EARTHQUAKE EFFECTS ON METROPOLITAN CITIES LIFELINES

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ABSTRACT

Water and wastewater pipelines in metropolitan cities are lifelines and significantly affect city dwellers normal life. Lifeline failure endangers human beings' health in a short period of time. Earthquakes in two different ways affect pipelines; wave propagation and permanent ground deformation. Wave propagation not only causes pipe breakages in large scale earthquakes but also is the main cause of pipe leakages in small scale earthquakes. Leakage is the main defect caused by wave propagation in water and wastewater pipelines. Leakages in different circumferences create ex-filtration or infiltration. In potable water pipelines leakages are the main cause of water loss and water pollution whereas leakage in the wastewater pipelines is the main cause of wastewater overflow and soil pollution. Leakages may cause significant health and environmental pollution issues alongside considerable pressure on system capacity and cost. Earthquake effects on Hutt City water and wastewater reticulation is discussed to show how vulnerable are lifelines in earthquake prone urban areas.

Keywords: Earthquakes, Vulnerability, Lifelines

INTRODUCTION

Water and wastewater pipelines vulnerability to earthquakes is a major concern of regional councils particularly in populated urban areas. Water pipeline reticulation is the main part of each urban area water system. Water reticulation provides required water consumption with accepted standard quality to public. Wastewater pipelines in wastewater system collect and transmit domestic and industrial wastewater to treatment plants and discharge points. Wastewater pipelines are not only the main part of each wastewater system but also are the most critical component within the whole wastewater system (Zare 2009).

In New Zealand the population is concentrated in urban areas and the population density of these areas slightly increases annually (Statistic-NZ 2009). Increasing standards of life in urban areas has resulted in the need for public facilities to increase significantly during the last century. Water and wastewater systems both have direct impacts on community, the malfunction of which rapidly affects a large number of people.

Earthquakes damage pipelines in two different ways, pipe breakages and pipe leakages (Wang et al. 1991; Lund et al. 1998; Chen et al. 2002). Katayama was the first to show the earthquake effects on water and gas pipelines in different cities in Japan (Katayama et al. 1975). He revealed how brittle and small diameter pipes are vulnerable to earthquakes. For instance, 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 pipe (Katayama et al. 1975).

Lund's work (1998) showed during the 1989 Loma Prieta earthquake, the lifelines were significantly affected by the earthquake. Lund (1998) indicated 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. Cast iron pipes had fixed joints such as bell and spigot joints caulked with cement or lead. 9000 feet of ductile iron pipes with rubber-gasket joint were used to repair and replace damaged pipes just in the Marina District with about 100 repairs. Lund (1998) mentioned after the 1989 earthquake, just a few main sewer line breaks were reported. Almost all sewer reticulations are not pressure networks and water invasion does not appear at the surface immediately after earthquake. He indicated the number of wastewater pipe repairs should be the same as water pipe repairs in the same area (Lund 1998).

The 1994 Northridge earthquake caused the most intensive and significant damage to US water supply after 1906 San Francisco earthquake. The Northridge earthquake caused about 1100 repairs in water pipelines, 93% of which belonged to pipes with a diameter of less than 24 inches (Jeon 2005). Damage to wastewater pipeline seems to be the same compared with water pipelines. Wastewater pipelines run by gravity force and if pipes do not obstruct, wastewater continue flowing and the damage will be appeared 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 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 et 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 (EERI 2004).

These examples all show, earthquakes could have significant effects on water and wastewater pipelines. Brittle and small diameter pipes are the most vulnerable pipes in each pipes network located in earthquake prone areas. According to magnitude of earthquake and pipeline characteristics damage varies from minor to significant.

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. Hutt City area is 37988 hectares and is located in Hutt river valley (Hutt-City-Council 2006). There are 34662 households in Hutt City which 20% of that are located in the central Hutt City region (Statistics 2009).

The particular geological characteristics of the Hutt City make lifelines vulnerable to earthquakes. Hutt City is a good instance to show how vulnerable are pipelines in cities located in earthquake prone regions and how earthquake is able to paralyze urban life. Pipe types and pipe diameter are two main factors which affect pipe vulnerability to earthquake and will be investigated in the Hutt City water and wastewater systems.

HUTT CITY WATER RETICULATION

The first water pipeline was installed in the south of Hutt City (Peton) in 1915; however, the Hutt City water reticulation was developed between 1945 and 1975. The Hutt City water reticulation services 36824 residential properties and 2512 commercial or industrial properties. The Hutt City water reticulation supplies water for 97701 residents. More than 14 Mega cubic meters of fresh water is conveyed to residential and commercial properties by the Hutt City water reticulation annually. The water reticulation in Hutt City includes 690 kilometres of pipelines with various pipe types and diameters.

Pipe material is the main parameter which shows pipe resistance and behaviour to external forces. Pipe material has a significant impact on pipe vulnerability to earthquakes (Bizier 2007). Pipes are constructed from different material types, each uses for specific purpose and new pipe materials are formulated annually to satisfy particular applications. City development and 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 the previous year even pipes with the same material (Bizier 2007).

Various pipe types have been installed in the Hutt City water reticulation including non-plastic pipes and plastic pipes. Non-plastic pipes include AC (Asbestos Cement), CI (Cast Iron), CU (Copper), DI (Ductile Iron), GI (Galvanised Iron), ST-CL (Steel-Concrete Line) and ST (Steel). PE (Poly Ethylene), PVC (Poly Vinyl Chloride) are plastic pipes in the Hutt City water network (Capacity-Co. 2007). AC, GI, ST_CL and PE pipes are main types of the water pipelines network in Hutt City and cover 38.7%, 19.4%, 19% and 9.9% of total water reticulation length respectively (Capacity-Co. 2007). The Hutt City water network was divided into two main groups, including ductile and brittle pipes according to pipe characteristics. Types of water pipes are derived by material types and pipe condition. For instance, fragile pipes-coverage in the Hutt City water reticulation is 53.65%.

Figure 1 shows the main types of pipe distributed in 8 urban zones in Hutt City. The figure shows that AC pipes are a predominant pipe type in 6 zones out of 8 zones in Hutt City.

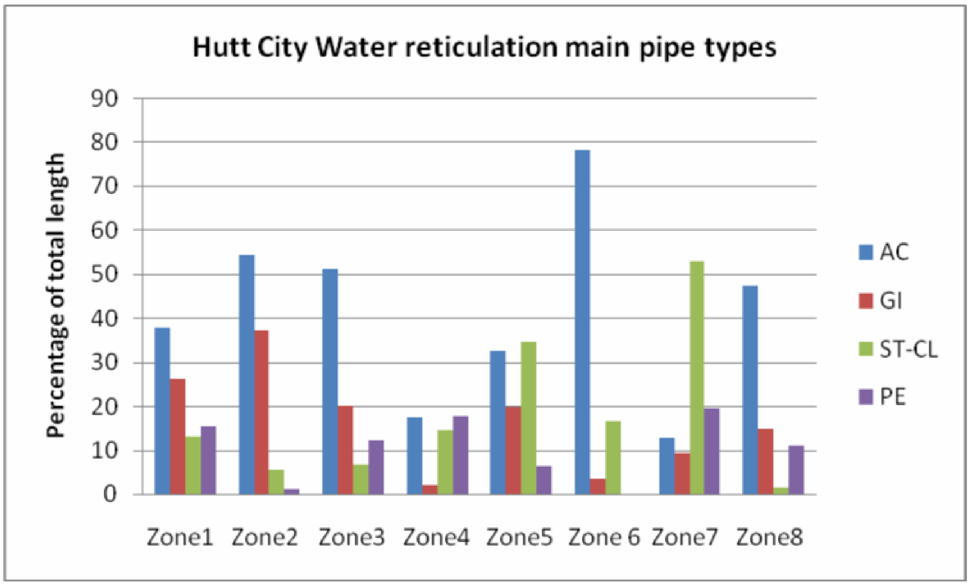

Figure 1: Hutt City water reticulation pipe distribution by pipe diameter

Pipe diameter not only is a representative of pipe capacity but also has direct impacts on pipe installation method, repair and cost. Earthquake vulnerability of pipeline varies by pipe diameter whereas small diameter pipes are more vulnerable compared with large diameter pipes (Wang et al. 1991; Eidinger 1998; Eidinger and Avila 1999; Schiff et al. 1999; Isoyama 2000; Chen et al. 2002; Allouche and Bowman 2006; ALA July 2002).

Pipe diameter in Hutt City water reticulation varies from 20 mm pipes to maximum pipe diameter of 525 mm. The predominant pipe diameters in Hutt City water reticulation are 100 mm, 150 mm, 40 mm and 50 mm pipes which consist 34.3%, 21%, 8.6% and 9.8% of total length of water reticulation system respectively.

HUTT CITY WASTEWATER PIPELINES

In order to show lifelines characteristics including water and wastewater reticulation, Hutt City region is divided to 8 urban zones. Hutt City region includes 8 urban area zones, 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)

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 Hutt City sewer reticulation comprises of different types of pipes which have been installed during the past century. The Hutt City wastewater reticulation can be classified into two distinct groups including non-plastic pipes and plastic pipes. Non-plastic pipes comprise of AC, Fibrolite Pipes (FIB), CI, RC, Ceramic pipes (CE), EW, S, Concrete Line Steel pipes (CLS) and Pitch Fibre pipes (PF). PVC, Modified Poly Vinyl Chloride pipes (MPVC), Un plasticized Poly Vinyl Chloride pipes (UPVC), PE, Medium Density Poly Ethylene pipes (MDPE) and High Density Poly Ethylene pipes (HDPE) are classified as plastic pipes (Hutt-City-Council 2008). The main wastewater pipe types installed in the Hutt City sewer reticulation system are RC, AC, EW and PVC which the percentage of each pipe type length are 30.3, 21.6, 16.6 and 13.1 of total length respectively. In order to have a rough estimation of pipe types in the Hutt City reticulation networks, the Hutt City sewers are divided into two main groups, ductile and brittle (FEMA 2003; O'Rourke and Deyoe 2004). Brittle pipes cover 81%

(528 km) of the whole wastewater pipelines length in Hutt City which are more vulnerable to earthquake compared with 19% of the ductile wastewater pipes.

Figure 2 shows main wastewater pipelines types in Hutt City wastewater reticulation for each 8 urban zones. The predominant wastewater pipe type in half of the 8 zones is EW whereas AC is the main pipe types in two zones.

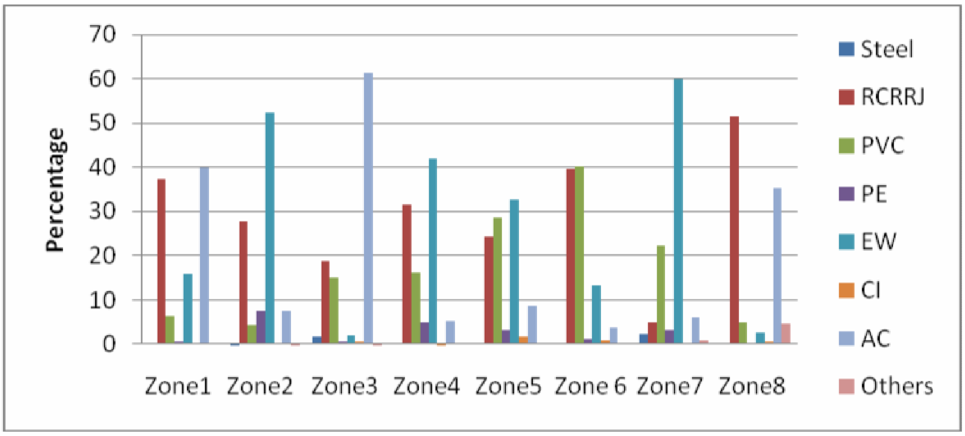

Figure 2: Hutt City wastewater pipe distribution various zones (material types)

The majority of wastewater pipelines in Hutt City are 150 mm pipes and make up 69.3% (452 km) of Hutt City sewers system. This is followed by 225 mm-diameter pipes, 300 mm pipes, 1350 mm pipes, 100 mm pipes, and 375 mm-diameter pipes and cover 9%, 5%, 2.9%, 2.4% and 2.3% of Hutt City sewer reticulation respectively.

HUTT CITY GEOTECHNICAL CHARACTERISTICS

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) (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 (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 (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 (Van Dissen 1992).

EARTHQUAKE SCENARIOS IN HUTT CITY WASTEWATER PIPELINES

Pipe type, length and diameter are three main factors affect pipe earthquake vulnerability and are categorised in each zone. The classification includes Hutt City reticulation networks and includes 568 km of wastewater pipelines, Fig. 4.

Wave propagation effects on pipelines can be estimated by various types of formulae. Earthquake parameters including pipelines characteristics are driving factors to choose and apply proper formula (see (Eguchi 1983), (Eidinger 1998), (Jeon 2005), (Toprak and Taskin 2007), (O'Rourke and Deyoe 2004), (ALA July 2001) and (FEMA 2003)). The accuracy of each practical formula used to calculate pipe damages are dependent on the accuracy of required data and data availability. (Toprak and Taskin 2007), (O'Rourke and Deyoe 2004), (ALA July 2001)). Damage estimation formulae are adequate tools to reveal the most vulnerable zones. Estimation of numbers of expected defects in earthquake prone regions is the main advantage of available formulae. In post earthquake management point of view having an estimation about number of defects in each types of wastewater pipeline in each region with different earthquake scenarios is reasonably beneficial.

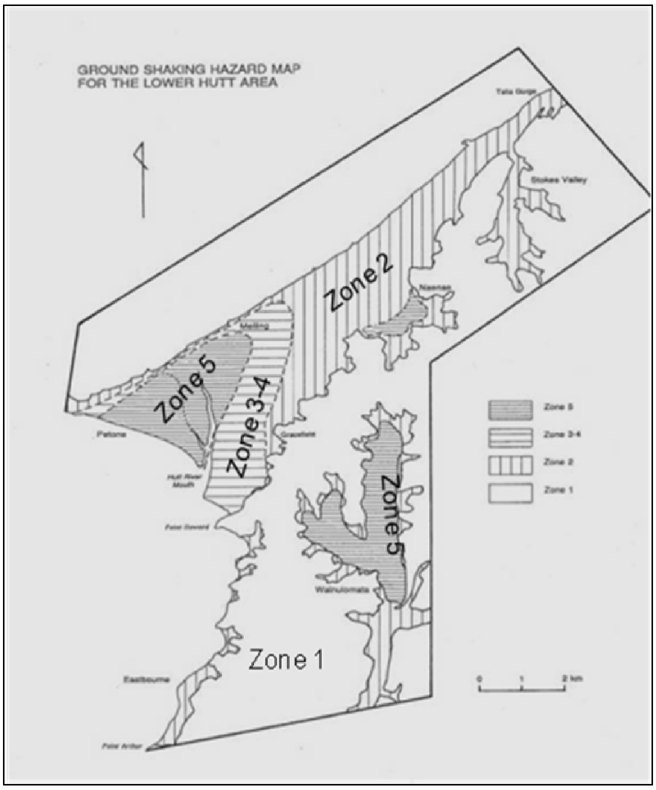

Figure 3: Hutt City Hazard map (Van Dissen 1992)

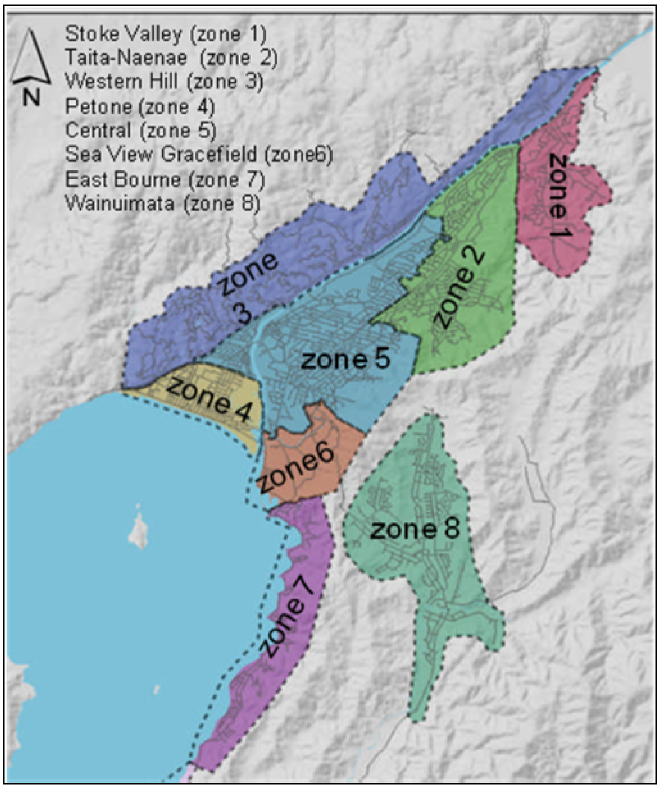

Figure 4: Hutt City wastewater reticulation zones

HAZUS is a well known formula which is applied to calculate wave propagation effects on different types of water and wastewater pipes. Wave propagation effects in pipelines are showed by number of breakages and leakages.

Expected earthquake damage to pipelines in each zone is calculated for two different material types; brittle and ductile. Pipe material, current condition of pipe, pipe remaining life and pipelines construction date are main factors that are used to classify two material types in each zone. Geological and geotechnical characteristics of each hazard zone are applied to establish each zone soil type.

Spectral acceleration of an earthquake prone region is used to calculate peak ground velocity (PGV) (FEMA 2003). Spectral Acceleration (SA) for the worst case scenario in Hutt Valley region is derived by Stirling's work for soil type B (Stirling 2002). HAZUS soil amplification factors were applied to estimate more accurate PGV in each urban zone (FEMA 2003).

Figure 5 shows the calculated defects in the Hutt City water reticulation caused by large scale earthquakes in each urban zone. Figure 5 reveals the water reticulation in zone 8 is the most vulnerable region in Hutt City. Wave propagation effects in zone 8 are expected to be 268 defects, which 90% of that is expected in fragile pipes. Hutt City central will be affected significantly by large scale earthquake. Damage in ductile pipes is 35% of the total defects in zone 5 compared with 10% in zone 8. Zone 3 and 4 cover 15.4% and 12.8% of the total defects in the Hutt City water reticulation.

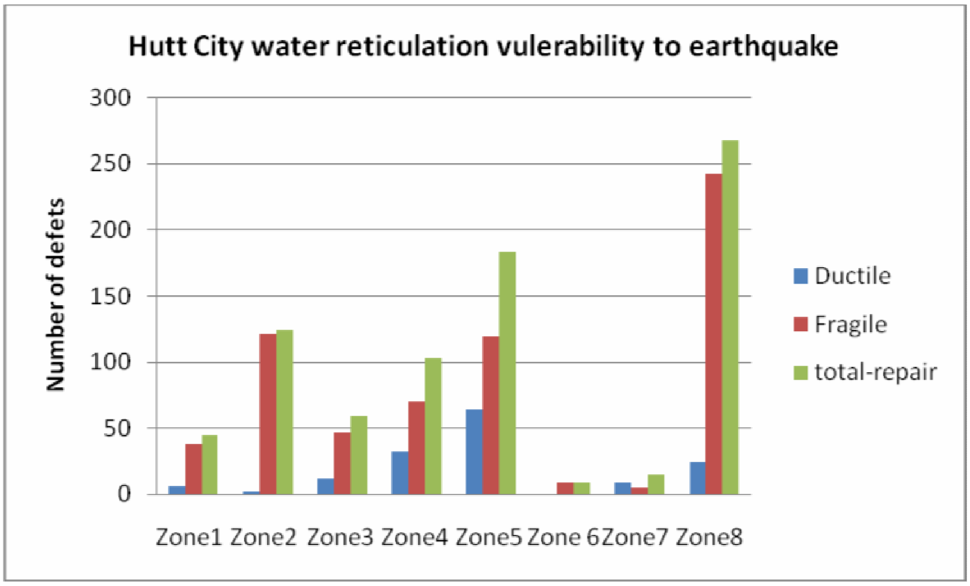

Figure 5: Hutt City water pipeline earthquake damages in 8 urban zones (HAZUS)

Figure 6 shows wave propagation effect on the Hutt City wastewater reticulation. The wastewater reticulation in zone 8 is the most vulnerable part compared with other urban zones. Hutt City central area is the second most vulnerable water reticulation.

The wastewater reticulation in zone 5 suffers more defects in an earthquake compared with the water reticulation in this region. Zone 4 is the third most vulnerable wastewater reticulation and the number of expected defects in zone 4 is half of the defects in zone 8.

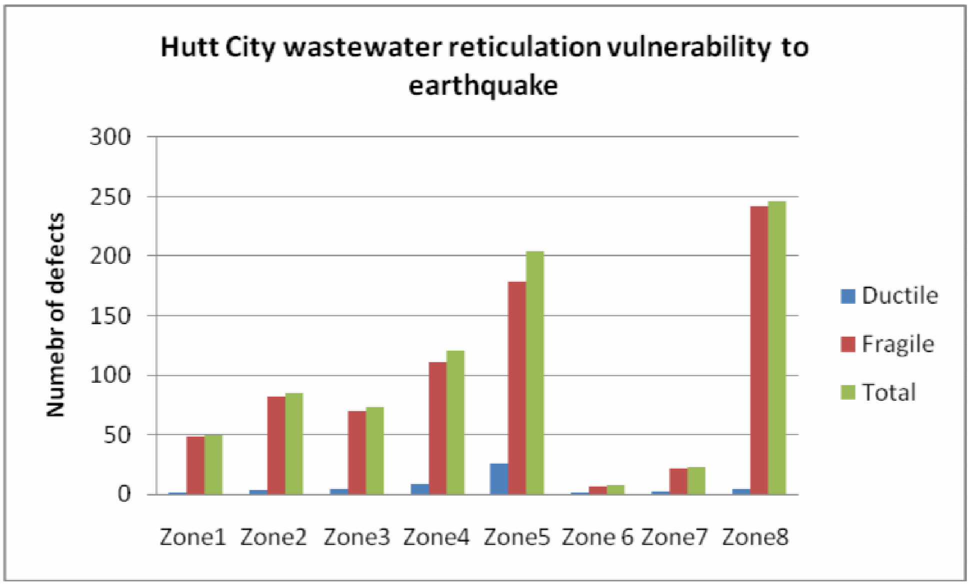

Figure 6: Hutt City wastewater pipeline earthquake damages in 8 urban zones (HAZUS)

CONCLUSION

Apart from some sort of uncertainty in the available fragility equations, the perception of earthquakes effects on pipelines is quite well known. On the other hand buried pipelines are not easily accessible to screening and fault investigating. Consequently, the importance of earthquake effects on pipelines when will be taken into account that an earthquake hits urban areas. Hutt City is an example of a small urban area which was shown how vulnerable are its' lifelines in each urban zone. Significant earthquakes can be turned into devastating disasters in a metropolitan city even if the above ground structures stand during earthquakes. Consequently, earthquake effects on lifelines especially in metropolitan cities which are located in earthquake zones should be considered and adequate plan for recovery and rehabilitation should be taken into account.

The number of expected defects in different zones caused by wave propagation only shows ground shaking effects. If permanent ground deformation is also added to the numbers of defects caused by ground shaking, the lifeline vulnerability gets worse. Earthquake effect on water and wastewater reticulation varies between different urban areas although the most vulnerable zone for both water and wastewater pipelines is the same. The number of expected defects in both water and wastewater reticulation seems to be approximately the same. Pressure water pipelines in earthquakes instantly suffer damage and require the most instant attention compared with wastewater reticulation.

Earthquake can affects wastewater pipelines significantly although most of the defects are not visible and hard to detect due to the hydraulic characteristics of wastewater flow. Enormous defects in water and wastewater pipelines after each notable earthquake deserve a proper recovery plan particularly for water pipelines. Inspection and detection plan is necessary after any notable earthquakes in wastewater reticulations.

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