, A.R., Cassaro, M., Godshack, A., , et al. (1998). The Loma Prieta, California, Earthquake of October 17, 1989: Performance of the built environment, lifelines, water and wastewater systems. Professional Paper 1552-A The Loma Prieta, California, Earthquake of October 17, 1989—Lifelines, USGS**:** a47-a62.

O'Rourke, M. and G. Ayala (1993). "Pipeline damage due to wave propagation." Journal of Geotechnical Engineering - ASCE **119**(9): 1490-1498.

O'Rourke, M. and E. Deyoe (2004). "Seismic damage to segmented buried pipe." Earthquake Spectra **20**(4): 1167-1183.

O'Rourke, T. D., S. Toprak, and Y. Sano (1998). Factors affecting water supply damage caused by the Northridge Earthquake. 6th US National Conference on Earthquake Engineering, Seattle, Washington.

R. J. Van Dissen, J. J. T., W. R. Stephenson, S. Sritheran, S. A. L. Read, G. H. McVerry, G. D. Dellow, P. R. Barker (1992). "Earthquake Ground Shaking Hazard Assessment for the Lower Hutt and Porirua Areas, New Zealand " Bulletin of New Zealand National Society for Earthquake Engineering **25**(4): 16.

Scawthorn, C., M. Miyajima, et al. (2006). "Lifeline aspects of the 2004 Niigata Ken Chuetsu, Japan, earthquake." Earthquake Spectra **22**(SUPPL. 1): S89-S110.

Schiff, A. J., N. Abrahamson, et al. (2000). "Chi-Chi, Taiwan, earthquake of September 21, 1999 lifeline performance." Technical Council on Lifeline Earthquake Engineering Monograph(18): 1-217.

Topark, S. (1998). Earthquake Effects on Buried Lifeline System, Cornell University. **Doctor of philosophy:** 307.

Toprak, S. and F. Taskin (2007). "Estimation of earthquake damage to buried pipelines caused by ground shaking." Natural Hazards **40**(1): 1-24.

Wang, L. R. L., J. C. C. Wang, et al. (1991). "GIS applications in seismic loss estimation model for Portland, Oregon water and sewer systems." U.S. Geol. Sur., U.S.A.

Zhao, J. X., Cousins, J., Lukovic, B., Smith, W. (2008). Critical factors for restoration of water supply pipelines in the Hutt City, New Zealand after a magnitude 7.5 earthquake from the Wellington fault. The 14th World Conference on Earthquake Engineering, October 12-17, 2008, Beijing, China.