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Prioritizing water distribution pipe renewal based on seismic risk and construction cost

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Abstract. Natural disasters such as earthquakes can cause damage to water distribution pipe, resulting in water interruption. For a contingency plan for earthquakes, calculating the possibility of failure and the consequence of failure are necessary. The empirical formula for the vulnerability of water distribution pipe after earthquake was developed considering deterioration effect with aging in this study. The degree of water outage was assumed to be a consequence of failure. The earthquake risk with pipe aging was obtained through the product of them. Although the risk alone might be used to prioritize pipe network improvement, it was recommended to consider the construction cost as well. It was also proposed to use a score-based method by graphically tabulating construction cost and risk. The methodology proposed was demonstrated on a real-scale water distribution pipe in Korea. The improved prioritization using the scoring method will help create a future earthquake preparedness plan for a water distribution system.

Keywords: fragility curve; pipe renewal prioritization; repair rate; seismic risk; water distribution pipe; water outage risk

1. Introduction

Natural disasters such as earthquakes have a large impact on infrastructure, especially water distribution system essential to human life. Korea is facing an increase in the frequency and intensity of earthquakes. The aged water distribution network has become more vulnerable by a seismic effect (Rajani and Tesfamariam 2007, Tabucchi *et al*. 2010). According to data from the Korean Ministry of Environment, 30 percent of Korean water distribution pipelines are more than 30 years old (MOE 2016b). All the more, Korea's water distribution system is at a time when aging is accelerating and experiencing the increasing frequency of pipeline damage (MOE 2016b). The aging pipeline is likely to be easily damaged by earthquakes and external influences. According to data from the Korean Ministry of Environment, 12 percent of 17,048 kilometers of water distribution system in Korea is earthquake-resistant, and the remaining 15,014 km is not prepared for earthquake (Jun *et al*. 2019, MOE 2016b). If the pipeline is damaged, it is expected that not only the cost of physical damage (i.e., the cost of recovering from damage) but also the cost of social and economic damage to the public will increase (FEMA 2003, Kim *et al*. 2019).

Water distribution system damage by earthquakes is affected by two groups of factors, which are the pipe and surrounding conditions (ACSE and ALA 2001, Isoyama *et al*. 2002). The pipe and surrounding conditions are aging and corrosion, diameter, wall thickness, depth of soil cover, joint type, material, site characteristics, fault crossing, continuous and segmented pipe. The earthquake factors are ground shaking, landslides, liquefaction, and settlement. Appurtenances and branches are also important factors for damage from earthquakes (ACSE and ALA 2001, Kang *et al*. 2017).

The relationship between the probability of pipe break and the level of seismic threat is stated as the fragility curve (ACSE and ALA 2001, Rajani and Tesfamariam 2007). The fragility curve is a mathematical expression that relates the probability of damage state with a particular level of earthquake hazard (Ellingwood 1998, Ghosh and Padgett 2010). The degree of earthquake is categorized by peak ground acceleration (PGA), peak ground velocity (PGV), or peak ground displacement (PGD). PGA is used for above ground facility while PGV and PGD are used for below-ground water distribution system (Ni *et al*. 2018). Once the original location of the earthquake is identified, PGA, PGV, and PGD can be calculated using attenuation models, which have been developed to describe the degree of earthquakes (Berglund *et al*. 2020, Hernandez 2017, Zhang *et al*. 2020).

The damage of a buried pipe is expressed as a repair rate (RR) per unit length of pipe, as a function of PGV or PGD as expressed by Eqs. (1) and (2). RR is expressed as linear and power model as shown at Eq. (1) and (2) in SI unit. The pipe failure probability (Pf) is calculated by Eq. (3) using the repair rate.

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$$RR_{PGV} = K_1 \times 0.01425 \times PGV \quad (1)$$

$$RR_{PGD} = K_2 \times 4.281 \times PGD^{0.319} \quad (2)$$

$$P_f = 1 - e^{-RR \times L} \quad (3)$$

where the repair rate is per 100 m of pipe length, PGV is measured in cm/s, and PGD is measured in cm. K_1 and K_2 are pipe characteristic constants and are related to pipe diameter and material (ACSE and ALA 2001). Since ductile iron and steel pipes were found to be less vulnerable than cast iron pipe, ductile iron pipes have a smaller K_1 value than cast iron pipes. A pipe with smaller diameter has higher K_1 value than smaller one with same material (ACSE and ALA 2001). Seismic damage to the Water distribution system was also proposed by the Japan Water Research Center (JWRC) as shown at Eq. (4) which does not consider seismic liquidation (Shima 2013). The correction factors, considering the kind of pipe, joint type, diameter, and topological characteristics, are shown in Table 1. Isoyama *et al*. (2000) statistically analyzed pipeline damage data from the 1995 Kobe earthquake and presented a correction factor that can modify R(v) according to pipe material, pipe dimeter, topography, and liquefaction (Isoyama *et al*. 2002). R(v) was suggested by various researchers as shown by Eqs. (5) and (6).

$$R_m = C_p \times C_d \times C_g \times R(v) \quad (4)$$

where,

R_m: Modified repair rate (failure/km)

C_p: Correction factor for pipe material and joint type

C_d: Correction factor for pipe diameter

C_g: Correction factor for topographic characteristics

R(v): Repair rate(failure/km)

$$R(v) = 9.92\times10^{-3}\times(v-15)^{1.14} \text{ for DCIP (Shima 2013)} \quad (5)$$

$$R(v) = 7.03\times10^{-6}(v-15)^{2.19} \text{ for DCIP (Isoyama et al. 2002)} \quad (6)$$

where v is maximum surface speed of seismic movement (cm/s) ($15 \leqq v < 120$).

The seismic damage from WDS depends on the degree of aging. In previous studies, the maximum bending stress change due to corrosion of pipe networks was noted, and the durability was estimated by the degree of stress change (Mazumder *et al*. 2020). They used the concept of physical fragility modifier (K_P) and modified Eq. (3) into Eq. (7).

$$P_f = 1 - e^{-K_p \times RR \times L} \quad (7)$$

$$K_p = \frac{\sigma_T}{\sigma_{T_0}} \quad (8)$$

where σ_T is the stress at time T under corrosive deterioration

Table 1 Correction factors for DCIP

Pipe materialand joint,	C_p	Diameter (mm),	C_d	Terrain topography,	C_g
DCIP(A)	1.0	50-80	2.0	Mountain, Hill	0.4
DCIP(K)	0.5	100-150	1.0	Sand, Gravel	0.8
DCIP(T)	0.8	200-250	0.4	Delta, Costal area	1.0
DCIP(clamped)	0	300-450	0.2	Bank, Dune	2.5
-	-	500-900	0.1	Landfill, Reclaimed land	5.0

and σ_{T0} is the stress on the pipe at the initial time. However, since there are various influencing factors in the water distribution pipe, it is not appropriate to use only maximum bending stress. In particular, the degree of corrosion is not significant over time in the pipes with internal coatings. The deterioration of water distribution pipe also depends on the installation methods of joint type, pipe diameter, pipe wall thickness, depth of soil cover, pipe material, site characteristics, fault crossing, continuous and segmented pipe. The method of solving these problems is to reflect the deterioration of a pipe over time in a statistical method using field data rather than a mechanical model. In this study, the deterioration of the pipe network is adopted using the empirical formula suggested by Park *et al*. (2014).

An earthquake will cause water outage risk. The commonly used method for determining the water outage risk takes into account the likelihood defined by Lawrence *et al*. (Lowrance and Klerer 1976) and the consequence of the event, which was also used for evaluation method by ISO (2001). USEPA (2012) used the concept of the risk to analyze the impact of failures of various components of a system on the water distribution system (USEPA 2012). The risk assessment criteria were established on the expected frequency of failures and the impact of failures for components that make up a system. The equation for determining the risks used by USEPA (2012) is shown in Eqs. (9) and (11) (USEPA 2012). In which, the water outage risk refers to the risk arising from the interruption of water supply, which can be caused by the pipe breakage, failure recovery, and replacement of pipes. US EPA also proposed a risk analysis method considering the ability to replace degradation in facilities (i.e., the ability of systems to reduce risk) (USEPA 2012).

$$\mathrm{Risk_{i,t}} = \mathrm{PoF_{i,t}} \times \mathrm{CoF_i} \quad (9)$$

where,

$$\mathrm{PoF_{i,t}} = \mathrm{FR_{i,t}} \times \mathrm{L_i} \quad (10)$$

$$\mathrm{CoF_i} = \mathrm{Q_i} \quad (11)$$

$\mathrm{Risk_{i,t}}$: Risk of *i* pipe failure at t year(m³/day)

$\mathrm{PoF_{i,t}}$: Probability of *i* pipe failure at t year(failure/yr)

$\mathrm{CoF_{i,t}}$: Consequence of *i* pipe failure(m³/failure)

$FR_{i,t}$: Failure rate of *i* pipe at t year(failure/km/yr)

L_i: Length of *i* pipe(km)

Q_i: Demand shortage when *i* pipe failed(m³/failure)

The aim of this study is to suggest the appropriate methodology for prioritizing pipe renewal with the risk of water interruption in the distribution system by earthquake and recovery cost. We suggested a method to predict the fragility of an aged pipe and to calculate the recovery cost, and finally suggested a method to prioritize pipe renewal for seismic risk comparing seismic risk and construction cost.

2. Methods

2.1 Target location

The areas studied in this study is a block of G city in Korea. The pipe network is shown at the Fig. 1. Table 2 summarizes design data on the pipe networks.

2.2 Pipeline construction cost

Construction cost of DCIP was calculated by applying the criteria recommended by Korean ministry of environment (MOE 2016a). This guideline was made to calculate approximate cost for pipeline. The suggested method calculates a cost based on pipe type, diameter, material of the construction, and construction cost according to pavement type. Table 3 shows approximate construction costs per meter of DCIP.

3. Results and discussion

3.1 Fragility curves with age

The repair rate per 100 m pipeline is calculated using Eq (1) and (2) using PGV and PGD respectively (ACSE and ALA 2001). The impact of pipe material, pipe diameter, and surrounding soil are considered by adding K_1 or K_2 as shown at Eqs. (1) and (2), or $C_p/C_d/C_g$ as shown at Eq. (4). The constants are supplied from the reference (ACSE and ALA 2001, Shima 2013). The aging effects on repair rate and fragility curves were suggested by previous researches, which used a method of adding a factor considering

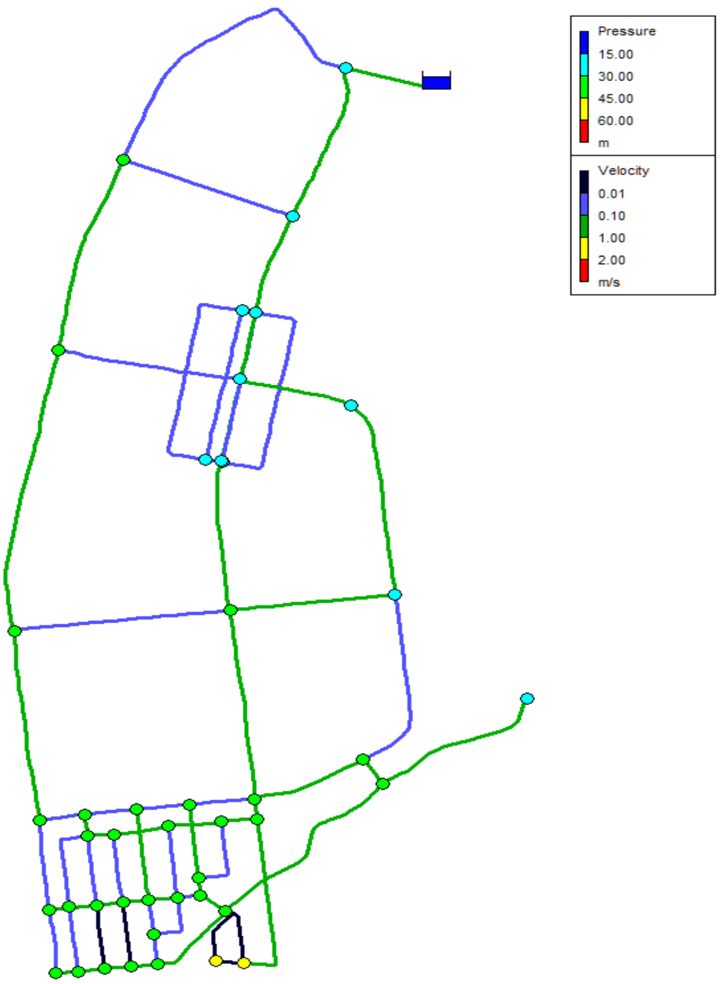


Fig. 1 The link and node of the target area

Table 2 Design data on the pipe networks of the city

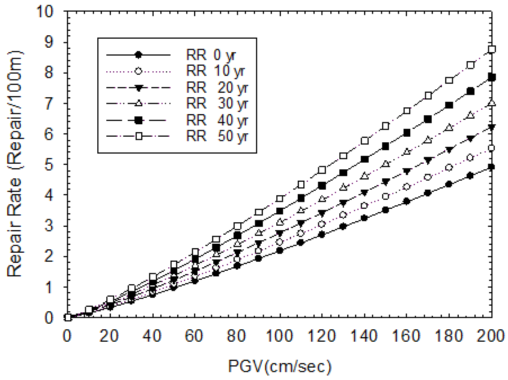
Pipe ID	Length(m)	Diameter (mm)	Material	Pipe ID	Length (m)	Diameter (mm)	Material
17729	35.27	80	DCIP	40876	290.81	100	DCIP
22436	31.33	80	DCIP	41224	160.31	100	DCIP
23305	29.81	80	DCIP	41299	345.93	100	DCIP
23810	35.47	80	DCIP	41572	305.49	150	DCIP
24701	36.92	80	DCIP	41707	458.76	200	DCIP
25185	27.45	80	DCIP	41851	469.91	250	DCIP
25391	28.60	80	DCIP	42286	153.56	300	DCIP
25591	37.98	80	DCIP	42462	87.81	350	DCIP
25921	34.74	80	DCIP	42537	70.45	350	DCIP
26228	103.55	80	DCIP	42831	133.28	400	DCIP
26692	130.41	700	DCIP	43112	242.43	80	DCIP
27050	35.53	80	DCIP	43165	246.48	100	DCIP
27135	35.29	80	DCIP	43220	243.95	100	DCIP
27240	35.94	80	DCIP	43221	347.59	100	DCIP
27300	168.82	80	DCIP	43384	317.91	200	DCIP
27403	36.81	80	DCIP	43555	315.37	250	DCIP
27524	90.55	80	DCIP	43781	71.02	350	DCIP
28303	42.37	80	DCIP	43786	304.40	350	DCIP
29056	60.30	350	DCIP	43906	252.47	500	DCIP
29335	48.99	80	DCIP	44574	20.54	100	DCIP
30843	102.05	80	DCIP	44578	1.49	100	DCIP
32357	102.76	350	DCIP	44580	18.61	100	DCIP
32719	142.43	350	DCIP	44584	0.68	100	DCIP
33300	103.68	80	DCIP	44586	108.39	500	DCIP
33529	109.04	80	DCIP	44592	276.86	200	DCIP
33776	115.28	80	DCIP	44593	36.31	200	DCIP
34001	129.63	80	DCIP	46140	303.33	100	DCIP
37443	54.67	80	DCIP	46141	248.60	100	DCIP
38294	32.09	200	DCIP	47255	72.05	80	DCIP
39429	46.77	80	DCIP	47256	74.97	80	DCIP
39552	145.28	80	DCIP	47257	243.50	100	DCIP
39813	49.26	80	DCIP	47258	222.45	100	DCIP
39832	118.54	80	DCIP	47259	292.84	150	DCIP
39877	145.69	80	DCIP	47261	237.36	400	DCIP
39935	126.11	80	DCIP	47263	162.71	500	DCIP
39936	110.63	80	DCIP				

Table 3 Approximate construction costs for DCIP

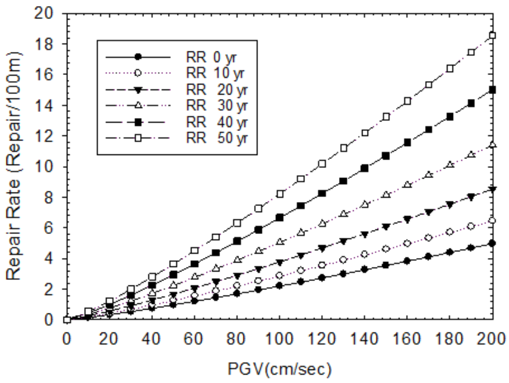
Pipe type	Diameter (mm)	Material	Construction cost on pavement			Sum (Korean Won/m)
			Soil	Asphalt	concrete	
DCIP	80	30,340	77,748	281,556	227,542	311,896
DCIP	100	36,751	81,324	289,172	234,034	325,923
DCIP	150	56,228	90,675	308,623	250,675	364,851
DCIP	200	75,270	97,268	325,316	264,558	400,586
DCIP	250	98,547	105,449	343,597	280,029	442,144
DCIP	300	124,441	112,793	361,041	294,663	485,482

Table 3 Continued

Pipe type	Diameter (mm)	Material	Construction cost on pavement			Sum (Korean Won/m)
			Soil	Asphalt	concrete	
DCIP	350	152,509	122,955	381,303	312,114	533,812
DCIP	400	181,534	166,224	434,672	362,674	616,206
DCIP	450	212,334	178,105	456,653	381,845	668,987
DCIP	500	246,898	188,092	476,740	399,122	723,638
DCIP	600	313,947	216,022	524,869	441,632	838,816
DCIP	700	508,994	242,505	571,552	482,695	1,080,546
DCIP	800	629,946	326,006	675,253	580,775	1,305,199
DCIP	900	785,592	365,075	734,521	634,424	1,520,113
DCIP	1000	938,450	423,316	812,962	707,246	1,751,412



(a)



(b)

Fig. 2 Seismic repair rate curve considering pipe aging effect for 600 mm (a) and 1650 mm (b) diameter pipe with aging correction factor (C = 1)

bending stress change over time by corrosion (Ji *et al*. 2017, Kleiner and Rajani 2001, Mazumder *et al*. 2020). However, earthquake resistance depends not only on pipe wall thickness but on many factors such as pipe material, connection method, diameter, and etc. Therefore, considering only wall thickness is limited approach. To overcome this, overall aging grading method was developed to assess pipe deterioration. Park *et al*. suggested pipe deterioration curve as Eqs. (12) and (13) for 600 mm and 1,650 mm diameter steel pipe, respectively (Park *et al*. 2014). This is an empirical equation made using various data from some Korean water mains and has an uncertainty. Hence, we used an aging correction factor (C) to help experts select empirical design variables (Mazumder *et al*., 2020) as shown at Eq. (14).

$$D_{650} = 0.8443 \times e^{-0.004x} + 0.0002x^2 - 0.00214x + 0.1437 \quad (12)$$

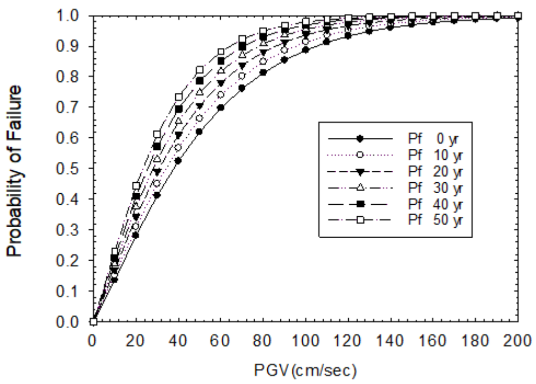
$$D_{1650} = 0.8383 \times e^{-0.011x} + 0.00002 \times x^2 - 0.0027 \times x + 0.064 \quad (13)$$

$$P_f = 1 - e^{-C \times 1/D_{650} \times RR \times L} \quad (14)$$

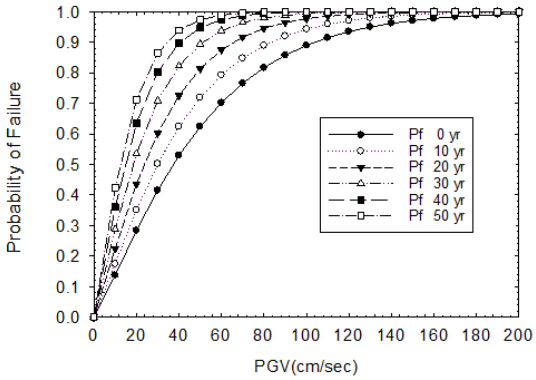
where, D_{650} and D_{1650} are deterioration index of pipe of diameter 650mm and 1,650mm, respectively. x is age of pipe in year. C is an age correction factor.

Fig. 2 is seismic repair rate curve considering pipe aging effect for 600 mm (Fig. 2(a)) and 1650mm (Fig. 2(b)) diameter pipe with aging correction factor (i.e., C = 1). These graphs show that repair rate increased as PGV and pipe page increase. It was known that pipe diameter is inversely dependent on the repair rate (Shima 2013). Fig. 2 suggest that it might be different with combined effect with aging. But this is quite difficult to conclude since the data is limited and is not verified with field data. Actually, maintenance and anti-seismic design for larger diameter pipe may make different results in a field. Fig. 3 shows seismic fragility curves considering pipe aging effect for 650 mm (Fig. 3(a)) and 1,650 mm (Fig. 3(b)) of diameter pipe with aging correction factor (i.e., C = 1). Fragility increased with PGV and pipe age. RR and fragility curve are also helpful to estimate approximate recovery cost after earthquake if recovery unit coat is provided.

Correction factor was suggested for the uncertainty of aged pipe condition. It is indeterminate how much aging correction factor can be used to obtain appropriate repair rate and possibility of failure. Although the final decision is up to a design engineer, sensitivity analysis could be used to estimate the influence of the constant. For sensitivity analysis, the correction factor ranged from 0.4 to 1.6. Figs. 4(a) and 4(b) show the difference by changing the correction factor for repair rate and possibility of failure, respectively. For suitable aging correction factor (C), further research required with ample earthquake data.

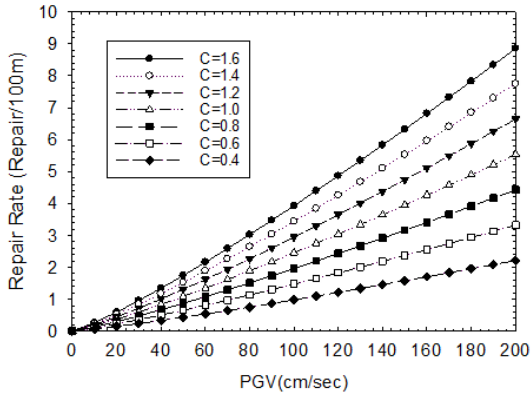


(a)

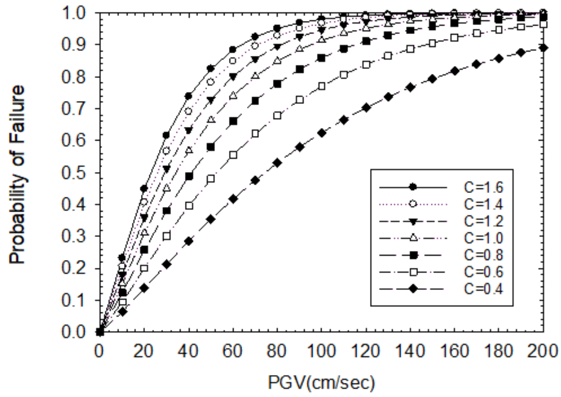


(b)

Fig. 3 Seismic fragility curves considering pipe aging effect for 600 mm (a) and 1650 mm (b) diameter pipe with aging correction factor (C = 1)



(a)



(b)

Fig. 4 Sensitivity analysis for 600 mm diameter pipe for correction factor. Repair rate for (a), seismic fragility for (b)

3.2 Piping damage after earthquake

The WDS in the target area was installed at 1993 and has the age (T) of around 27 years old as of 2020. The aging factor is 0.72627 from Eq. (10). The aging correction factor(C) is assumed to be 1. Table 4 summarizes the probability of failure, consequence of failure, risk, and construction cost. The consequence of failure the amount of water which is not available at the link after earthquake. The amount at the link is average water requirement of two adjacent nodes. The probability of failure (failure/100m) and risk is shown according to PGV(cm/sec). Risk is obtained by multiplying probability of failure and consequence of failure. The water outage risk for each pipe is calculated by Eq. (7). The cost of restoration due to pipeline damage was calculated. DCIP and asphalt pavement were assumed for calculation. The results are shown in Table 4.

3.3 Prioritize pipe renewal strategy

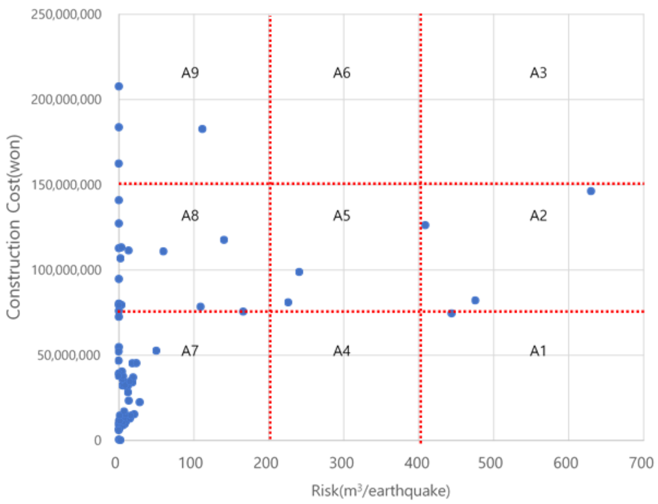
Replacing fragile pipes before an earthquake is a good contingency plan. Pipe replacement prioritization is also necessary to make decisions for aged pipes and pipes that are expected to suffer from heavily seismic damage. Because the replacement of the pipeline requires a large amount of construction budget, the aging risk and construction cost of the pipe should be considered (Eidinger 2010). The aging factor was excluded from the evaluation since the construction of the pipeline in the area was carried out 27 years ago at the same time. In order to prioritize pipeline replacement for earthquakes, high-risk pipes should be replaced first. However, if the replacement cost is too high, a complex economic perspective needs to be considered. A risk and budget diagram were used to solve this problem as shown at Figs. 2 and 3. The x-axis is plotted for risk and the y-axis is plotted for replacement cost. In this graph, nine zones were separated, of which method can be chosen by the strategic judgment of the water works' engineer. First of all, the A1 region in the Fig. 5(a) has significant risk after earthquake, but the replacement cost is relatively small. This is an area that needs the first preparatory renewal construction. The A9 region, on the other hand, has little damage, but it costs a lot of construction costs. These areas have the lowest priority. In the other regions, it is possible to determine priorities using the scoring method as shown at Table 5. The risk is 1 point for the lowest region and 3 points for the highest region. The highest construction cost is 1 point and the lowest is 3 points. After scoring, the final score can be obtained by multiplying the risk and construction cost scores with each other, and it would be better to replace the pipe networks with high scores in advance. However, the "willingness to pay" is also important to be prepared for earthquake damage (Eidinger 2010, Lee *et al*. 2017).

Table 4 Risk and recovery cost calculation with correction factor (C = 1)

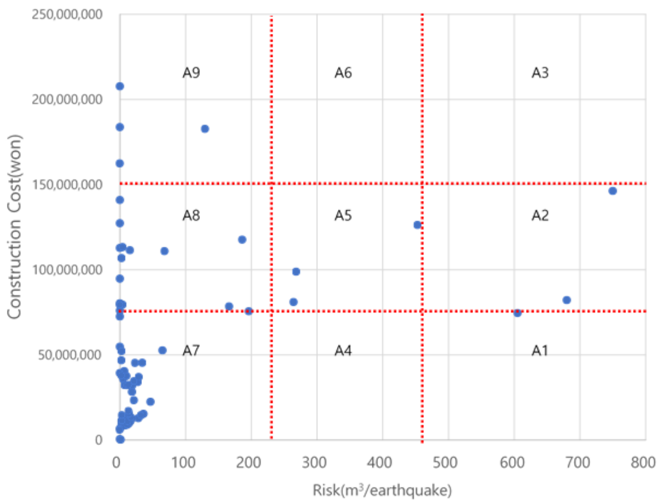
Link ID (Pipe)	Length (m)	Diameter (mm)	Probability of failure (PoF) PGV (cm/sec)					CoF (m^3/failure)	Risk (m^3/failure) PGV (cm/sec)					Unit construction cost Won/m	Total construction cost (Won)
			30	60	90	120	150		30	60	90	120	150		
17729	35.27461	80	0.23	0.44	0.61	0.73	0.82	35.8	8.1	15.8	21.7	26.1	29.2	311,896	11,002,010
22436	31.32709	80	0.20	0.40	0.56	0.69	0.78	32.7	6.7	13.2	18.5	22.5	25.5	311,896	9,770,794
23305	29.80663	80	0.20	0.39	0.55	0.67	0.76	2.2	0.4	0.9	1.2	1.5	1.7	311,896	9,296,569
23810	35.47464	80	0.23	0.44	0.61	0.73	0.82	22.3	5.1	9.9	13.6	16.3	18.3	311,896	11,064,398
24701	36.91767	80	0.24	0.46	0.62	0.75	0.83	22.3	5.3	10.2	13.9	16.6	18.5	311,896	11,514,474
25185	27.45457	80	0.18	0.36	0.52	0.64	0.73	17.1	3.1	6.2	8.8	10.9	12.6	311,896	8,562,971
25391	28.59808	80	0.19	0.38	0.53	0.65	0.75	32.7	6.2	12.3	17.4	21.4	24.5	311,896	8,919,627
25591	37.98277	80	0.24	0.47	0.63	0.76	0.84	35.8	8.7	16.6	22.7	27.1	30.1	311,896	11,846,674
25921	34.7356	80	0.22	0.44	0.60	0.72	0.81	26.2	5.9	11.4	15.7	19.0	21.3	311,896	10,833,895
26228	103.55347	80	0.53	0.82	0.94	0.98	0.99	7.7	4.1	6.3	7.2	7.5	7.6	311,896	32,297,913
26692	130.40989	700	0.61	0.88	0.97	0.99	1.00	0.0	0.0	0.0	0.0	0.0	0.0	1,080,546	140,913,885
27050	35.53285	80	0.23	0.44	0.61	0.73	0.82	9.9	2.3	4.4	6.1	7.3	8.1	311,896	11,082,554
27135	35.29028	80	0.23	0.44	0.61	0.73	0.82	26.2	5.9	11.5	15.9	19.1	21.4	311,896	11,006,897
27240	35.94186	80	0.23	0.45	0.61	0.74	0.82	2.2	0.5	1.0	1.3	1.6	1.8	311,896	11,210,122
27300	168.8221	80	0.71	0.94	0.99	1.00	1.00	69.4	49.2	65.1	68.6	69.2	69.3	311,896	52,654,938
27403	36.81474	80	0.24	0.45	0.62	0.75	0.83	7.7	1.8	3.5	4.8	5.7	6.4	311,896	11,482,370
27524	90.55418	80	0.48	0.78	0.91	0.97	0.99	23.3	11.3	18.1	21.2	22.5	23.0	311,896	28,243,487
28303	42.36771	80	0.27	0.50	0.67	0.79	0.87	32.7	8.7	16.4	22.1	25.9	28.5	311,896	13,214,319
29056	60.29754	350	0.36	0.63	0.80	0.89	0.95	15.0	5.3	9.4	12.0	13.4	14.2	533,812	32,187,550
29335	48.99016	80	0.30	0.55	0.73	0.84	0.91	23.3	7.0	12.9	17.0	19.6	21.1	311,896	15,279,835
30843	102.04849	80	0.53	0.81	0.93	0.98	0.99	22.3	11.7	18.1	20.8	21.8	22.1	311,896	31,828,516
32357	102.75995	350	0.53	0.82	0.93	0.98	0.99	0.0	0.0	0.0	0.0	0.0	0.0	533,812	54,854,494
32719	142.43046	350	0.65	0.90	0.98	0.99	1.00	0.0	0.0	0.0	0.0	0.0	0.0	533,812	76,031,089
33300	103.68141	80	0.53	0.82	0.94	0.98	0.99	17.1	9.1	14.0	16.0	16.7	17.0	311,896	32,337,817
33529	109.0356	80	0.55	0.83	0.94	0.98	0.99	31.3	17.2	26.1	29.5	30.7	31.1	311,896	34,007,767
33776	115.28024	80	0.57	0.85	0.95	0.99	1.00	6.6	3.7	5.6	6.3	6.5	6.5	311,896	35,955,446
34001	129.6299	80	0.61	0.88	0.97	0.99	1.00	7.7	4.7	6.8	7.5	7.6	7.7	311,896	40,431,047
37443	54.67388	80	0.33	0.59	0.77	0.87	0.93	23.3	7.7	13.9	17.9	20.3	21.7	311,896	17,052,564
38294	32.09008	200	0.21	0.41	0.57	0.70	0.79	69.4	14.5	28.5	39.7	48.3	54.6	400,586	12,854,837
39429	46.77406	80	0.29	0.54	0.71	0.82	0.90	7.0	2.0	3.8	5.0	5.8	6.3	311,896	14,588,642
39552	145.27639	80	0.65	0.91	0.98	1.00	1.00	26.2	17.1	23.8	25.6	26.0	26.1	311,896	45,311,125
39813	49.25891	80	0.30	0.56	0.73	0.84	0.91	67.3	20.3	37.4	49.1	56.5	61.0	311,896	15,363,657
39832	118.53681	80	0.58	0.86	0.96	0.99	1.00	32.7	19.0	28.1	31.3	32.3	32.6	311,896	36,971,157
39877	145.68834	80	0.66	0.91	0.98	1.00	1.00	35.8	23.4	32.5	35.0	35.6	35.7	311,896	45,439,610
39935	126.1108	80	0.60	0.87	0.96	0.99	1.00	0.0	0.0	0.0	0.0	0.0	0.0	311,896	39,333,454
39936	110.62522	80	0.55	0.84	0.95	0.98	1.00	26.2	14.5	21.9	24.8	25.7	26.0	311,896	34,503,564
40876	290.80768	100	0.88	0.99	1.00	1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	325,923	94,780,911
41224	160.30555	100	0.69	0.93	0.99	1.00	1.00	0.9	0.6	0.8	0.9	0.9	0.9	325,923	52,247,266
41299	345.92562	100	0.92	1.00	1.00	1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	325,923	112,745,116
41572	305.49313	150	0.89	0.99	1.00	1.00	1.00	14.9	13.3	14.8	14.8	14.8	14.8	364,851	111,459,474
41707	458.75987	200	0.97	1.00	1.00	1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	400,586	183,772,781
41851	469.91001	250	0.97	1.00	1.00	1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	442,144	207,767,891
42286	153.56323	300	0.67	0.92	0.98	1.00	1.00	657.8	443.7	605.4	646.6	655.6	657.4	485,482	74,552,184
42462	87.81167	350	0.47	0.76	0.90	0.96	0.99	1.4	0.7	1.1	1.3	1.4	1.4	533,812	46,874,923
42537	70.45317	350	0.40	0.69	0.85	0.93	0.97	15.0	6.0	10.3	12.7	13.9	14.5	533,812	37,608,748

Table 4 Continued

Link ID (Pipe)	Length (m)	Diameter (mm)	Probability of failure (PoF) PGV (cm/sec)					CoF (m³/failure)	Risk (m³/failure) PGV (cm/sec)					Unit construction cost Won/m	Total construction cost (Won)
			30	60	90	120	150		30	60	90	120	150		
42831	133.27595	400	0.62	0.89	0.97	0.99	1.00	765.1	476.2	680.0	742.7	759.7	763.8	616,206	82,125,440
43112	242.42779	80	0.83	0.98	1.00	1.00	1.00	200.0	166.0	196.3	199.7	200.0	200.0	311,896	75,612,258
43165	246.48448	100	0.83	0.98	1.00	1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	325,923	80,334,961
43220	243.95064	100	0.83	0.98	1.00	1.00	1.00	2.8	2.4	2.8	2.8	2.8	2.8	325,923	79,509,124
43221	347.5856	100	0.92	1.00	1.00	1.00	1.00	2.8	2.6	2.8	2.8	2.8	2.8	325,923	113,286,142
43384	317.91308	200	0.90	0.99	1.00	1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	400,586	127,351,529
43555	315.37258	250	0.90	0.99	1.00	1.00	1.00	454.3	409.0	451.8	454.2	454.3	454.3	400,586	126,333,840
43781	71.01976	350	0.40	0.69	0.85	0.93	0.97	1.4	0.6	1.0	1.2	1.3	1.4	533,812	37,911,200
43786	304.39553	350	0.89	0.99	1.00	1.00	1.00	0.4	0.4	0.4	0.4	0.4	0.4	533,812	162,489,987
43906	252.47191	500	0.84	0.98	1.00	1.00	1.00	132.1	111.2	130.0	131.9	132.0	132.0	723,638	182,698,268
44574	20.53937	100	0.14	0.29	0.42	0.53	0.63	0.0	0.0	0.0	0.0	0.0	0.0	325,923	6,694,253
44578	1.48914	100	0.01	0.02	0.04	0.05	0.07	0.0	0.0	0.0	0.0	0.0	0.0	325,923	485,345
44580	18.60884	100	0.13	0.26	0.39	0.50	0.59	2.8	0.4	0.7	1.1	1.4	1.7	325,923	6,065,049
44584	0.68404	100	0.00	0.01	0.02	0.03	0.03	200.0	1.0	2.2	3.6	5.0	6.5	325,923	222,944
44586	108.39006	500	0.55	0.83	0.94	0.98	0.99	200.0	109.4	166.5	188.7	196.5	199.0	723,638	78,435,166
44592	276.86139	200	0.87	0.99	1.00	1.00	1.00	69.4	60.2	68.6	69.3	69.4	69.4	400,586	110,906,797
44593	36.30611	200	0.23	0.45	0.62	0.74	0.83	69.4	16.2	31.2	42.9	51.4	57.3	400,586	14,543,719
46140	303.32533	100	0.89	0.99	1.00	1.00	1.00	269.0	239.7	267.1	268.9	269.0	269.0	325,923	98,860,702
46141	248.6029	100	0.84	0.98	1.00	1.00	1.00	269.0	225.3	264.5	268.6	268.9	269.0	325,923	81,025,403
47255	72.04847	80	0.41	0.69	0.85	0.93	0.97	67.3	27.5	46.8	57.3	62.7	65.2	311,896	22,471,630
47256	74.96932	80	0.42	0.71	0.86	0.94	0.97	31.3	13.2	22.2	27.0	29.3	30.4	311,896	23,382,631
47257	243.49519	100	0.83	0.98	1.00	1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	325,923	79,360,683
47258	222.45249	100	0.80	0.97	1.00	1.00	1.00	0.0	0.0	0.0	0.0	0.0	0.0	325,923	72,502,383
47259	292.837	150	0.88	0.99	1.00	1.00	1.00	0.9	0.8	0.9	0.9	0.9	0.9	364,851	106,841,872
47261	237.36413	400	0.82	0.98	1.00	1.00	1.00	765.1	630.1	749.8	763.6	764.9	765.1	616,206	146,265,201
47263	162.70714	500	0.70	0.93	0.99	1.00	1.00	200.0	139.1	186.3	197.3	199.5	199.9	723,638	117,741,069



(a)



(b)

Fig. 5 Priority decision using risk and construction cost for 600 mm diameter pipe at PGV = 30 for (a) and at PGV = 60 for (b)

Table 5 Grading for priority of pipe renewal

Zone	Risk	Cost	Total
A1	3	3	9
A2	3	2	6
A3	3	1	3
A4	2	3	6
A5	2	2	4
A6	2	1	2
A7	1	3	3
A8	1	2	2
A9	1	1	1

4. Conclusions

An earthquake destroys a water distribution system and results in various water outage large and small. In order to prepare for damage caused by earthquakes, calculating the possibility of failure and the consequence of failure are necessary. The pipe's material, the installation methods of joint type, pipe diameter, pipe wall thickness, depth of soil cover, pipe material, site characteristics, fault crossing, continuous and segmented pipe affect possibility of failure. In particular, it is better to utilize the empirical formula rather than the mechanical model that considers only a single variable. In this study, we used the empirical formula to calculate the vulnerability (i.e., possibility of failure) to the seismic intensity of pipe networks over time. This made it possible to find a pipe network vulnerable to earthquakes. The degree of water outage in the water distribution system is assumed to be a consequence of failure. It was possible to calculate the risk through their product. Although this risk alone may be used to prioritize pipe network improvement, but it is recommended that the construction cost is considered. In this work, we propose a score-based method by graphically tabulating construction costs and risks. The improved prioritization of the scoring method will help create a future earthquake preparedness plan for the water supply network.

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