Estimation of Priority Rank of Water Pipeline Replacement through Risk Analysis

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Water pipeline is the most important infrastructure in our daily life. However, pipeline deterioration is now causing problems for water supply service in Korea. Aged water pipelines need to be efficiently replaced to prevent problems. The present study aims to introduce efficient, gradual pipeline replacement plans, particularly analyzing risks through predicting the number of pipeline damages, the restoration time and water shortage volume. The results were put together and the overall risk ranking was estimated using predicted risk index (PRI). As a result, the highest PRI was given the highest priority for replacement. From these analyses, pipelines were assessed and given a risk ranking. In order to confirm replacement effects utilizing the PRI order, the Monte Carlo simulation was applied to three case studies with changed replacement order. Due to the random occurrence of pipeline accidents in terms of space and time, the Monte Carlo simulation can yield approximate solutions. The results of the Monte Carlo simulations in each case allowed us to confirm the effects of replacement in order of PRI, and can contribute to the decision-making concerning pipeline replacement plans for distribution networks.

Key Words : failure rate, pressure dependent demands, PRI, replacement planning, distribution network

1. INTRODUCTION

(1) Background and purpose

The water pipeline is the most basic facility of social infrastructure. With the increasing quality of life, the level of consumer demand is also increasing. While water supply services work to supply sufficient high-quality water to meet demands, they are facing difficulty due to the deterioration of the water distribution network, particularly in the case of water pipelines laid in the 1970s during rapid industrialization in Korea. These aged water pipelines are approaching 40 years in use, which is the standard facility age of water pipelines as proposed by the enforcement regulations for local public enterprises¹). The biggest problem with aged pipelines is the occurrence of accidents such as water leakage or pipeline burst, leading to financial loss and inconvenience for consumers who are supplied by the water pipelines in question. The current reported average revenue water ratio in Korea is 83.5% and most of the non-revenue water ratio is caused by leakage from aged waterworks facilities in the water distribution system²).

To prevent these problems, water pipelines must be efficiently replaced. In the past, replacement commenced from the oldest buried water pipeline. However, given the complex natural and artificial factors that influence water pipeline accident, water pipelines must be analyzed in conjunction with priority plans. Nazif and Karamouz quantified the readiness of systems for disasters. This readiness was developed into an algorithm based on three system performance indexes of reliability, resiliency, and vulnerability³); Choi et al. expanded this research by proposing new factors to formulate a reliability index
that can be applied to small water pipeline networks.

Unlike previous studies, the present study introduced pipeline risk with quantitative approach. In addition, future replacement plan with an order of replacement was also set by quantitative rank of risks. Since pipeline accidents occur at random times and spaces, the Monte Carlo simulation was also applied. The aim of this study is to help the stable establishment of efficient water pipeline replacement plans.

(2) Study area

This study was conducted by analyzing data collected from the diagnosis of water pipeline defects in City S in Korea conducted between 2009 and 2010. City S is composed of 127 small blocks. The present study chooses one small block as the study area among 127 small blocks (Fig.1).

The small blocks in this study area is supplied about 2400 m³ of water every day. The water pressure ranges from 280kPa to 440kPa. This research focused only on the water distribution pipelines, excluding transmission pipelines without service line branch and service pipelines of 75mm or less. The water distribution system was also simplified by excluding transmission pipelines and service pipelines. Table 1 shows the data of the studied network with only distribution pipelines.

<table>
<thead>
<tr>
<th></th>
<th>Distributed amount (m³/day)</th>
<th>Total length (m)</th>
<th>DCIP ratio* (%)</th>
<th>Range of diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>City S</td>
<td>345,968</td>
<td>1,111,432</td>
<td>88</td>
<td>80 to 1200</td>
</tr>
<tr>
<td>Small block</td>
<td>2,400</td>
<td>7,832</td>
<td>100</td>
<td>80 to 300</td>
</tr>
</tbody>
</table>

* Ductile cast iron pipe (DCIP) length / Total length

2. RISK ANALYSIS

First, the present study defined pipeline accidents as pipeline damages cause of natural leakage or burst. In order to maintain or prevent the pipeline accidents, it is necessary to repair quickly at leakage point or set plan of pipeline replacement. As in the previous step of this analysis, pipelines with high accidents rate were analyzed for entire distribution area considering soil environments and replacement rate by economic evaluation. In order to determine priority of replacement pipelines in a small block, this study aims to quantify the impact on water consumers in pipeline accident. Because the study area is mostly residential area, suspension or reduction of working pipeline accidents was not concerned in this study.

Three representative indexes for risk analysis of pipeline network were selected from existing researches to examine firstly, how many times does pipeline damage occurs; secondly, how long does it takes to repair damaged pipelines; and lastly, how much water shortage is caused by damaged pipelines. This study carried out quantitative risk analyses using these three indexes according Fig.2.

The small block is composed of 142 water pipelines. Pipeline No. 142, particularly, is directly connected to the transmission pipeline, so that all water supplies will be blocked if this pipeline is destroyed. Consequently, No. 142 pipeline is the most significant pipeline and the establishment of a special emergency plan was deemed necessary. Given this, No. 142 pipeline was thus excluded from the risk analysis.

![Fig.2 Flowchart of this study by risk analysis](Image)
(1) Prediction of the number of pipeline damages

In this study, a failure curve was obtained through a survey on waterworks departments in order to predict the failure time of pipelines. According to reliability engineering, the failure rate is given by Eq. 1a. In this study, Eq. 1a was judged appropriate prediction model of pipeline damages because it has an around 0.9 correlation coefficient with actual data from the paper of Arai et al.6). For this study, the pipeline is divided into a constant length (4m here) of virtual sub-items, and it is assumed that accidents occur in each sub-item. In paper of Arai et al.6) the failure rate (%/year) is expressed as Eq.1a conducted from reliability engineering. Assuming that each accident occurs at each sub-item, the failure rate is converted into the number of accidents per year (number/km/year). The constants $a$ and $b$ were estimated for each type of pipe material from the data of regression analysis of past accidents. The expected number of damage occurrences is then calculated as Eq.1b.

\[ h(t) = a t^b \]  
\[ N = \int_{t_1}^{t_2} a (\tau + t)^b \, dt \]

where, $t$: degree of time, $\tau$: age of pipeline, $N$: the total number of damaged sub-items from $t_1$ to $t_2$.

(2) Prediction of restoration time

When accidents on pipeline occur, the service must be quickly restored to normal. If the restoration time is delayed, the incurred consumer damage will increase and add a risk factor to maintenance management.

The accident restoration time is influenced by complaint registration, transportation time to accident area, human factors such as manpower, depth of pipeline burial, pipeline diameter, road width, packaging type of buried land, and numerous other pipeline burial-related environmental factors. This study excludes human factors and focuses on the pipeline burial, pipeline diameter, road width, dent area, human factors such as manpower, depth of pipeline burying, and multiple regression equation that is then applied to analyze past records of accidents to generate a prediction model of pipeline damages because it has an around 0.9 correlation coefficient with actual data from the paper of Arai et al.6). For this study, the pipeline is divided into a constant length (4m here) of virtual sub-items, and it is assumed that accidents occur in each sub-item. In paper of Arai et al.6) the failure rate (%/year) is expressed as Eq.1a conducted from reliability engineering. Assuming that each accident occurs at each sub-item, the failure rate is converted into the number of accidents per year (number/km/year). The constants $a$ and $b$ were estimated for each type of pipe material from the data of regression analysis of past accidents. The expected number of damage occurrences is then calculated as Eq.1b.

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(3) Prediction of water shortage volume

Water shortage volume was predicted to investigate the influence on consumers until the pipeline accident is restored. Water shortage in a water distribution system occurs due to the lockage of valves in accident pipelines during restoration, causing an isolated demand point in this process. This is called a direct water shortage. Meanwhile, an accident in a pipeline can result in decreasing water pressure in nearby pipelines. This is called an indirect water shortage. For this study the pressure dependent demands (PDD) model of WaterGEMS V8 commonly used software7) for hydraulic analysis of water distribution system was used to estimate direct and indirect water shortage volume.

Most water distribution analysis programs used in the field are conducted with the demand dependent analysis (DDA) model. The DDA model8) is a way to calculate the head under the assumption that water demand at each node is always satisfied (Eq.2a), but has problems when the water distribution is abnormal.

On the other hand, the PDD model9) assumes that demand at each node is fully satisfied only if the minimum required water pressure at that node is satisfied (Eq.2b). Otherwise, demand at the node is partially satisfied by relational formula between nodal demand and water pressure. This model is more reliable than the DDA model when the water distribution is abnormal, such as due to a pipeline accident.

### Table 2 The statistics of items for multiple regression analysis

<table>
<thead>
<tr>
<th>Independent variable</th>
<th>Unit</th>
<th>Variable</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laying depth</td>
<td>(m)</td>
<td>$X_1$</td>
<td>1.22</td>
<td>0.7</td>
<td>1.8</td>
</tr>
<tr>
<td>Road width</td>
<td>(m)</td>
<td>$X_2$</td>
<td>13.3</td>
<td>4</td>
<td>39</td>
</tr>
<tr>
<td>Diameter</td>
<td>(mm)</td>
<td>$X_3$</td>
<td>167.5</td>
<td>80</td>
<td>300</td>
</tr>
</tbody>
</table>
\[ Q'_i = Q_i \]  
(2a)

\[ \frac{Q'_i}{Q_i} = \begin{cases} 
0 & \text{if } H_i \leq 0 \\
\left( \frac{H_i}{H_p} \right)^a & \text{if } 0 < H_i < H_p \\
1 & \text{if } H_p \leq H_i 
\end{cases} \]  
(2b)

where, \( H_i \): calculated pressure at node \( i \), \( Q_i \): requested demand at node \( i \), \( Q'_i \): calculated demand at node \( i \), \( H_p \): pressure threshold above which the demand is independent of nodal pressure (input parameter), \( a \): exponent of pressure demand relationship \( 9 \).

In this study an accident occurrence on each pipeline is assumed and a simulation was conducted by blocking the water flow in the accident pipeline. The water shortage was calculated by below equation (Eq.3).

\[ \Delta Q_j = \sum_{j=1}^{n} Q_{ri} - \sum_{i=1}^{n} Q'_{ji} \quad (j = 1, 2, ..., n) \]  
(3)

where, \( \Delta Q_j \): water shortage volume when accident occurred on \( j \) pipeline, \( Q'_{ji} \): calculated water at node \( i \) when accident occurred on \( j \) pipeline, \( m \) and \( n \): the number of nodes in the water distribution network and the number of pipelines respectively.

The Korean Waterworks facility standard proposes a minimum dynamic water pressure of 300–350kPa for direct water supply to a 5-story building \( 10 \). The maximum height of direct water supply was assumed to be 5 stories in this study area; thus, the pressure threshold \( (H_p) \) was set at 300kPa. Besides, this study was utilized actual GIS information of study area in order that the hydraulic analysis of water distribution system is able to be corresponded with actual condition of the study area.

Water shortage due to pipeline accidents was also ranked from the largest to the smallest amount of shortage.

(4) Calculation of predicted risk index (PRI)

Each risk ranking was obtained through 3 risk analyses. However, each analysis has a different risk ranking, requiring an overall risk ranking to balance each risk ranking. Consequently, the predicted risk index (PRI) was introduced in this study to estimate the overall risk ranking. PRI is a quantitative approach used to compensate for the method of deriving overall risk ranking from obtained risk analysis.

In this study, the PRI was calculated by multiplying the expected number of pipeline damages with the restoration time and amount of water shortage. That is, the PRI in this case indicates the water shortage in the future period from \( t_1 \) to \( t_2 \).

\[ PRI_j = N_j \times RT_j \times \Delta Q_j \quad (j = 1, 2, ..., n) \]  
(4)

where, PRI\(_j\): amount of water shortage when accident occurs on \( j \) pipeline (m\(^3\)), \( N_j \): expected number of damage occurrences on \( j \) pipeline, \( RT_j \): restoration time (hr.), \( \Delta Q_j \): water shortage volume (m\(^3\)/hr.), \( n \): the number of pipelines.

(5) Examination of replacement order effect

Before the study, annual replacement rate was proposed considering the budget of pipeline replacement. The average pipeline age is around 20 years in this study area, so there is no need to start pipeline replacement immediately. This study assumes pipeline replacement to start after 20 years and the period of the replacement project is set for the next 60 years, because in order to match the useful life of the latest DCIP. In the simulation, pipelines of study area are not replaced in the first 10 years due to the budget of other small blocks. After that, pipeline replacement is simulated for the next 25 years, with no replacement for following 25 years. So after 60 years, the replacement plan will be reconsidered for the next 60 years.

In order to compare the effect of replacement order, three scenarios were set: (A) 4%/year replacement in order of aged pipeline, (B) 4%/year replacement in order of PRI, and (C) without replacement. Here, “without replacement” (Scenario C) means that pipelines are not replaced but repaired after damage according to their age, whereas in other scenarios the considerably few damaged pipelines are repaired after replacement. These scenarios also help confirm the effect of the replacement order.

In addition, the Monte Carlo simulation was applied in this study. Since pipeline accidents occur at unspecified times and places randomly, the Monte Carlo simulation was used to approximate solutions such as for pipeline damages. Moreover the Monte Carlo simulation can be help to consider various influences, such as the underground soil condition, traffic load above and pipeline life. As mentioned before, pipeline damages can be predicted by using Eq.1a.

To calculate pipeline damages utilizing the Monte Carlo simulation, the present study assumes that a pipeline at the age of \( \tau \) (year) will be damaged after the failure time \( (E) \). And then the probability of failure \( (R) \) from \( t \) to \( t+\Delta t \) is expressed as Eq. 5a.

\[ R = 1 - \exp \left[ - \sum_{j=1}^{n} h(t) \Delta t \right] \]  
(5a)

The failure time \( (E) \) is calculated under various influences such as the underground soil condition and traffic load above. Moreover \( R \) is distributed
within range between 0 and 1. Therefore using the inverse function of Eq.5a, the failure time \( E \) is obtained from Eq.5b through substitution of uniform random number \([0~1]\) for \( R \).

\[
E = \left( \frac{\beta \alpha + 1}{\alpha} - \frac{\beta + 1}{\alpha} \ln(1 - R) \right)^{-\frac{1}{\beta + 1}} - \tau
\]  

(5b)

where, \( E \): failure time, \( R \): uniform random number, \( \tau \): age of pipeline, \( \alpha \) and \( \beta \): constants corresponding to the pipe material.

In this study the Monte Carlo simulation ran at 1000 iteration times, which was empirically found to be sufficient. In order to evaluate each scenario (A, B, C) the averages of each iteration result are used as the expected values in the future.

3. RESULTS AND DISCUSSION

(1) Results of the prediction of the number of pipeline damages

The number of pipeline damages occurring in 60 years without replacement could be predicted by synthesizing each failure rate of pipelines. The results are shown in Fig.3. Risk ranking is obtained by descending order of pipeline damages number.

For pipeline No. 118, nearly six damage incidents were predicted with the highest risk. On the other hand, pipeline No. 3 was predicted with almost zero occurrence of pipeline damage in 60 years, which is the last rank in the risk ranking. This indicates that No. 3 pipeline has minimum risk in this study area.

(2) Results of restoration time prediction

Prior to the regression analysis, a correlation analysis was carried out. In order to examine this model to determine whether it is likely to be linear or non-linear, the correlation coefficient of the logarithmic data of independent variables was also estimated as shown in Table 3.

As the above results, the restoration time \( Y \) has a non-linear relation with road width \( X_2 \). Based on the results of the correlation analysis, a multiple regression analysis was then carried out. 145 samples were used for estimation obtaining non-linear Eq.6.

\[
Y = -5.575X_1 + 2.893\log(X_2) + 0.016X_3 + 9.238
\]  

(6)

The variance analysis results were examined to verify the statistical significance of the regression equation. The result showed a significant probability of 0.000 (\(<\alpha=0.05\)). This means that the regression model is admissible for this study.

Eq.6 was applied to all pipelines of the study area and the predicted restoration times were obtained (see Fig.4). The average restoration time of the pipelines in the study area was about 7 hours.

Pipeline No. 4 with a diameter of 300mm buried at a depth of 1.3m under a 45m-wide road showed a restoration time of almost 11 hours, which was the longest predicted time. In contrast to that, Pipeline No. 121 with a diameter of 80mm buried at a depth of 1.7m under a 5m-wide road showed a restoration time of almost 3 hours, which was the shortest.

(3) Results of water shortage volume

First, water distribution system analysis...
conducted using the PDD method in the normal state with 300kPa pressure threshold of each node without damage in any pipeline. As a result, the total amount of supplied water was 2240m³/day. There was no difference between the DDA and PDD water distribution system analyses in the normal state.

To estimate the water shortage that will occur due to pipeline damages in this study area, each pipeline from No. 1 to No. 141 was assumed to have been damaged once at a time using the PDD method. The results are shown in Fig.5.

Fig.5 shows groups in order from the largest to the smallest amount of water shortage in the bold line, bold dotted line, line with triangle and dotted line. If the bold lines were damaged by accident, the amount of water shortage would be over 14m³/day. And then the bold dotted line was indicated that the amount of water shortage would be over 3m³/day, and pipelines which have over 2m³/day water shortage were expressed lines with triangle. On the other hand, in the case of dotted lines, there are 71 pipelines and amount of water shortage would be under 2 m³/day.

Pipeline No. 1 in particular is in a very important location as it is directly connected with pipeline No. 142 and the result shows that this pipeline would have the greatest water shortage of 186.81m³/day (8.3%). This analysis revealed that the water shortage is strongly influenced not only by the pipeline diameter or the distance of the connected pipe to the transmission pipeline, but also by the complicated configuration of the distribution network.

Fig.5 Network of predicted water shortage volume

(4) Results of PRI

Using Eq.4, the PRI of each pipeline was calculated to decide the ranking of the largest water shortage. The results are shown in Fig.6.

The PRI results predicted pipeline No. 1 would have the highest risk because of the highest water shortage. On the other hand, pipeline No. 3 was predicted with the lowest risk in 60 years. Based on the above results, the priority of pipeline replacement can be set by the PRI. The highest PRI was given the utmost priority for replacement. These results also present the estimated priority of the replacement of each pipeline from 1st to 141st rank (excluding pipeline No. 142). Consequently, the pipeline with No. 1 risk ranking should be the first to be replaced.

![Fig.6 Calculation of PRI](image)

(5) Examination of replacement order effect

The study period was set to 12 terms over 60 years (1 term = 5 years), and Monte Carlo simulation was conducted for scenarios A, B, and C. As mentioned before, the study set the rate of annual replacement at 4%, the replacement period from 3 terms to 7 terms for 25 years, which was expected in the balance of all small blocks. From these Monte Carlo simulations, the expected value of pipeline damages for each term in each case was obtained. Following this, the restoration time, the water shortage, and the PRI were calculated and compared over the entire simulation term for all three cases.

Table 4 indicates the details of the standard grades for the replacement order and their average values. In scenario A the older pipes would be replaced at an earlier term, and pipes of same age with a larger diameter will have priority. In scenario B, whose priority is PRI, some of the older pipes with fewer risks to consumers would be replaced after the replacement of the newer pipes with greater risks.

<table>
<thead>
<tr>
<th>Group (Order of replacement)</th>
<th>Rank of risk</th>
<th>Scenario A</th>
<th>Scenario B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. diameter (mm)</td>
<td>Avg. age (years)</td>
<td>Avg. diameter (mm)</td>
<td>Avg. age (years)</td>
</tr>
<tr>
<td>1st</td>
<td>1-30</td>
<td>108</td>
<td>25</td>
</tr>
<tr>
<td>2nd</td>
<td>31-60</td>
<td>80</td>
<td>24</td>
</tr>
<tr>
<td>3rd</td>
<td>61-90</td>
<td>84</td>
<td>22</td>
</tr>
<tr>
<td>4th</td>
<td>91-120</td>
<td>149</td>
<td>17</td>
</tr>
<tr>
<td>5th</td>
<td>121-142</td>
<td>148</td>
<td>12</td>
</tr>
</tbody>
</table>
Fig. 7 shows the accumulated number of pipeline damages for each scenario. In the case of scenario C, the line sharply rises as the time lapses along the terms, showing acceleration of the number of damages. On the other hand, the two other scenarios show a deceleration after 4 or 5 terms as a result of replacement. In other words, Fig. 7 clearly demonstrate that, in the case of the network studied, reducing pipeline accidents by replacement is effective after up to 50% of pipeline replacement has been attained. The effect is expected to be consistently maintained until the end of the period planned.

![Fig.7: The accumulated number of pipeline damages](image)

To investigate the effect of replacement order in this study, a graph showing the accumulated PRI was drawn, as shown in Fig. 8. In the case of scenario C, the PRI also accelerated according as time lapsed along the terms. In scenario A, the line increases until the end of 6 terms and decelerates from the 7th term. However, in scenario B, the line decelerates after 3 terms. The effect of replacement order by PRI is clearly demonstrated by these results. When comparing the two graphs, there is a difference between scenarios A and B. From Table 4 we can see that in scenario A there is a tendency to replace pipelines from ones with small diameters, but in the case of scenario B it is the opposite, i.e. replacement would tend to begin from pipeline with large diameters. In this way, it is evident that PRI is more affected by diameter than pipeline age. In other words, if we consider the PRI for scenario A, replacement would not become effective until the end of 6 terms, while for scenario B we can expect to obtain stabilized effectiveness with very little water shortage after 3 terms.

![Fig.8: Results of accumulated PRI](image)

Finally, the numbers of pipeline damages, restoration time, water shortage, and PRI for each scenario are given in Table 5 to show the effect of replacement. In the case of scenario B, the restoration time is a little longer than in scenario A, indicating that replacement in order of PRI can give us desirable alternatives for preventing the risks.

### Table 5: Total of expected values

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Number of pipeline damages (no.)</th>
<th>Restoration time (hr.)</th>
<th>Water shortage (m³/hr.)</th>
<th>PRI (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>30</td>
<td>218</td>
<td>41</td>
<td>372</td>
</tr>
<tr>
<td>B</td>
<td>34</td>
<td>238</td>
<td>16</td>
<td>143</td>
</tr>
<tr>
<td>C</td>
<td>157</td>
<td>1140</td>
<td>148</td>
<td>1345</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

This study attempted to analyze risks through three analyses. The first analysis was for predicting the number of pipeline damages in the future. The second analysis was for estimating the restoration time by utilizing past records of pipeline accidents. The third analysis was conducted to calculate the amount of water shortage to investigate the indirect impact on consumers when a pipeline accident occurs. From these analyses, we were able to obtain the quantitative rank of risk in each analysis. After completing the 3 analyses, the PRI was proposed in order to generate an overall risk assessment. The PRI can help propose risk evaluation for providing sufficient guarantee of stable distribution service. As a result of the study, 141 pipelines were assessed with a risk ranking from 1st rank to 141st rank. In order to examine the effect of replacement order based on PRI, three scenarios were set and compared. The comparison shows that replacement in order of PRI can prevent risks, rather than replacement in order of aged pipelines.

This study has proposed a risk prediction method for waterworks pipeline network management, and can be expected to be used to assist the decision-making when devising pipeline replacement plans, as well as in the maintenance and management of water distribution systems. Moreover unlike past researches, this study conducts to quantify the impact of pipeline accidents on water consumers. It helps waterworks set the specific replacement or maintenance plan. This study will be updated by a future study aimed at determining the replacement rank of 127 small blocks in the entire study area, which will consider the total cost (repair cost and replacement cost) and the benefit using PRI.
REFERENCES

1) Ministry of Science and Technology : Development of protection and reduction techniques of the water leakage, 21C Frontier R&D Program 4-2-1, pp. 81-82, 2004 (In Korean).


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