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VULNERABILITY ASSESSMENT OF WATER SUPPLY NETWORK AGAINST SEISMIC HAZARDS: A CASE STUDY IN VANCOUVER

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Abstract: The recognition of vulnerability in water distribution system is a critical aspect regarding infrastructure resilience evaluation. Water supply system is represented as a complex network of interconnected distribution mains and nodes spatially distributed over a large area. This study proposes a method of resilience analysis of the existing pipelines in water distribution system for Vancouver, British Columbia as a function of failure in pipelines or repair rate for common seismic hazards incorporating the seismic vulnerability index applied in a Geographical Information System (GIS). The paper presents an outline of quantitative assessment of risk, based on the identification of governing parameters influencing the pipeline behavior, particularly for West Point Grey, Vancouver, BC as the area is prone to high seismic attacks. The pipeline behavior is considered as a function of parameters like pipe diameter, length, and materials, etc. which are demonstrated having a coefficient. They represent individual influences on the links connected to nodes of the system, and the seismic vulnerability of each pipeline is determined using empirical formulas in context with transient ground deformation (TGD), permanent ground deformation (PGD) and liquefaction impacts. The concept of integrating the Vulnerability Index (VI) with damage rate with a graphical map is to carry out a clear understanding of the efficiency of emergency response of each element in the system and prioritizing the potential pipeline candidates for replacement. This method will allow adopting a risk-based strategy to withstand seismic vulnerabilities in the water system of Vancouver.

1 INTRODUCTION

The idea of vulnerability concerns about the perception involving the indication of a situation where system undergoes adverse effects caused by potential threats from both natural and human-made hazards. The world has witnessed an evidential increase in the series of incidents of natural catastrophes like earthquakes causing severe damage to structures in the last few decades. This phenomenon makes it essential to find out methods that are capable of estimating vulnerability for future seismic attacks to carry out the initial standing for alternative emergency plans and strategized backups for the assurance of the system’s functional performance (Godschalk 2003, Li and Mahmoodian 2013). The vulnerability of structural systems subjected to seismic hazards is growing as an important consideration throughout the design of sustainable cities and operation of facility management. The water supply network (WSN) system is a significant part of civil infrastructure arrangements. Its complication of operation and a large number of elements indicate that all members of the system cannot be considered structurally resistant equally during hazard (Chen et al. 2014). Earthquakes are the most dangerous natural hazard to a water distribution network, and seismic vulnerability evaluation is necessary to recognize its danger to different stages of damage and to guarantee the system security (Godschalk 2003, Chen et al. 2014). Water distribution systems (WDS) are subject to damages like the breakdown of the old pipes, failure due to transient and permanent deformation during the earthquake. (Fabbrocino et al. 2004). With the growing demand for providing an accurate, transparent and conceptually sound solution to evaluate seismic vulnerability of infrastructural systems, very few solutions have been proposed to date. The reason that makes it difficult to get a clear concept regarding this matter is that of the uncertainty of intensity of the future seismic attack (Dhungel et al. 2012). However, it may also depend on systems existing physical condition, aging effect, the individual resiliency of the component based on their typology, and interdependency between systems for the overall reliability (Li and Mahmoodian 2013 and Mehani et al. 2012). Considering all these factors, a robust technique is proposed for the assessment of seismic vulnerability for water distribution networks in this study in West Point Grey (WPG).

2 URBAN WDS AND COMPLEX NETWORK

The modern world's water service facility strongly depends on the functioning of reliability assets in the form of networks combining nodes, pipes, valves, and storage services that severe concern to water utility management and operates with the vulnerability of critical elements, which are exposed to disturbances and hazards. Moreover, an accurate understanding of the critical locations in water distribution pipelines can provide vital facts that may be used to update lifelines management performances and rehabilitation programs prominent to more realistic risk valuations and the development of protective strategies to assure network survival in the situation of extreme natural events like an earthquake (Yazdani and Jeffrey 2010). Reliability evaluation of water distribution network (WDN) performance in the aspects of seismic hazard is reliant on a close and precise definition of system characteristics like resilience and robustness. A resilient system displays decreased failure probabilities and reduced time to recovery, characterized by four infrastructural understanding of robustness, redundancy, resourcefulness, and rapidity which integrates the ideas of risk (probability of fracture also known as pipeline fragility). Therefore, research on estimation of the tolerance of the system to resist and overcome failure and its consequences accepting enlarged attention from the scientists and engineers for more complex infrastructures like pipeline networks. (Yazdani and Jeffrey 2010).

Complex networks like WSN are performed by the demand and distribution regulations in such a way that the behavior and interface of the distinct elements, taken compositely with the non-trivial network configurations, may have the impact on the overall system performance. Vulnerability analysis of complex network like WSN using graph theory methods deals with the study of identification of structural resilience, critical locations and failure probability of lifelines and interconnected nodes (Albert et al. 2000). This process is accomplished by utilizing simulation techniques which consider the impacts of a hazard of efficiency and performance of the system as an outcome of random failures or breakage. Remarkable studies regarded with the infrastructural analysis and estimation of the vulnerability in complex networks include resilience assessment for water distribution network (Zio and Sansavini 2007). While a comprehensive assessment of vulnerability requires access to information including field data and topological aspects of the network that are entailed for operational considerations and will be used for quantifying susceptibility of components. This work aims to provide more insight towards vulnerability of water distribution systems by obtaining the probability of the degree of damage to a given structure (distribution mains in this study) exposed to different earthquake scenarios.

2.1 Seismic Risk for Water Supply Network

Water pipelines network can be spread over a big area where diverse variabilities of soil condition may come across. Numerous approaches to damage estimation have been established and published in the literature previously. The primary studies disclaims the damage risk (number of breaks per kilometer) as damage probability matrices (DPM's) in which the earthquake intensity is considered by the Modified Mercalli Intensity (MMI) (American Lifelines Alliance, 2001). The FEMA (Federal Emergency Management Agency) and the NIBS (National Institute of Building Sciences) funded a project to generate a tool for valuing the damage under earthquake hazard (Zohra et al. 2012). The technique was executed in the software HAZUS incorporating a geographic information system (GIS). The earthquake intensity is specified for peak ground velocity (PGV), peak ground acceleration (PGA) or peak ground displacement (PGD). For the lifelines, only the PGV (which intrigues most leaks) and PGD (which incites most failures) are considered for vulnerability estimation (Eidinger et al. 1999). One limitation of this method in HAZUS is that the diameter of the pipes is not taken a vital parameter for damage detection (American Lifelines Alliance 2001).

On the other hand, breakable pipes (asbestos, cement, concrete, cast iron and steel welded and ductile pipes (Poly Vinyl Chloride, steel welded, etc.) are classified to each seismic hazard and assigned with coefficient values. As one of the initial works about a seismic improvement of water systems have analyzed preparedness, performance, and mitigation for East Bay Utility water distribution network for earthquakes scenarios. In those works, seismic hazard models were used to predict levels of ground shaking, liquefaction, landslides, and surface faulting caused by the earthquakes scenario (American Lifelines Alliance 2001).

3 STUDY AREA

West Point Grey WSN consists of 2,053 individual pipeline links. It is a considerably large network spread over 455 hectares area of land with approximately 52.9 km (1 km = 0.62 miles), shown in Figure 1(a) and 1(b), with distribution pipeline to serve about 12,795 consumers (West Point Grey census, Statistics Canada, 2011). Initial installation of the pipe was noted at 1900, and final installation was at 2017.

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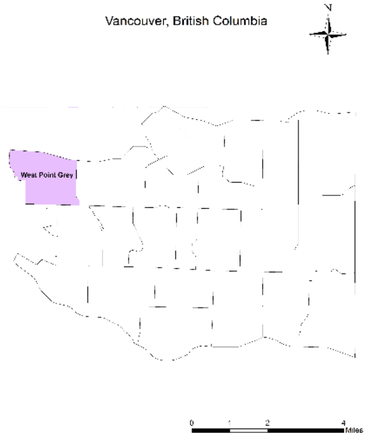
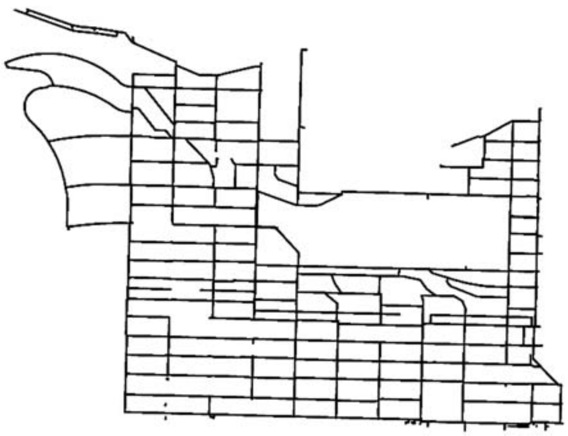


(a)



(b)

Figure: 1(a) Study area West Point Grey, Vancouver   Figure: 1(b) Pipe distribution network, WPG

Vancouver is near to the edge of two of these plates: the massive North American plate and the smaller Juan de Fuca plate moving towards an area called the Cascadia Subduction Zone which generates large earthquakes (called "megathrust quakes") and even may register greater than magnitude 9.0. In Vancouver Smaller but potentially more damaging earthquakes can happen in the Strait of Georgia, or deep under the Coast Mountains and in the west of Vancouver Island. There is evidence that built strain and the squeezing of the crust caused by this two, can result in 500 or so small earthquakes that are located in southwestern British Columbia each year. The less frequent (once per decade, on average, damaging crustal shocks (e.g., a magnitude 7.3 earthquake on central Vancouver Island in 1946). (NRC) Geological and historical evidence also shows that enormous (magnitude 9) earthquakes with high intensities have struck this coast every 200-850 years and the most recent one occurred on January 26, 1700.

4 METHODOLOGY

Analyzing the studies specified in the literature, this research presents a method for quantifying vulnerability index (VI) for easy and useful evaluation of the seismic vulnerability of pipes. The proposed method is established on statistical models for vulnerability analysis of lifelines concerning the following individualities, diameters, materials type, seismic intensity and soil conditions.

4.1 Statistical Model for Pipelines Damage

The statistical method is broadly used for valuation of damage to pipeline networks underground shaking and ground deformations. A distinctive technique can be derived from Zohra et al. (2012), and Nojiima (2008) for calculating the number of pipe breaks and joint failure is compounding the extended length of the pipeline with damage rate carried out as the average number of pipe breaks and nodes failure per unit length.

[1] $N = L \cdot R_{fm}(x)$

Where N is denoted as the number of pipe breaks and joint failure. L is the extended length of the pipeline (km), x is ground motion parameter taken for PGA (peak ground acceleration), PGV (peak ground velocity), or SI (spectral intensity), and $R_{fm}(x)$ is the damage rate (breaks/km which is calculated from the following equation.

[2] $R_{fm}(x) = C_d \cdot C_p \cdot C_g \cdot R_f(x)$

Here, $R_f(x)$ is obtained as standard damage rate (breaks/km) as a function of ground motion parameter x. C_d represents correction factor for pipe diameter, presented in Table 1, C_p is the weighting factor for pipe material/joint type, shown in Table 2, and C_g expresses the correction factor for ground and liquefaction, both modified from Nojiima (2008).. As discussed later, standard damage rate $R_f(x)$ (breaks/km) is determined for a combination of a particular type of pipe material, joint, and pipe diameter from damage statistics from past earthquakes and historical evidence. While the context of Equation (1) and (2) are common to various models of statistical estimation methods, different models have different sets of correction factors and standard damage rate function. Statistical availability of data influences the reliability of correction factors. Weighting factors are composed of the illustration of the correction factors suggested by Takada et al. (1998) from damage data from the Kobe event.

4.2 Evaluation method of vulnerability index of pipelines

The total number of pipeline failures projected using Eqn. 1 comprises three major influencing components on which numerical assessment of vulnerability are developed: the length of pipeline L, material properties, e.g., pipe diameter and type (C_d and C_p), and hazard intensity (severity of ground motion x and ground condition C_g). Concentrating attention on the term vulnerability, a simple but useful method termed "Vulnerability Index (VI) method" to quantify the comparative vulnerability of buried pipeline is proposed according to (Zohra et al. 2012) and Menoni et al. (2007). Equation 3 shows the Vulnerability Index,

[3] $VI = C_d.C_p.C_f.C_s.C_g.C_i.C_l$

VI is evaluated from equation three by considering the number of parameters powering the behavior of the pipe with weighting factor derived from (Chauche et al. 2004) and (Zohra et al. 2012). Where C_f is the weight factor for fault crossings according to Table 3. C_s is the weight factor for settlement and landslide shown in table 4, C_g is the weight factor for ground type given table 5, C_i is the weight factor for the seismic intensity according to table 6 and C_l is the correction factor for liquefaction according to Table 7.

4.2.1 Pipes diameters

Many scientists over the past few decades have considered that the pipe diameter has some impact on the ability of the pipe to withstand the effects of earthquakes without failing. Some study suggests that fragility curves have a constant varying from 1.0 to 0.0 as pipeline diameter rises from 4 inches to more than 40 inches. Some other reviews include empirical evidence presenting a fall in damage rates for bigger diameter welded steel pipe, but it was unable to show significances for cast iron or asbestos cement pipe. Further research regarding this matter comprises empirical evidence displaying a drop in damage rates for cast iron, asbestos cement, and ductile iron pipes, with the increase in diameter. A possible explanation for this phenomenon is tried to find out based on the strength of mechanics principles. Combining all these case studies with physical indications, it was evidential that seismic activities show the influence of diameter of pipes on the number of break and rate of failure where small-diameter pipe has revealed high damage rates in most of the earthquakes with accumulation of location in the foul soil areas low-quality control and experienced more damage than the larger ones (American Lifelines Alliance 2001).

4.2.2 Pipe material

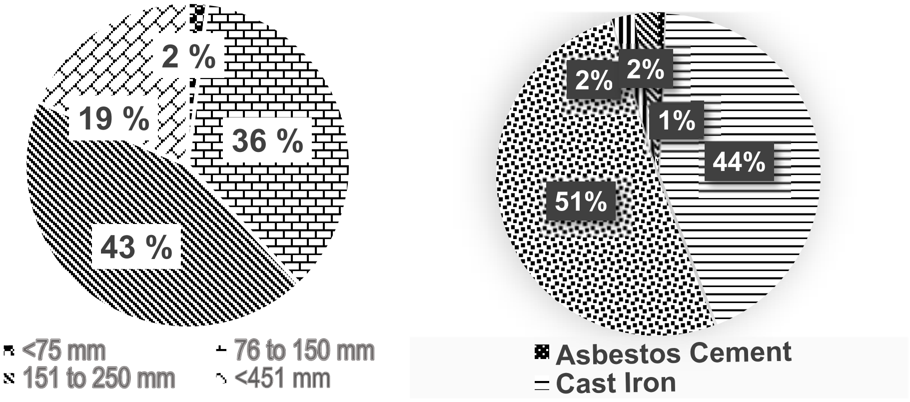
The material of pipe is one the most significant factor that gives a various range of results in finding out seismic vulnerability mostly for two reasons. The first one is materials inherent capability to withstand the shock and resist failure during an earthquake. Secondly, aging and corrosion in pipelines will accentuate the damage. This phenomenon is often noticed in steels, especially segmented ones. Cast Iron pipes (CIP) and threaded steel are also susceptible to corrosion failure as it reduces the thickness of the material and increases stress concentration. Among all the elements, screwed and threaded steel shows a higher rate of damage and incidents of corrosion failure under seismic attacks (Menoni et al. 2007)

Table 1: Weighting factors for diameters

Diameters (mm)	Factor
ø <75	1.60
75 < ø <150	1.00
150 < ø <250	0.90
250 < ø <450	0.70
450 < ø <1000	0.50
ø > 1000	0.40

Table 2: Weighting factors for pipe materials

Material	Factor
Ductile Iron	0.30
Cast Iron	1.00
Steel	0.30
Poly Vinyl Chloride	1.00
Asbestos Cement	2.50



(a) (b)

Figure. 2. Distribution of water supply pipelines (by number) grouped by (a) pipe material; (b) pipe diameter

According to the report from American Lifelines Alliances (American Lifelines Alliance 2005), about 75 to 90 percent of all pipe in the US installed at the era of 1945 is mostly cast iron. The other materials used for this purpose comprised riveted steel, wood, and wrought iron. In some cases of the inadequacy of data on actual pipe material, it is practical to accept that most WSN in this region developed before 1945 used the cast iron pipe. For pipe installed since 1945, different elements were introduced to be used for pipeline installation of lifelines. For pipelines having a diameter up to 12 inches, asbestos cement (AC) were often used for about a period of 40 years (from 1945 to 1985) although they are no longer used for new construction and are not a good option for replacement of new pipelines. Polyvinyl chloride (PVC) pipes grown the acceptability of extensive uses for diameters up to 12" from many water agencies, especially, Since 1985. However, Welded steel pipe is more new in practice from the early 1900s, because it can be used for pipes having a diameter of 12” and larger than that. The ductile iron pipe has been widely in use since the 1940s for all pipe diameters (12” and more).

4.2.3 Fault Crossings

From the aspects of seismic motions, fault crossings have a significant role in the identification of the level of vulnerability as localized permanent ground deformations happen in surface fault rupture areas. Damage to segmented pipes, (e.g., CIP) will be more when crossing surface ruptured faults. For cast iron pipe, use of “bell and spigot” connections are one of the most common use also known as “segmented” construction. However, cemented joints are also standard in practice and can be set as a default. On the other hand, butt-welded continuous steel pipes are prone to accommodate more fault crossing displacements which may range from an inch and up to a few feet. The amount of fault offset dislocation known as permanent ground displacement (PGD). The ductile iron pipe can have both segmented and mechanically restrained joints while continuous butt-welded steel lifelines are less susceptible to damage. The angle of the pipeline-fault crossing has a considerable impact on its response to the earthquake, and the performance will escalate as the angle of the pipeline-fault intersection increases and American Lifelines Alliance 2001). However, for both segmented and continuous pipes, it is useful to avoid bends. Burial depth is also considered an essential factor at fault crossings. It is observed that a pipeline with 3 feet depth can tolerate about four times more fault displacement than a pipe with 10 feet of depth due to less frictional resistance by the soil. In the study area, apart from the end nodes, all other nodes were connected to pipelines in the range of 2 to maximum 4. For several intersections, a high value is assigned to the weight factor of the faulty crossing.

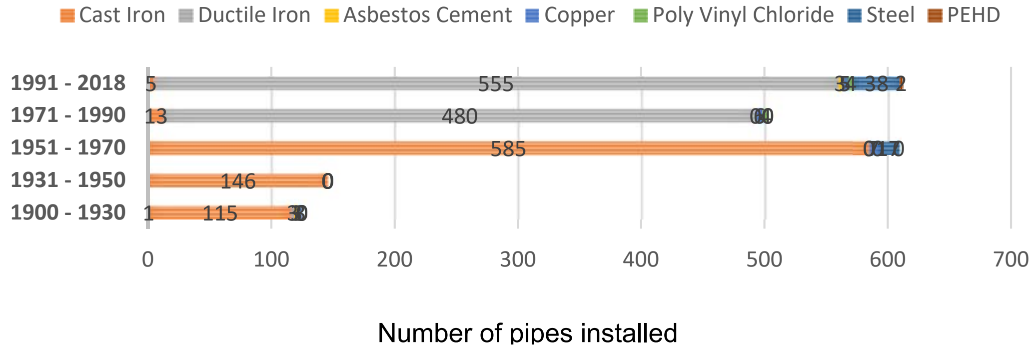


Figure: 3 Type and number of installed pipe in WPG at the different period

4.2.4 Landslides and Settlements

Permanent deformations of soil are known as landslides resulting localized, severe damage to buried lifelines. The volume of the landslide will depend on various factors including soil type, topology, and climate. Further landslides will take place if the earthquake happens during the rainy or winter season. It can range from some small and displacements of only a few inches of soil to a comparatively bigger one with 100,000 cubic yards or more of soil mass over many feet of expansions, damaging a considerable area. The quantity of landslide movement is carried out as permanent ground displacement (PGD), and the phenomenon of breaking of pipelines occurring due to relative vertical settlements at transition zones from fill to better soil, and localized liquefaction prone region, is known as settlement. (American Lifelines Alliance 2001)

4.2.5 Soil Type

Landslides are conditional to the topology of the area and ground type. An inherent risk is expected in the areas of high slope, and the landslide occurrence probability is increased by high precipitation, low soil stability, weak vegetation. In the study area, West Point Grey, a landslide is very commonly observed due to the mountainous landscape of Vancouver Island, British Columbia, Canada. British Columbia (BC) faces significant landslides each year due to earthquakes. The region’s steep, hilly topography high amount of rainfall and unconsolidated glacial sediments create susceptibility against seismic attack. Hard rock is taken as least likely soil type to experience landslides (although, there is a remaining possibility of rockslides), they are not considered as higher risk in comparison to organic soil which can absorb more moisture from high precipitation, making it most likely to end up in debris flows (American Lifeline Alliances, 2001).

For the preparation of vulnerability maps, it is essential to present the seismic hazard concerning levels the ground situation. Therefore a reference ground condition is obligatory to numerical esteem values and to compare between pipelines to find out the potential lifeline candidates for replacement. We have adopted Site Class C (very dense soil and soft rock) according to NBCC2005 which is defined by a 360 to 750 m/s average shear wave velocity in the uppermost 30 m (Halchuk and Adam 2004) since it denotes the more substantial number of influential motion recordings. Considering all these factors, Cg was assigned as for moderate to medium weathered rock and dense soil. Additionally, it represents the closest situations to the study area for ground conditions that were implied by the strong ground motion relationships cast for the 1985 hazard maps for BC (Adams and Halchuk 2005).

Table 3 Weighting factors for settlements and landslides

Settlement/Landslide	Factor
No Risk	1.00
Average Risk	2.00
Important Risk	2.40

Table 4: Weighting factors for seismic intensity

Intensity (MMI)	Factor
MMI<8	100
8 MMI<9	2.10
9 MMI<10	2.40
10 MMI<11	3.00
11 MMI	3.50

4.2.6 Seismic Intensity

A comparison in NBCC2005 (section 2.2) shows that between 1985 and 2005 PGA, 10%/ 50-year values for Vancouver increases upward from 0.21 to 0.26 due to change in source zone boundary position. The transfer to 2%/ 50-year hazard has made two impacts including, the firm ground 2%/ 50-year ground motions are about twice the 10%/ 50-year motions. And at the 2%/ 50-year probability level more massive earthquakes are expected than before leading to larger magnitudes (Adams and Halchuk 2005). To achieve a realistic assessment of seismic vulnerability for lifelines, three probabilistic seismic hazard scenarios were anticipated for West Grey Point, Vancouver, Canada based on historical seismic incidents. An earthquake with higher magnitude (M 8.7 to M 9.2) occurred off Vancouver Island on the Cascadia subduction zone in 1700 A.D. We chose to adopt three intensity scenarios for earthquake concerning a line source for SC1: MMI<8, SC2: 8<MMI<9 and SC3: 9<MMI<10.

4.2.7 Liquefaction

Seismic soil liquefaction has the likelihood to occur in specific soil units and can cause permanent ground deformations. A substantial amount of breakage will happen in the areas of liquefaction-induced lateral spreading. The location of the pipe to the ground movement can affect the extent of the damage (O'Rourke and Nordberg 1992).

Table 5: Weighting factors for liquefaction

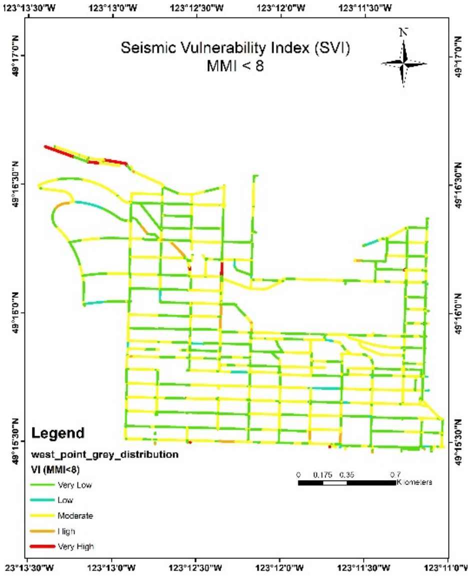
Liquefaction	Factor
0 ≤PL<5	1.00
5 ≤PL<15	2.00
15 ≤PL	2.40

VI is derived by using equation 3 for WPG, Vancouver. In this classification when the vulnerability index ranges from very low to very high as Class 1 to Class 5 respectively. Between zeros to seven, the vulnerability of the lifelines is considered very low and the green color is associated. For seven to twelve it shows low vulnerability. When it is more than twelve, it means an average situation and the pipe is taken as moderately vulnerable, marked by yellow. Index having value more than twenty and thirty is classified under high and very high zone respectively. These values are specified for Vancouver allowing for the earthquake intensity, soil type, and geological location.

Table 6: Vulnerability Index (VI) with pipe classification

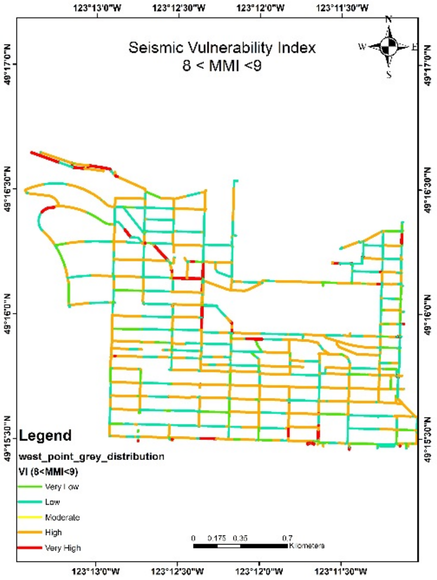
Class	Range	Evaluation	Color of Identification
1	0 < VI < 7	Very Low	Green
2	7 < VI < 12	Low	Blue
3	12 < VI < 20	Moderate	Yellow
4	20 < VI < 30	High	Orange
5	VI > 30	Very High	Red

5. SEISMIC VULNERABILITY INDEX FOR WDN IN WEST POINT GREY



(a)

Figure: 4(a) Seismic Vulnerability Index (SVI) for earthquake MMI < 8 (SC1)



(b)

Figure: 4(a) Seismic Vulnerability Index (SVI) for earthquake 8 <MMI < 9 (SC2)

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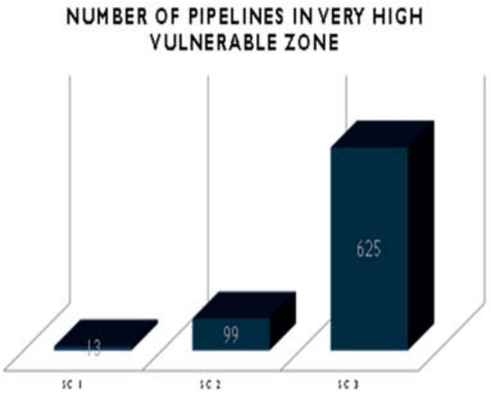

Figure: 5 No. of most vulnerable pipes in all SC1, SC1, SC2 and SC3

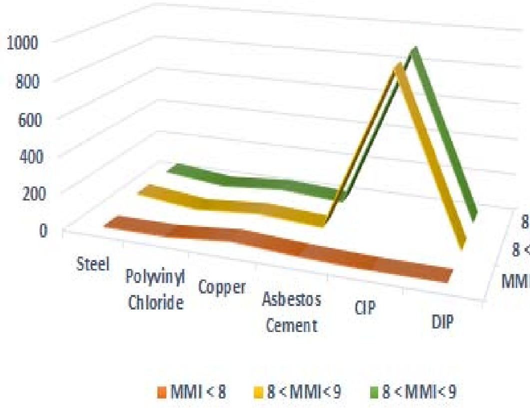

Figure: 6. Variation of pipelines in high to very high vulnerability with the material of pipeline

The GIS may be a useful way to demonstrate the results of an SVI assessment and classification of the water supply network. Figure 4 (a), Figure 4 (b) and Figure 7 shows the ranking of the pipelines in WPG. In Figure 5, it is displayed that, for SC1, total pipes in Class 5 are 13. In SC2, it is 7.6 times than pipelines in SC1 indicating 4 percent new pipelines are added to Class 5 from Class 4. In case of SC3, vulnerability is increased 6.3 times than SC2 and almost 48 times than SC1. It is also found for SC3 that, another 25 percent of new pipelines joined Class 5 from Class4. Figure 6 shows that initially in SC1 material most susceptible to seismic attack is Copper. In both SC2 and SC3, the highest damage is observed in cast iron pipelines

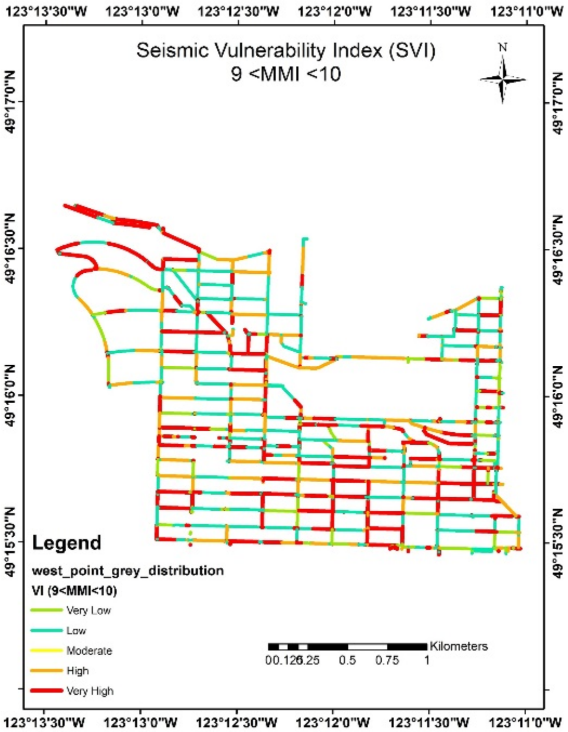

Figure: 7 Seismic Vulnerability Index (SVI) for earthquake 9< MMI< 10

6. CONCLUSION

A method for vulnerability analysis of lifelines under seismic hazard integrated into GIS is presented in this paper. The outcomes of this method would be used for enhancing the resilience and robustness of water distribution network under seismic activities. The preparedness can be improved for significant earthquakes attacks by evaluating how a lifeline system is prone to damage or failure. Following this technique, establishing emergency plans will be easier to incorporate with the concept of the resiliency of the utility to breakage.

The appraisal is acquired as an index followed by multiplication of corresponding factors that affect the loss and damage and was set with the higher priority according to the different seismic intensity level. This practice can be further used to achieve a feasible retrofitting for the lifeline and developing plans and actions for maintenance and repairing. The advantage of this method is, instead of the whole system in general, it carries out the vulnerability of each component individually. Also, it can project the change in susceptibility under different seismic scenarios. Moreover, it is possible to feed a GIS with all this generated value illustrating not only the damage but also the location of pipelines in the network. Despite the fact, the soundness of the result depends on the availability of data, with adequate information, this method can be an excellent tool for developing adaptation strategies and action planning against disaster consequently improving plans for mitigation and damage reduction in urban contexts, concerned to geographical and spatial factors that significantly affect seismic risk.

Acknowledgments
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