Wastewater Pipeline Vulnerability to Earthquakes

Zare[1], M. R. And Wilkinson[2] S.

1. Corresponding Author: PhD student, Department of Civil and Environmental Engineering, Faculty of Engineering University of Auckland
   Email: mzar004@aucklanduni.ac.nz

2. Associate Professor, Department of Civil and Environmental Engineering, Faculty of Engineering University of Auckland
   Email: s.wilkinson@auckland.ac.nz

Abstract:

Wastewater pipeline vulnerability to earthquakes is a major concern of regional councils particularly in regions located in populated urban areas. Wastewater pipelines not only are the most critical part of each wastewater system but also are the most vulnerable part in most wastewater systems located in earthquake prone areas. Gravity is the driving force in most wastewater pipelines, consequently failure detection, especially leakage detection, is a time consuming and difficult task compared with failure detection in pressure pipes after an earthquake. Wave propagation is one of the two main factors which causes pipe leakages and breakages. Wastewater reticulation failure has the capability to endanger the health and the environment of each earthquake struck urban area. Earthquake vulnerability of wastewater reticulation in Hutt City is a distinct instance which shows how vulnerable a wastewater network can be.

Key words: earthquake, wastewater pipeline, damage

Introduction:

Wastewater pipeline vulnerability to earthquakes is a main concern of regional councils, particularly in regions located in populated urban areas. Wastewater pipelines are the most critical and vulnerable part of each wastewater system and deserve particular attention. Wastewater reticulation failure has the capability to endanger the health and the environment of the earthquake struck urban area.

In New Zealand the population is concentrated in urban areas, in which the population density of these areas slightly increases annually (Statistic-NZ 2009). By increasing the standard of life in urban areas the need for public facilities has been increased significantly during the last century. One of the public facilities which directly impacts on the function of a community is its wastewater system, the malfunction of which can rapidly affect a large number of people. Wastewater systems in densely populated areas have been designated as a lifeline which deserves particular attention due to their direct impact to community health.

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). Katayama was the first to show the earthquake effects on water and gas pipelines in the different cities in Japan (Katayama, Kubo et al. 1975). He revealed how brittle pipes are vulnerable to earthquakes. He added that pipes with small diameter are more vulnerable compared to large diameter pipes. Katayama also illustrated how earthquakes affected pipelines. Katayama (1975) reported that during the 1964 Niigata earthquake in the city of Niigata a total number of 215 severe damages were reported. The Tokachi-oki earthquake in 1968 struck Tokyo and caused 405 severe damages (breakages and joint separations) in 953 km of water pipeline. This earthquake showed that earthquakes can have significant impact on asbestos cement pipes compared with cast iron pipes (Katayama, Kubo et al. 1975).

Lund's work (1998) showed during the 1989 Loma Prieta earthquake, the wastewater system was significantly affected by the earthquake in the region. Lund (1998) also mentioned that the earthquake in San Francisco Bay area caused 350 main repairs to be made mostly on 4, 6, and 8 inch diameter Cast Iron (CI) water pipes. The cast iron pipes with fixed joints such as bell-and- spigot were caulked with cement or lead. 9000 feet of ductile iron with rubber-gasket jointing was used to repair and replace damaged pipes just in the Marina District, alone accounting for about 100 repairs. Lund (1998) mentioned after the 1989 earthquake, just a few main sewer line breaks were reported. Most sewer reticulation systems are not pressure networks and water invasion does not appear at the surface. Consequently the number of wastewater pipe repairs should be the same as water pipe repairs in the same area.

The 1994 Northridge earthquake, after the 1906 San Francisco earthquake, caused the most intensive and significant damage to the US water supply. The Northridge earthquake caused about 1100 repairs in pipelines, 93 % of which belonged to pipes with diameter less than 24 inches (Jeon 2005). Damage to wastewater pipelines seems to be the same as in water pipelines. Wastewater pipelines are run by gravity force, consequently if pipes do not obstruct the flow, wastewater will continue to flow and the damage will not appear until later (Schiff 1995).

In the 2004 Niigata Ken Chuetsu earthquake in Japan, the wastewater reticulation suffered severe damage. This earthquake with a magnitude of Mw=6.6 caused damage to a total of 900 local pipelines and 1300 manholes (Scawthorn, Miyajima et al. 2006). 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 wastewater pipelines represented about 12% of the total real damage. The maximum damage rate (number of damages per kilometre) reported in Scawthorn et al (2006) belonged to the Yoita region and equated to a value of 1.9 in the wastewater pipelines and 0.31 in the Ojiya's water pipeline. Scawthorn at al. (2006) revealed that UPVC and steel pipes suffered significantly more damage compared with ductile iron and cast iron pipes. The authors mentioned that failure in UPVC pipes was in the joints due to pull out and body breakage whereas in ductile iron pipes, the damage was due to a seismic joint type failure. The authors also emphasized that joint failure in steel pipes occurred in their threaded joints.

Pender's work (1987) showed that during the Edgecombe earthquake (NZ) in 1987 sewage pipelines suffered serious damage. The most number of damages were reported in 150 mm and 200 mm asbestos pipes. Pender 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 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 earthquake (NZ). 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 Bam earthquake in Iran damaged 70 to 80 % along the 49 km of water distribution network in 2003. 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 pipeline characteristics, the number of breakages and leakages can vary from minor to significant.

Considering the Hutt City geotechnical characteristics and some particular characteristics of the city's wastewater pipelines, this city wastewater reticulation is vulnerable to earthquakes. The effects of earthquakes on the wastewater pipelines in Hutt City were taken into account to reveal the vulnerability of the wastewater reticulation system in this city. The geotechnical characteristics of Hutt City, beside the earthquake hazard zones, have been ascertained from available resources as the main factors which affect the earthquake vulnerability of the city. All required pipe parameters, as the second factor which directly effects earthquake vulnerability of pipelines, were collected from available responsible parties. In order to ascertain the vulnerability of wastewater pipelines all geological and reticulation data was combined together and geological zone characteristics were transferred to urban zones.

Hutt city wastewater pipelines:

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 remains a part of the trunk wastewater system. All urban areas in Hutt City are covered by the wastewater system and are operated by the Hutt City council. The function of the wastewater system in Hutt City is to collect, treat and dispose of wastewater from residential properties, business properties and industries within Hutt City. Wastewater collected by the Upper Hutt city reticulation also adds to the Hutt City collection system. Collected wastewater through the wastewater trunk system is conveyed to the Hutt City treatment plant at Seaview. Treated effluent is transferred through 18 km of the 1350mm pressure pipeline to the discharge point at Pencarrow in the eastern entrance of Wellington harbour (Capacity-Co. 2007).

The main parameter, which shows pipe resistance and behaviour in earthquakes, is pipe material which has a significant impact on pipe vulnerability to earthquakes (Bizier 2007). Pipes can be made with different types of materials and each pipe type is applied for a specific purpose. New pipe materials are formulated annually to satisfy special applications. Development of the city in new regions or upgrading old facilities requires new pipelines in order to provide services to those regions. Pipes which are used for urban facilities each year usually have different characteristics compared with pipes, which were used in previous years even for pipes with the same material (Bizier 2007). As a result, old wastewater reticulations comprise of various types of pipes with different characteristics.

In order to illustrate the wastewater pipeline characteristics in the Hutt City wastewater system, the pipelines have been 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 pipe material. Hutt City sewer reticulation comprises of different types of pipes which have been installed during the past century. This reticulation system comprises of Asbestos Cement (AC) pipes, Fibrolite pipes (fibro product of asbestos material (FIB)), Cast Iron (CI) pipes, Reinforced Concrete (RC) pipes, Earthenware and Ceramic pipes (CE and EW), Poly Vinyl Chloride (PVC) pipes, Modified Poly Vinyl Chloride (MPVC) pipes, Un plasticized Poly Vinyl Chloride (UPVC) pipes, Poly Ethylene (PE) pipes, Medium Density Poly Ethylene (MDPE) pipes, High Density Poly Ethylene (HDPE) pipes, Steel (S) pipes, Concrete Lined Steel (CLS) pipes and Pitch Fiber (PF) pipes (Hutt-City-Council 2008).

Reinforced concrete pipes, asbestos cement pipes, earthenware ceramic pipes and poly vinyl chloride 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 is followed by AC at 21.6%, EC at 16.6% and PVC at 13.1%.

The remainder of the Hutt City wastewater system comprises of various types of pipes. Figure 1 discloses the minority of wastewater pipeline material distribution in the Hutt City wastewater reticulation system.

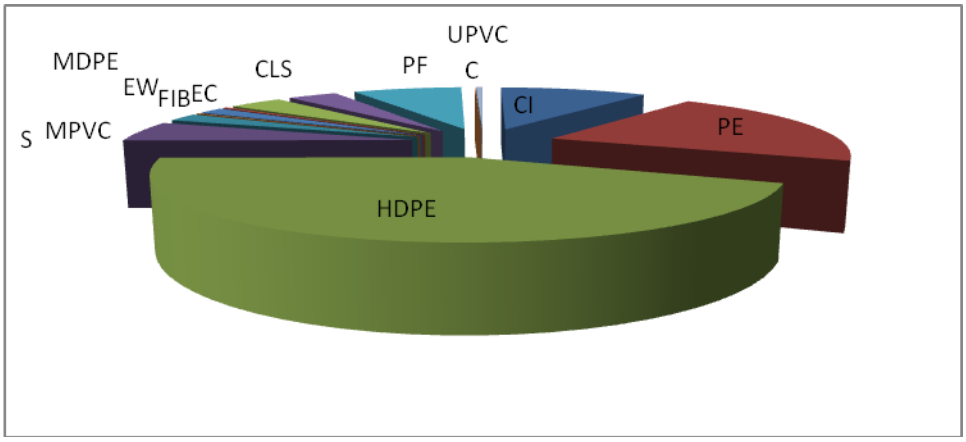

Figure 1: Hutt City sewer classified by material types (minority)

In order to provide a rough estimate for the Hutt City reticulation network, the Hutt City sewers are divided into two main groups: sewers with ductile behaviour and sewers with brittle performance (see FEMA 2003; O'Rourke and Deyoe 2004). According to the above, 81 % (528 km) of the whole wastewater pipeline reticulation system in Hutt City is brittle and more vulnerable to external forces compared with 19 % of the system consisting of ductile wastewater pipes.

Pipe diameter is one of the main parameters which as well as being representative of pipe capacity, directly affects pipe installation and repair cost. In the earthquake vulnerability point of view small diameter pipes are more vulnerable in contrast with large pipe sizes (Wang, Wang et al. 1991; Eidinger 1998; Eidinger and Avila 1999; Schiff, Abrahamson et al. 1999; Isoyama 2000; Chen, Shih et al. 2002; Allouche and Bowman 2006; American Lifelines Alliance July 2002).

The majority of wastewater pipelines in Hutt City are 150 mm pipes and make up 69.3% (452 km) of the Hutt City sewer system. Figure 2 shows the pipe diameter distribution of wastewater pipes in Hutt City versus length of the pipe diameters (excluding the main pipe diameter (150mm pipes)).

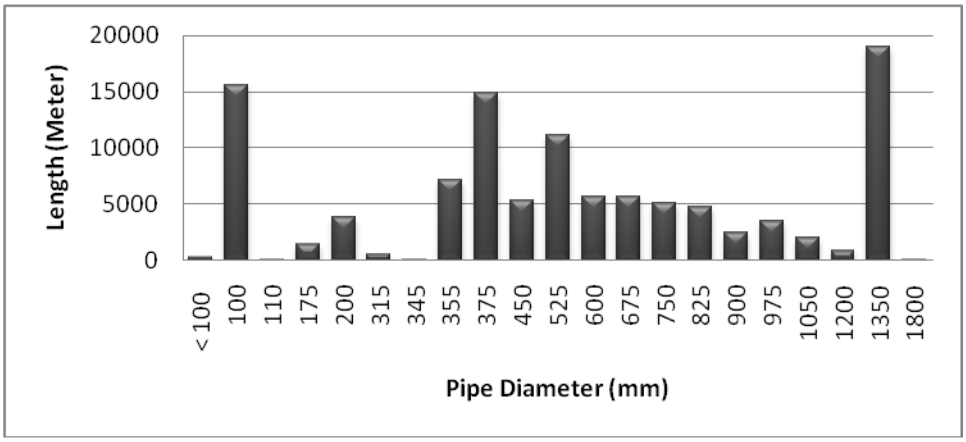

Figure2: Hutt City wastewater pipeline distribution (Minor pipe Diameter)

Hutt City Geology and hazard zones

Hutt City is geologically 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).

Dellow (1992) collected and classified geological characteristics of the Hutt valley region including sediment types and near surface soil types. Hutt City is located on the variable Quaternary-age sediments and can be classified by their strength characteristics 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 (in this sediment SPT is less than 20 blows for 300 mm). On the other hand, sand and gravel are the main materials in loose to compact sediments, (in this soil SPT is more than 20 blows for 300 mm), (G. D. Dellow 1992). Near-surface soft sediments with thickness greater than 10 m are the predominant soil types in the Lower Hutt valley and include Petone, Lower Hutt urban and city centre. The total length of the Quaternary-age sediment in Lower Hutt valley is 300 meters including near surface soft sediment. Soft sediment thickness decreases from the sea shore in Petone onward to the Hutt City centre and varies from a maximum of 27 m to 10 m. In the Wainuiomata region located in the two tributary valleys of Wainnuiomata river near-surface sediment thickness varies from 10 m near the hill side to 32 m in the middle of valley. Total Quaternary-age sediment thickness in Hutt valley varies from 50 m in the hill sides to 300 m near the sea shore (G. D. Dellow 1992).

Van Dissen (1992) considered the geological and geotechnical characteristics of Hutt Valley to divide Lower Hutt into 4 different zones for two scenarios. Two different scenarios were taken into consideration to delineate earthquake ground shaking hazard in the Hutt City regions. Moderate to large, shallow, distant earthquakes which cause shaking on bedrock with Modified Mercalli Intensity V-VI is classified as scenario one whereas scenario two is for large, local, Wellington fault earthquakes. Hutt City is divided by four different zones which vary from zone 1 which is under laid by bedrock to zone 5 which is under laid by more than 10 m of flexible sediment with a maximum shear wave velocity of 200 m/s. Zone 2 is under laid by compact alluvial and fan gravel whereas zones 3-4 lies on 20 m sediment with a layer of small thickness of soft sediment and compact gravel and sand (G. D. Dellow 1992).

Van Dissen (1992) showed ground shaking hazard varies from zone 1 to the worst hazard case in zone 5, (see Fig. 3). According to this earthquake hazard classification, Petone, the southern part of Hutt City central and Wainuimata are all located in zone 5. In scenario one, the Modified Mercalli Intensity varies from V-VI in zone 1 to VIII-IX in zone 5. Peak ground acceleration in scenario one changes from the highest value of 0.3g to 0.01g in zone 1. Amplification of ground motion which results from direct impact of soil types varies from 1-3 times in Zone 1 to 10-20 times in Zone 5 in scenario one. The earthquake hazard caused by the Wellington fault has a significant effect on the MMI and Peak Ground Acceleration (PGA) of the different zones in Hutt City. For instance MMI varies from IX in zone 1 to XI in zone 5 and peak ground acceleration varies from 0.5 to 0.8g (R. J. Van Dissen 1992).

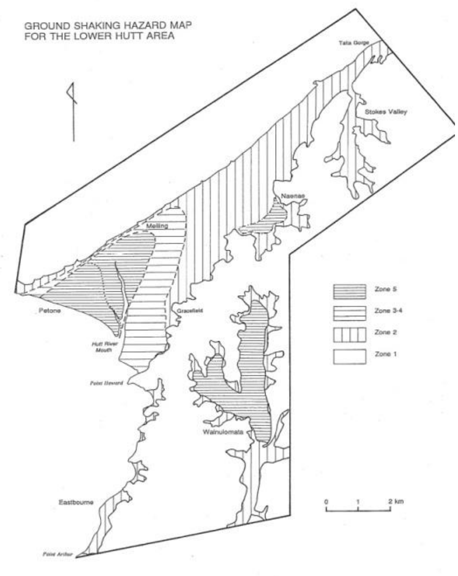

Figure3: Hutt City Hazard map (Van Dissen 1992)

Earthquake scenarios in Hutt City wastewater pipelines,

Wastewater reticulation in Hutt City is divided into 8 zones, (see Fig. 4), including Stokes Valley (zone 1), Taita and Naenae (zone 2), Western Hills (zone 3), Petone (zone 4), Hutt Central (zone 5), Seaview (zone 6), Eastbourne (zone 7) and Wainuiomata (zone 8) (Capacity-Co. 2007). Pipe types, pipe length and pipe diameter are categorised in each zone as factors which affect earthquake vulnerability. The classification just comprises Hutt City reticulation networks and includes 568 km of wastewater pipelines.

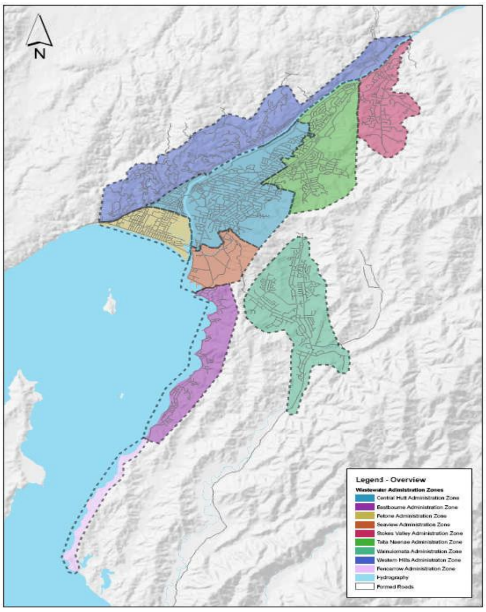

Figure4: Hutt City wastewater reticulation zones

Wave propagation effects on pipelines can be estimated by various types of formulae. Formula selection correlates with proper available pipeline data and each region's available geological and geotechnical characteristics (see (Eguchi 1983),(FEMA 2003), (Eidinger 1998), (Jeon 2005), (Toprak and Taskin 2007), (O'Rourke and Deyoe 2004), (ALA July 2001)). The accuracy of applied formulae is entirely pertinent to the accuracy of required data and data availability. Damage estimation formulae are adequate tools to compare vulnerability of each region and reveal the most vulnerable zones, although, to estimate the number of expected defects in earthquake prone regions is the main advantage of these available formulae. From the post earthquake management point of view, having an estimate of the number of defects in each type of wastewater pipeline is quite beneficial. In order to calculate wave propagation effects on different wastewater pipe types, Eguchi's graphs have been used (O'Rourke and Ayala 1993).

Eguchi was the first to divide earthquake effects on pipelines into two main groups; wave propagation effect and permanent ground deformation. Eguchi's graphs delineate wave propagation effect of earthquake for various types of pipe which compare uniquely with other equations. MMI as an available earthquake parameter is used to estimate the number of defects in each type of pipe. All geological zones were overlapped to the municipal zones and each municipal zone covered a maximum of three geological zones. The number of defects in each geological zone inside a municipal zone calculated and added to find total number of defects in each municipal zone.

All types of wastewater pipes in Hutt City are classified into 5 main groups according to their similar characteristics (see figure 6 and 7). Damage rates were derived from Eguchi graphs for each main pipe types. The number of defects in each municipal zone was calculated by multiplying damage rate to length of each pipe type.

Figure 5 shows classification of wastewater pipelines according to their material types in each urban area in Hutt City region.

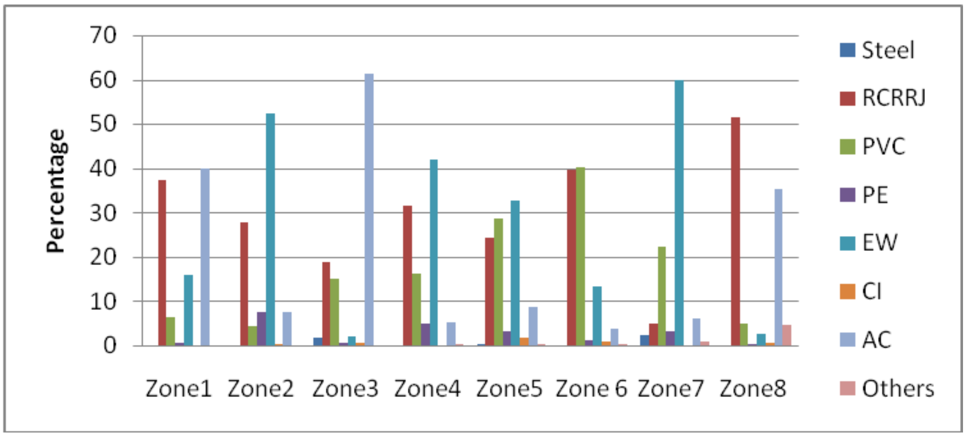

Figure 5: Hutt City wastewater pipe distribution various zones (material types)

Figure 6 shows Wainuimata wastewater reticulation is the most vulnerable region in Hutt City in the case of moderate earthquakes or scenario one. Almost all 107 defects in zone 8 are expected to occur in two main types of wastewater pipelines: Concrete pipes and Asbestos Cement pipes. The Wainuimata wastewater reticulation, even in the event of 5 or 6 MMI earthquakes, is susceptible to a high damage rate and an adequate inspection and repair plan should be considered for this region. After moderate earthquakes, even if no immediate visible damage is detected, health and environmental issues because of wastewater infiltration in defects can be predominant. It should be taken into account that wastewater pipelines in this region are in a poor condition and the number of expected repairs in this region could exceed expectations.

The Peton wastewater reticulation can suffer significantly in the same level earthquake, although the number of defects is less than half compared with Wainuimata. The number of expected defects in a moderate earthquake in Peton is 52, followed by Hutt Central and Tiata-Naenae, which would have 43 and 38 expected defects respectively. Other regions, zone 6, 7, 1 and 3, in moderate earthquakes are predicted to behave well. For instance the maximum number of expected defects in Zone 3 is only 5 defects. Wastewater reticulation in zone 6 behaves well, although due to existing corrosion in this region at least some defects can be expected.

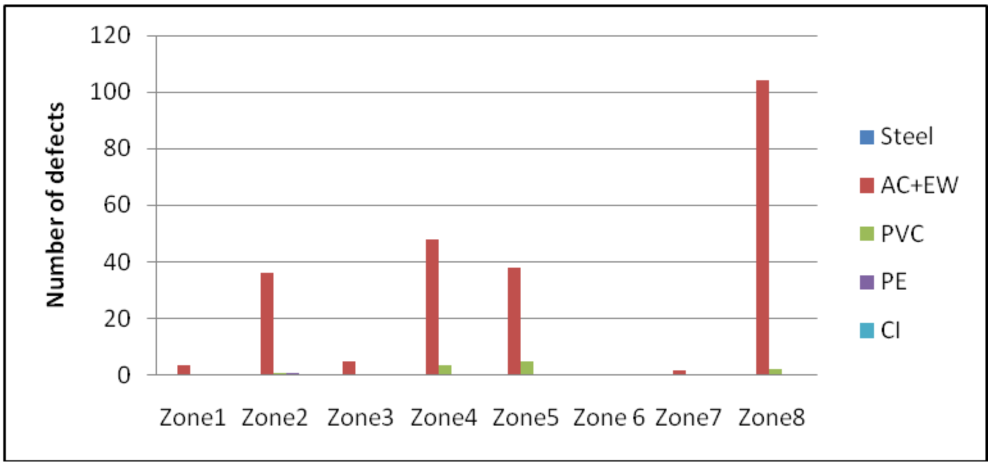

Figure 6: Wave propagation effects on Hutt City wastewater reticulation (Scenario 1)

Hutt City wastewater pipelines suffer overwhelmingly from earthquakes in scenario two, with the number of expected defects being more than 200 in each of the four regions.

Figure 7 exposes Hutt City central region as the most vulnerable zone in large scale earthquakes. The number of wave propagation defects is 508 in the Hutt City central region and is followed by zone 8 with 399, zone 4 with 210 and zone 3 with 205 defects. The expected number of defects in zones 1, 2, 4, 5 and 8 due to some particular conditions such as poor pipe quality and poor construction are anticipated to exceed the estimated number of defects.

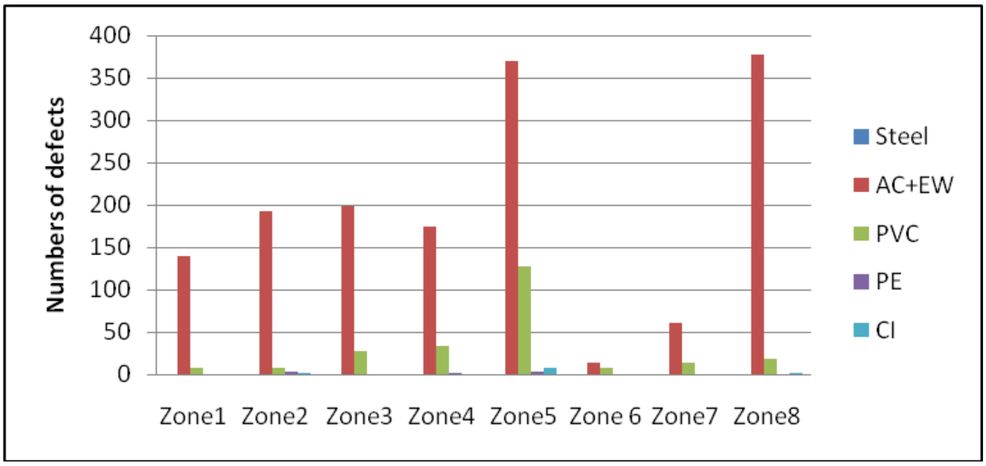

Figure 7: Wave propagation effect on Hutt City wastewater reticulation (scenario 2)

Conclusion:

The study of wastewater reticulation vulnerability in Hutt City is a good instance to show how earthquakes affect wastewater pipelines in urban areas. Although many cities in NZ are located in earthquake prone zones there is not a significant perception of how vulnerable a wastewater reticulation system can be in urban areas. This work shows how vulnerable cities located in earthquake prone areas may be and how the magnitude of expected earthquakes significantly increases the number of expected defects.

Wave propagation effects on wastewater pipelines during moderate earthquakes probably do not cause instant and easily detectable defects on wastewater pipelines. Leakages are the predominant damage effect of moderate earthquakes. Wastewater reticulation systems should be inspected and probable defects should be corrected after an earthquake in order to minimize long term impact on human health and environment.

Apart from wave propagation, permanent ground deformation can significantly increase the number of immediate expected defects particularly in large scale earthquakes. Permanent ground deformation and wave propagation effects should simultaneously be applied to evaluate overall vulnerability of wastewater pipelines. Various types of formulae have been updated to estimate wave propagation effect of earthquakes. These formulae require more accurate geological and pipe characteristics data. All required data is not always available. The applied formula provides an appropriate sense of pipeline vulnerability in various types of pipes. The accuracy and reliability of each particular available formula should be evaluated for each particular region.

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