A long-term plan for water pipeline rehabilitation considering preventive maintenance

Mincheol Kim, Toyono Inakazu, Akira Koizumi and Jayong Koo

ABSTRACT

Water pipelines deliver water of daily-life demand to customers. However, pipelines tend to be damaged after years of use. Thus, many waterworks are now faced with the major task of water pipeline rehabilitation. However, budgets for pipeline replacement are limited. The present study aims to propose a long-term plan for water pipeline rehabilitation under limited rehabilitation budgets that utilizes a damage occurrence model. Especially, this study attempts long-term rehabilitation planning by efficiently allocating a budget for pipeline rehabilitation. First, a simulation model is used to obtain the failure rate curve which uses reliability theory and data analysis for pipeline leakage accidents, and Monte Carlo simulation is applied to the simulation model. Secondly, in order to set the best planning, several cases with changed annual replacement rate are applied to this study. Finally, the simulation model is applied to key pipelines. The key pipelines are vital pipelines located in central districts. Thus, the replacement of key pipelines is considered to be the priority. From these steps, this study is expected to provide desirable alternative plans for water pipelines when the budget for replacement is limited.

Key words | affected population, failure rate, Monte Carlo simulation, replacement planning, water pipeline

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INTRODUCTION

The main purpose of water pipelines is to deliver water while satisfying demands for quality, quantity, and water pressure. However water pipelines age with the passage of time. Thus, many countries are now faced with the major task of water pipeline rehabilitation. Aged pipelines cause leakage and other problems for water supplies. Rehabilitation planning is needed to maintain these pipelines effectively. However, budgets for pipeline replacement are limited. Therefore, rehabilitation planning with greatly reduced economic cost is needed for effective budget allocation.

Several studies have presented and proposed different techniques in an effort to plan the rehabilitation of water pipelines. Shehab *et al.* (2010) developed a cost-estimating model for water and sewer pipelines that utilizes a neural network and regression model. Malm *et al.* (2012) proposed a future replacement model by using historical data. The replacement model utilizes survival functions to determine the percentage of a group of pipes that reaches a particular age.

The aim of the present study was to propose a long-term plan for water pipeline rehabilitation that utilizes a damage occurrence model. In particular, this study attempted long-term rehabilitation planning by efficiently allocating a budget for pipeline rehabilitation. Pipeline accidents that occur at unspecified times and places can be quantified by Monte Carlo simulation (MCS). The simulation model consists of post-damage maintenance (without replacement = repairing) and preventive maintenance (replacement). Unlike previous studies, our focus was on not only the economy aspect but also an assessment of the affected population. After conducting an evaluation from a benefit/cost perspective, we propose a highly effective rehabilitation plan.

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SIMULATION MODEL

This simulation model was used to obtain the failure rate curve based on Equation (1), which uses reliability theory and data analysis for pipeline leakage accidents (Arai *et al.* 2008):

$$h(t) = kt^c \ (k, c, t\text{: real number}) \tag{1}$$

where t is the pipe age, and k and c are the constants for each pipe material type. In order to consider various influences, such as the underground soil condition and traffic load above, Equation (1) can be expanded to Equation (2). Because these influences are shown at random time and space, we apply a probability distribution function adopting a variable (R) into Equation (2). A uniform random number [0, 1] is substituted for R in Equation (2). Damage or leakage of the pipeline can be expected to occur after the failure term is reached (Mori *et al.* 2010).

$$E = \left\{ \tau^{c+1} - \frac{(c+1) \cdot \ln(1-R)}{k} \right\}^{1/c+1} - \tau \ (E \text{ is the failure term}) \tag{2}$$

MCS was applied to this model following the number of future years from the start to the end of rehabilitation planning. To calculate the failure term utilizing MCS, R is substituted with a uniform random number generated by the Mersenne twister. τ denotes the pipe age in the start year of MCS.

The simulation model considers pipelines to be divided into virtual sub-items with a fixed length (Kim *et al.* 2011). The failure of each sub-item can be predicted by the failure rate function. We can then assume that breakage or leakage occur when sub-items reach the failure term, and the sub-items will undergo repairs. Some older sub-items will be replaced by SDIP (ductile cast-iron pipe (DCIP) with quake-proof joint) under a budget restriction of rehabilitation planning.

The total cost is obtained from the accumulated repair and replacement costs over the whole period of simulation. The unit cost of replacement (per pipeline length) and unit cost of repair (per failure) can be obtained from a function using the pipe diameter. On the other hand, when accidents occur on the pipelines, the total affected population is calculated by summing up the population living in the downstream area rather than in the damaged part.

This simulation model can also estimate the affected population in the future. In order to estimate the future population, the simulation model reflects the population decrease rate (PDR). Korea's population is expected to decrease in the future. In particular, population statistics for Seoul show that the population will decrease by 1% every 5 years (0.2%/year). Thus, PDR was assumed to be 1% per term in this study.

In order to efficiently set long-term rehabilitation planning, a simulation model with an analytical process was applied to several case studies, as shown in Figure 1.

DETERMINATION OF NUMBER OF ITERATIONS

MCS can yield more accurate results by increasing the number of iterations. However, this also increases the

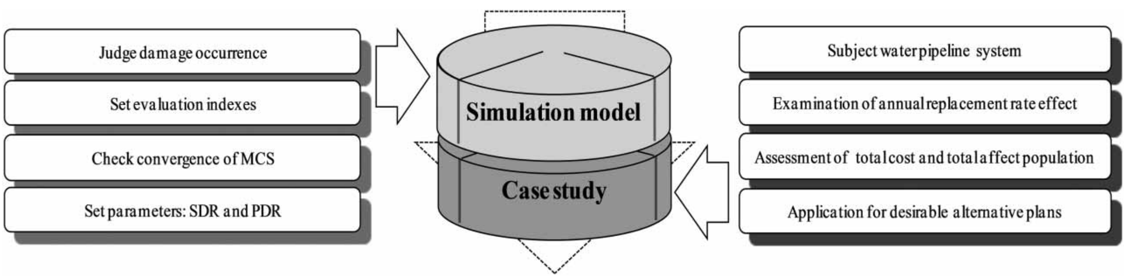

Figure 1 | Analytical process flow (SDR, social discount rate; PDR, population discount rate).

computation time. Therefore, an appropriate number of iterations is needed to effectively calculate the results against time. The number of iterations was determined in the following steps:

1. The study period was set to 10 terms over 50 years (1 term = 5 years).
2. The scenario focused only on pipeline repair (without replacement).
3. MCS initially calculated 1,000 iterations.
4. The number of iterations was determined against the result of 1,000 iterations (margin error ±0.5%).

In step 3, 1,000 iterations were empirically found to be sufficient in this study.

The study focused on a simulated pipeline system, as shown in Figure 2. The system consisted of one reservoir, 21 nodes, and 21 pipes. Pipelines '1–17' were made of cast-iron pipe (CIP) and the other pipelines were made of DCIP. The population was assumed to be about 48,000 people.

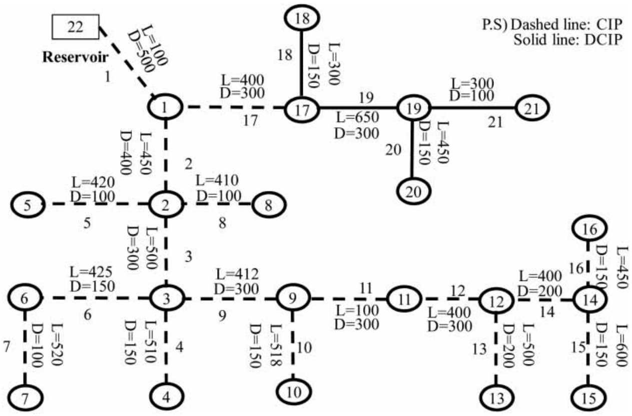

Figure 2 | Simulated pipeline system.

The simulation results according to the above steps are described next. First, Figures 3 and 4 show the average total cost (ATC) over 50 years and average total affected population (ATAP) over 50 years, respectively, based on 1,000 iterations.

The above graphs show that the ratio curve was in the margin of error (±0.5%) after 300 iterations. In other words, by 300 iterations we can get the result with a quite acceptable margin of error.

In MCS, selected data should make up a normal distribution. In order to confirm the data distribution, a histogram was applied to the obtained results. In order to confirm the determined number of iterations, the histograms were drawn according to the number of iteration times without replacement, as shown in Figure 5. If the distribution for a determined number of iterations is similar to that for 1,000 iterations, the number of iterations can be judged as being appropriate. Histograms were drawn according to the average number of total pipe failures.

The histogram results were also evaluated by referring to a statistics table, as shown in Table 1. A comparison of the mean values showed that the mean value for 300 iterations was almost the same as that for 1,000 iterations. In conclusion, 300 iterations was found to be appropriate in this study.

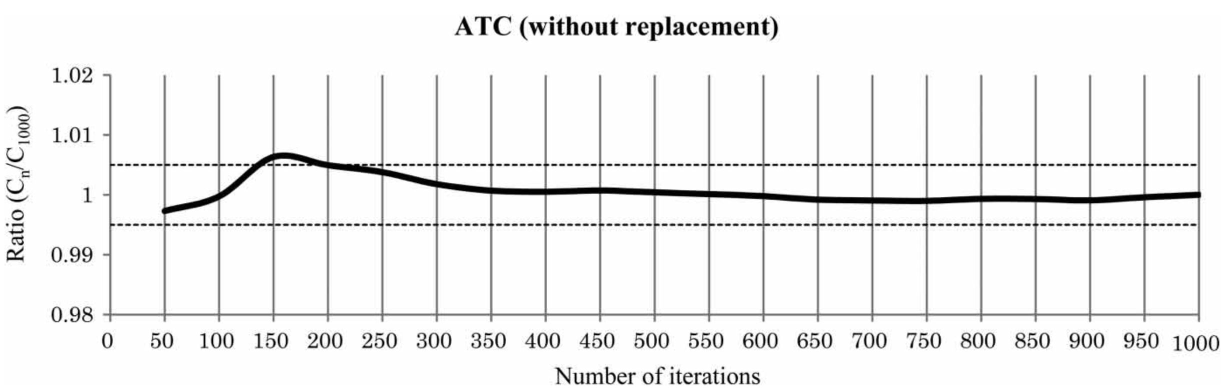

Figure 3 | ATC ratio until 1,000 iterations.

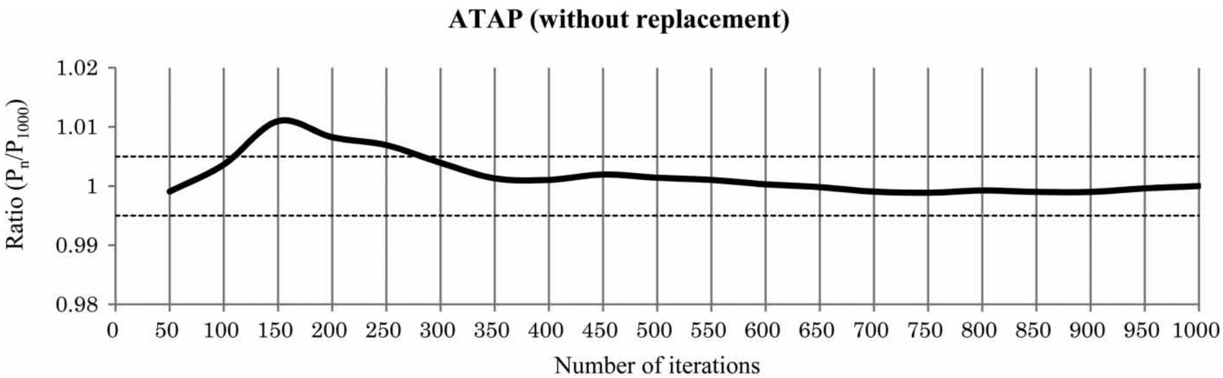

Figure 4 | ATAP ratio until 1,000 iterations.

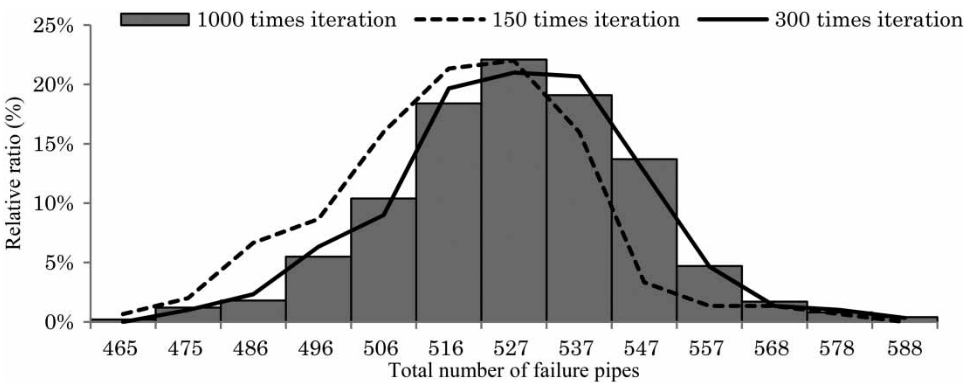

Figure 5 | Histograms for total number of failure pipes at each iteration time.

Table 1 | Statistics table for histograms

	150 iterations	300 iterations	1,000 iterations
Mean	523.42	521.83	521.89
Standard deviation	19.12	18.67	19.06
Max	588.00	588.00	588.00
Min	471.00	468.00	465.00

EXAMINATION OF REPLACEMENT RATE EFFECT

To compare the effect of replacement rate, seven cases for the annual replacement rate were set (without replacement, 0.5, 1, 1.5, 2, 2.5 and 3%). The ATC and ATAP were calculated and compared over the entire simulation term for each case. MCS was performed by using a random number with the same number of seeds for each case. Figure 6 shows the average total repair cost and total replacement cost at each annual replacement rate.

The average total repair cost decreased according to the annual replacement rate, but the average replacement cost increased. Moreover, the ATC (average total repair cost + average total replacement cost) also decreased up to 2%. On the other hand, the ATC increased from 2.5%. At 2.5%, even though the average total repair cost was smaller than that at 2%, the average total replacement cost was higher than that at 2%. The second cycle of replacement restarted because the first cycle finished by 40 years. Thus, the ATC increased again from 2.5%. In conclusion, 2% is the most economical replacement rate. Below, Figure 7 shows the ATC and ATAP results.

Figure 7 also contains the ATAP for each case. For example, the ATAP at 1% is almost half of the ATAP without replacement, and it means that the risk of water supply

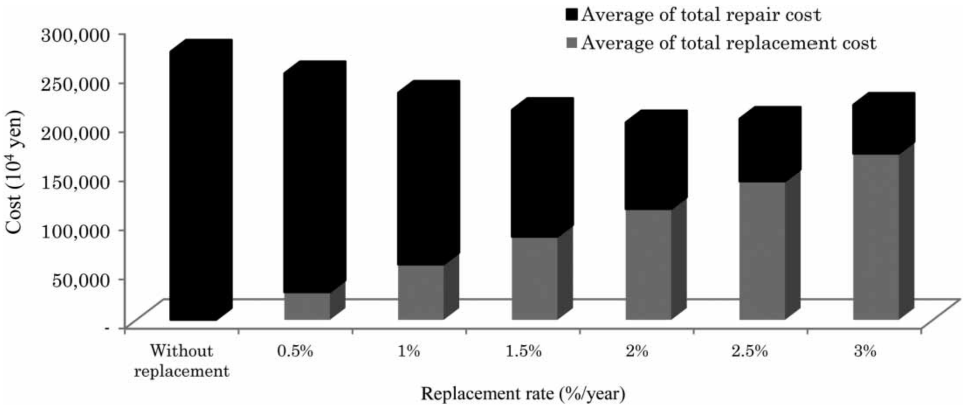

Figure 6 | Results for average cost at each replacement rate.

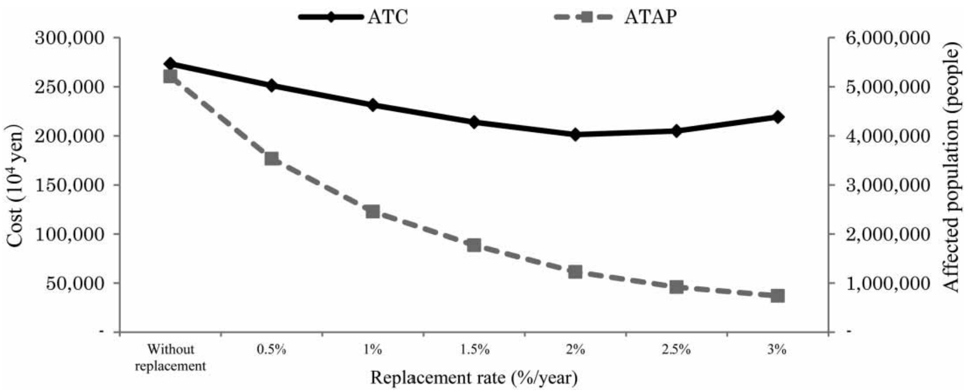

Figure 7 | ATC and ATAP results for each case.

interruption at 1% is supposed to be almost half of the risk without replacement. So the gap of ATAP (ΔP) between some replacement case and without replacement case is used as an index of the benefit by replacement of water pipes. In general, the evaluation of planning depends on the level of efficiency by a ratio of benefit to cost. In the study, we calculated $\Delta P/C$ in order to evaluate the effect of a promotion of replacement planning. Table 2 shows the obtained $\Delta P/C$ for each replacement rate. The results show the cases in order from greatest to smallest $\Delta P/C$: 2.5, 2, 1.5, 3, 1, and 0.5%. In conclusion, the 2.5% case was the most effective one to offer benefit in proportion to investment.

Table 2 | Results of ΔP/Cost

Replacement rate (%/year)	ATC (10^4 yen)	ATAP (people)	ΔP (people)	$\Delta P/C$ (people/10^4 yen)
Without replacement	273,227	5,210,165		
0.5	251,177	3,532,256	1,677,909	6.68
1	231,331	2,456,843	2,753,322	11.90
1.5	213,863	1,771,257	3,438,908	16.08
2	201,159	1,227,494	3,982,671	19.80
2.5	204,800	917,605	4,292,560	20.96
3	219,087	740,984	2,791,273	12.74

To investigate the effect of the PDR in the simulation, sensitivity analysis was carried out for seven cases, as presented in Table 3. The entire study area consists of a central district and other districts. Future population growth or decrease may be dependent on the economic condition change and the organization of city planning projects in the study area. Cases '2–5' and the standard case were applied with the same value of the PDR over the entire

Table 3 | Change in future population under each case

Case	Standard	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Central district	1%/term decrease	5%/term decrease	2%/term decrease	Constant	1%/term increase	2%/term increase	5%/term increase
Other districts	1%/term decrease	3%/term decrease	2%/term decrease	Constant	1%/term increase	2%/term increase	3%/term increase

area. For case 6, different PDR values were applied based on a supposition of the increasing centralization of the population. And case 1 was the opposite hypothetic case.

The results are shown in Figure 8. In all PDR cases, ATAP is gradually decreased according to the increase of replacement rate. $\Delta P/C$ was then calculated again according to the changed PDR. The results are shown in Figure 9. Judging by $\Delta P/C$ in Figure 9, all of the PDR cases indicate that the 2.5% annual replacement rate is the best scenario with high efficiency. In other words, the sensitivity analysis results showed that the future population growth or decrease (the settings of PDR) do not have an important effect upon the selection of the most efficient case of replacement rate.

For most waterworks, the replacement cost of pipes reaches a large percentage of total budgets and the economy aspect is the most important factor under the severe restrictions. From this economy preferential viewpoint, this study found 2% to be the most reasonable replacement rate.

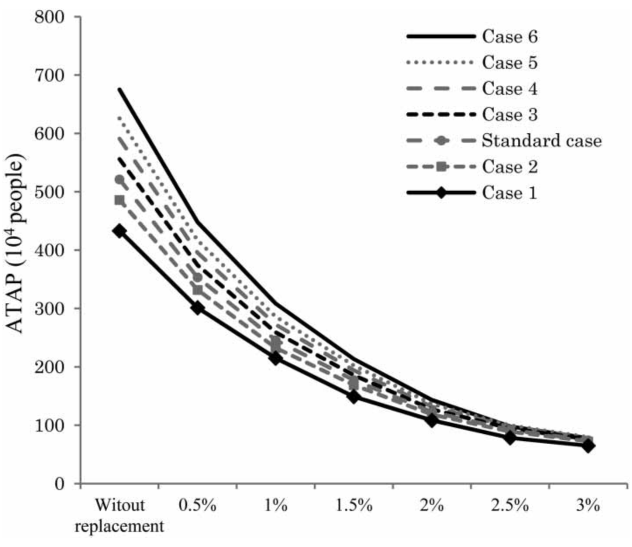

Figure 8 | Tendency of sensitivity analysis.

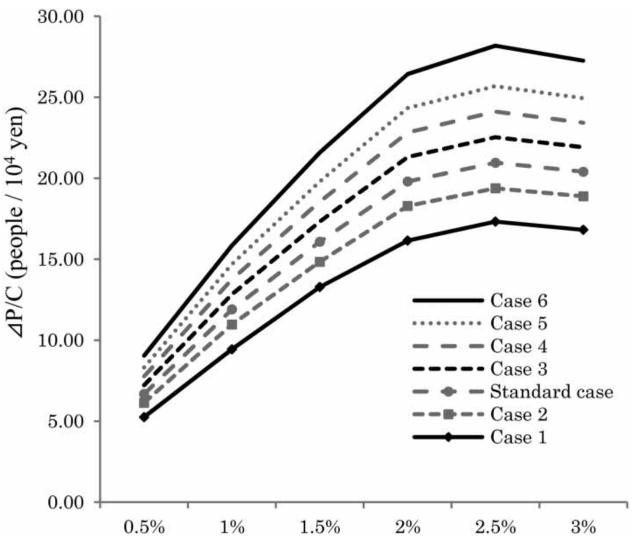

Figure 9 | Changed ΔP/C values.

APPLICATION FOR KEY PIPELINE REPLACEMENT PLANNING

Key pipelines are vital pipelines located in central districts with public establishments distributed densely around them, such as hospitals, schools, and government organizations. If accidents occur on key pipelines, the damage is serious. Thus, the replacement of key pipelines is considered to have the priority.

A simulation model was applied to key pipelines. Specifically, pipelines 1, 17, 18, 19, 20, and 21 in Figure 2 were considered to be key pipelines and given the utmost priority for replacement. Regardless of the fact that non-key pipelines are also renewed at the same time, we established five

Table 4 | The allocation of budget for the key pipelines and non-key pipelines

Ratio of budget allocation (%)	Term	1, 2	3	4	5	6	7	8	9	10
Key pipeline/non-key pipeline	3 TBA	100/0	47/53	0/100	0/100	0/100	0/100	0/100	0/100	0/100
	4 TBA	62/38	62/38	62/38	0/100	0/100	0/100	0/100	0/100	0/100
	6 TBA	41/59	41/59	41/59	41/59	41/59	0/100	0/100	0/100	0/100
	8 TBA	31/69	31/69	31/69	31/69	31/69	31/69	31/69	0/100	0/100
	10 TBA	25/75	25/75	25/75	25/75	25/75	25/75	25/75	25/75	25/75

scenarios for the prioritized key pipelines to be completely replaced by 3, 4, 6, 8, and 10 terms of budget allocation (hereafter TBA). The budget allocation method is described in Table 4. For example in the case of 4-TBA, in '1–4' term 62% of annual budget is allocated for key pipelines replacement with 38% allocation for non-key pipelines, and after fully completing key pipeline replacement (in '5–10' term) full annual budget is used for non-key pipelines replacement. The overall annual replacement rate was set at 2% in order to replace each pipe once in 50 years (planning period in this study). Replacement of the non-key pipelines occurred in order of age of the pipeline.

These five scenarios were implemented using MCS with 300 iterations under the condition that PDR was 1%/term. As shown in Figure 10, the most economical scenario was 10-TBA for the entire area. On the other hand, ATAP for key pipelines was smallest at 3-TBA. In other words, the 3-TBA scenario provided the minimum risk for key pipelines. Because the difference in ATC values is rather small and the most important objective is to minimize the affected population, the most reasonable scenario is 3-TBA in conclusion. This result indicates that in terms of the impact on society the prioritizing replacement of key pipelines requires a higher total cost than that in the normal case.

CONCLUSIONS

In the present study, a long-term planning method for water pipelines is proposed. Unlike other studies, our study considered not only the economy aspect but also the aspect of society impact. In order to set the best long-term planning of water pipeline rehabilitation with preventive maintenance, the simulation model and simulated pipeline system were proposed. The simulation model involved the post damage maintenance and the maintenance prevention, utilizing a failure rate curve. Moreover, because the failure of pipelines is influenced by various factors, the failures of the pipeline were calculated by MCS. On the other hand, the simulated pipeline was composed of CIP and DCIP

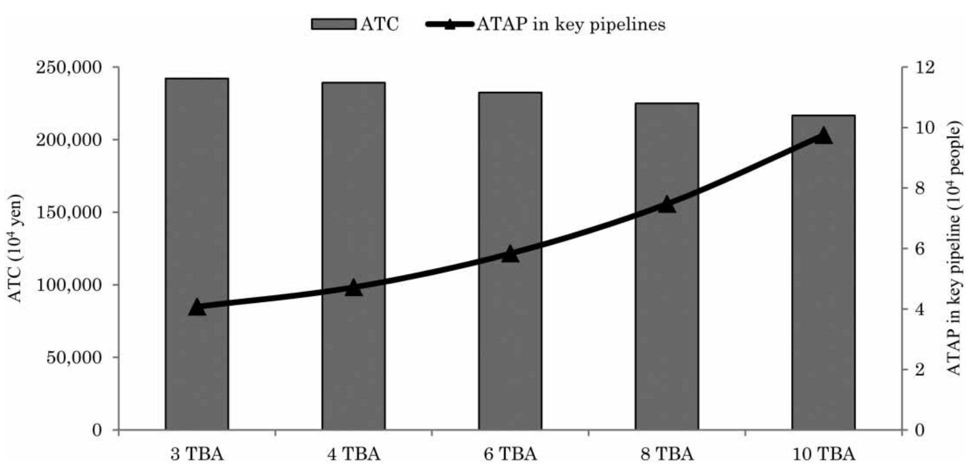

Figure 10 | Comparison of the ATC and ATAP for key pipelines.

and the project period was set to 10 terms over 50 years. Using the simulation model and the simulated pipeline system, several scenarios were set by annual replacement rate which were under the same conditions. Under each scenario, the occurrences of pipeline failure were simulated and the ATC and the ATAP were calculated by MCS. Then in case of key pipelines, replacement planning was simulated in the same way.

As a result, an examination of the replacement rate revealed that although 2% was found to be the most economical replacement rate, 2.5% is the most effective rate for damage prevention and maintenance of pipelines. In the case of prioritized replacement of key pipelines, although the 10-TBA scenario was the best in terms of economics, the 3-TBA scenario was the best in terms of the impact on society. The present study is expected to provide desirable alternative plans for water pipelines when the budget for replacement is limited, by considering future conditions in the study area.

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