A study on appropriate investment of pipeline rehabilitation for water distribution network

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Abstract In Japan most of the water distribution networks were constructed during the 1960s to 1970s. Since these pipelines were used for a long period, pipeline rehabilitation is necessary to maintain water supply. Although investment for pipeline rehabilitation has to be planned in terms of cost-effectiveness, no standard method has been established because pipelines were replaced on emergency and ad hoc basis in the past. In this paper, a method to determine the maintenance of the water supply on an optimal basis with a fixed budget for a water distribution network is proposed. Firstly, a method to quantify the benefits of pipeline rehabilitation is examined. Secondly, two models using Integer Programming and Monte Carlo simulation to maximize the benefits of pipeline rehabilitation with limited budget were considered, and they are applied to a model case and a case study. Based on these studies, it is concluded that the Monte Carlo simulation model to calculate the appropriate investment for the pipeline rehabilitation planning is both convenient and practical.

Keywords Appropriate investment; integer programming; Monte Carlo simulation; pipeline rehabilitation; water distribution network

Introduction

In order to increase water supply in Japan, many waterworks facilities were constructed. Since most of the water pipelines were constructed during the 1960s to 1970s, they are aged, and rehabilitation of these pipes is necessary to maintain the stability and safety of water supply. Although aged water mains have partially been repaired and replaced now, comprehensive planning was not made in terms of cost-effectiveness. For example, asbestos cement pipes were replaced because asbestos is determined to be a cancer-causing material. Aged normal cast-iron pipes without lining were renewed or coated with lining material on the inside surface in order to prevent rust to adhere to the water pipe. Therefore, a method to plan for the maintenance of water supply on an optimal basis with a fixed budget for a water distribution network is examined in this study.

Rehabilitation of aged pipelines is necessary because they have a higher possibility to cause damage to the water supply. For example, the risks of aged pipelines include corrosion, water leakage caused by loose joint, flow difficulty due to adhesion of rust and detachment of lining material, water contamination caused by rust-colored water or detachment of lining material, etc. According to the Japan Water Works Association (2002), the total length of water supply pipelines that have been used for more than 20 years (as of 1998) was about 180,000 km, which is approximately a third of the total length of water mains in Japan. Therefore, the rehabilitation planning of water
distribution network to maintain the stability and safety of water supply is an important matter.

According to the Society for the Study of Local Public Enterprise (2002), water supply pipeline assets in Japan consist of about 60 ~ 70% of water facility assets, and this value is about 10 times the annual revenue of water sales. Furthermore, since most water pipelines in a region are usually constructed in the same period, many pipes will become superannuated at almost the same time in the near future. Therefore, even if many pipelines need replacement at the same time, it is impossible to replace them in a short period because budget for the maintenance of water distribution network is limited. Hence, it is necessary to consider how to use limited budget to maximize the effects of pipeline rehabilitation.

In order to plan for the appropriate investment of pipeline rehabilitation, a method to quantify the benefits due to pipeline replacement is examined. Furthermore, the models applying Integer Programming and Monte Carlo simulation are examined to calculate the appropriate pipeline rehabilitation from the numerous combinations ($2^N$; $N =$ amount of pipelines $\times$ planning periods) of a water distribution network.

**Quantification of benefits due to pipeline rehabilitation**

The risks of aged water pipes include possible shutdown of the water supply, limited water supply, water leakage, or water contamination. Preventing such losses can be considered as the benefits of pipeline rehabilitation. Expected business losses and increased costs caused by shutdown or limited water supply due to pipeline damage are used in this paper because they can be quantified. Benefits due to pipeline rehabilitation are calculated by estimating the difference between the cases when a pipeline is replaced and when it is not.

In this study, expected losses and increased costs caused by shutdown or limited water supply due to the pipeline damage are quantified in order to estimate the benefits by pipeline renewal. Such losses, proposed by Odanagi et al. (2003), are shown in Table 1. The quantified losses and costs are classified into three major categories as follows: 1) Domestic water users, 2) Business or commercial water users, 3) Water supplier. The effects relating to inconvenience due to shutdown and cost needed for measuring by the water supplier due to shutdown or limited water supply are excluded in this study because such costs are difficult to estimate. Furthermore, although reduction of water supply revenue can be considered as a loss for water supplier, it is excluded because it can also be considered as a savings for the water user.

In order to calculate the losses and costs for water users shown in Table 1, the percentage of water shortage ($S$) is needed, and it is calculated by the water demand and the structure of water distribution network. The percentage of water shortage ($S$), according to Odanagi et al. (2002), is the proportion of normal water supply that can be supplied to the user when a pipeline is damaged. By defining the unit losses due to the water shortage ($S$), losses and increase costs for water user can be estimated. When the network structure is applied, losses due to the damage of pipelines relatively nearer to the reservoir will be larger.

Since benefits of pipeline rehabilitation is affected by factors which change over time such as population, water demand, and the damage rate of a pipeline, it is necessary not only to estimate the benefits of pipeline rehabilitation, but also the period for pipeline replacement. The damage rate of pipeline is estimated based on a statistical approach, which is influenced by the type of pipe and the period it had been used. Furthermore, since benefits are estimated as the difference between the cases with and without pipeline...
renewal, benefits of pipeline rehabilitation can be expressed as equation (1).

\[
L_i(t^0) - L_i(x^0_t) = (LD_i + LU_i + LR_i) \cdot (d_i(t^0) - d_i(x^0_t)) \cdot t_i
\]  

(1)

where,

- \( i \): Pipeline (\( i = 1, 2, ..., m \)) (\( m \) is the amount of pipelines in the water distribution network)
- \( t \): Period (\( t = 1, 2, ..., T \)) (\( T \) is the planning period)
- \( x^0_t \): A vector that shows whether pipeline \( i \) is replaced until the period \( t \), \( x^0_t = (x^0_t, x^0_t, ..., x^0_t) \)
- \( x^0_t = 0 \) when pipeline \( i \) is not rehabilitated in period \( t \)
- \( x^0_t = 1 \) when pipeline \( i \) is rehabilitated in period \( t \)
- \( 0^0 = (0, 0, ..., 0) \): A vector that shows pipeline \( i \) is not rehabilitated until period \( t \)
- \( L_i(t^0) \): Expected losses/costs in period \( t \) when pipeline \( i \) is not rehabilitated until period \( t \)
- \( L_i(x^0_t) \): Expected losses/costs in period \( t \) when pipeline \( i \) is rehabilitated due to the vector \( x^0_t \)
- \( LD_i \): Expected costs for domestic user in period \( t \) when pipeline \( i \) is damaged
- \( LU_i \): Expected losses for business and commercial user in period \( t \) when pipe \( i \) is damaged
- \( LR_i \): Cost for repairing pipeline \( i \) when it is damaged
$d_i^t(0^t)$: Damage rate of pipe in period $t$ when pipeline $i$ is not rehabilitated until period $t$

$d_i^t(x_i^t)$: Damage rate of pipe in period $t$ when pipeline $i$ is rehabilitated due to the vector $x_i^t$

$l_i$: Length of pipeline $i$

The statistical approach applied to the damage rate of pipeline shown in equation (1) is illustrated in Figure 1. According to Kobayashi (1988), the damage rate of pipeline is statistically expressed by the relationship between the type of a pipe and the period it is used. If a pipe is not replaced, its damage rate will increase faster as time passes (point “A” of Figure 1). When the pipe is replaced, its damage rate will be reset to the damage rate of a new pipe with a lower damage rate (point “B” of Figure 1) because generally a better type of water pipe will be selected for replacement. Equations for the damage rate of pipes indicated in Figure 1 are shown in items (2)–(4) below.

\[
 u_{ki}^t = u_{ki}^{t-1} \cdot (1 - x_i^t) + \hat{u}_k \cdot x_i^t \\
 = u_{ki}^0 \prod_{r=1}^t (1 - x_i^r) + \prod_{r=1}^{t-1} \prod_{\mu=r+1}^t (1 - x_i^\mu) + \hat{u}_k \cdot x_i^t \tag{2}
\]

\[
y_i^t = y_i^{t-1} \cdot (1 - x_i^t) + t \cdot x_i^t = y_i^0 \prod_{r=1}^t (1 - x_i^r) + \sum_{r=1}^{t-1} \tau \cdot x_i^r \cdot \prod_{\mu=r+1}^t (1 - x_i^\mu) + t \cdot x_i^t \tag{3}
\]

\[
d_i^t(x_i^t) = \sum_k f_k(u_{ki}^t, t - y_i^t) = \sum_k f_k(x_i^t) \tag{4}
\]

where,

$u_{ki}^t$: A variable that will be 1 (or 0) if pipeline $i$ is (or is not) a type $k$ pipeline at the period $t$

$\hat{u}_k$: A factor of vector $(\hat{u}_1, \hat{u}_2, ..., \hat{u}_k) = (0, 0, ..., 1)$ that will be 1 (or 0) when type $k$ pipe is (or is not) $K$ after the pipe replacement

$y_i^t$: The period pipeline $i$ had been used at period $t$

$f_k(x_i^t)$: A function that indicates the damage rate due to the type of pipeline $k$

**Appropriate investment for pipeline rehabilitation of water distribution network**

In order to consider how to use the limited budget to maximize the effects of pipeline rehabilitation, Integer Programming (IP) and Monte Carlo simulation (MCS) were examined. Explanations of these two methods are discussed below. Comparing the two methods, IP was found to be weak in that it cannot be applied to a model that has many variable
combinations even if SAS software is used. On the other hand, MCS has no limitation on the number of calculation variables. Although the results calculated by MCS are not guaranteed as the optimal solutions as in the case with IP, the results calculated by applying MCS were the same as the optimal solutions obtained by IP for the model case. In this study, MCS is proved to be the more useful method for calculating the model case presented later in this paper. Moreover, there was even one case study which could not be calculated by IP, but was estimated by using MCS. Hence it is concluded that using the MCS method for the determination of appropriate pipeline rehabilitation is both convenient and practical.

Estimating optimize pipeline rehabilitation by applying integer programming

Integer programming (Greenberg, 1971) can be applied to maximize the benefits of pipeline rehabilitation by using the function shown in equation (5) with the constraints shown in equations (6)–(8).

Function to maximize the benefits of pipeline rehabilitation.

\[
\max \sum_{i=1}^{m} \sum_{t=1}^{T} (L_i^f(0^t) - L_i^r(x'_t)) \tag{5}
\]

This variable indicates that whether pipeline \( i \) should or should not be replaced in period \( t \).

\[
x'_t = 0 \text{ or } 1 \quad (i = 1 \cdots m, t = 1 \cdots T) \tag{6}
\]

This equation is used for limiting the budget for pipeline rehabilitation. It shows that budget remaining for not using in a period is allowed to be carried over to the next period.

\[
\sum_{i=1}^{m} \sum_{t=1}^{T} C_i \cdot x'_t \leq \sum_{t=1}^{T} \hat{C}^t \quad (t = 1 \cdots T) \tag{7}
\]

where,

- \( C_i \): Cost for renewing pipeline \( i \)
- \( \hat{C}^t \): Cost (Budget) limited for pipeline rehabilitation in the period \( t \)

This equation prevents each pipeline to be replaced twice because the durability of water main is generally longer than the planning period.

\[
\sum_{t=1}^{T} x'_t \leq 1 \quad (i = 1 \cdots m) \tag{8}
\]

Estimating optimize pipeline rehabilitation by applying Monte Carlo simulation

Monte Carlo simulation (Sasieni et al., 1959) can be applied to maximize the benefits of pipeline rehabilitation using the concepts indicated in the flow diagram of Figure 2, which are summarized below.

1. A random number is generated to decide the renewal pipes in each period respectively for maximizing the benefits due to pipeline rehabilitation. It will be excluded for replacement if the pipe chosen by the random number was previously decided for replacement, or the total cost needed for replacing exceeds the budget.

2. Pipes decided for renewal in each period will be used to calculate the \( TB \) (Expected total benefits) for evaluation when the period \( t \) exceeds \( T \) in the workflow. If the present \( TB \) is larger than the previous \( TB \), results calculated will be recorded. Otherwise, these results will be deleted.

3. When the repeated simulation numbers exceed the fixed iteration amount, the simulation will stop; otherwise results estimated for replacing pipes in each period will be reset and another simulation will be started.
Model case

Although IP has the weak point that it cannot be applied when there are many variable combinations, it is used in the model case shown in Figure 3 to compare with the results of MCS. In the model case, the curves shown in Figure 4 are used to calculate the damage rate of each type of pipe. The water demand and population are assumed as constant during the 5 planning periods.

After calculation of the model case, results estimated by MCS were found to be the same as the optimal solutions calculated by IP. As can be seen from Figure 3, the pipes that are relatively nearer to the reservoir, and pipes that had been used longer were selected for renewal in the earlier period. Furthermore, since the factors of water demand, pipe length and pipe diameter, excluding pipe type, are symmetric with respect to the reservoir, asbestos cement pipes are selected in an earlier period than ductile iron pipes corresponding to the symmetric pipes. All of these results are appropriate for rehabilitation. Since MCS does not have any limits on the amount of variables for calculations as is the case with IP, and model using MCS can be calculated by the computer that can run Microsoft Excel. Therefore, MCS is considered as a convenient method.

![Figure 2](https://iwaponline.com/ws/article-pdf/5/2/31/417598/31.pdf)

**Figure 2** General workflow using MCS to obtain the effective pipeline rehabilitation in the limited budget

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![Figure 3](https://iwaponline.com/ws/article-pdf/5/2/31/417598/31.pdf)

**Figure 3** Water distribution network used for the model case and the results calculated
Case study

In order to estimate an optimize pipeline rehabilitation in the case study, MCS is applied. Since the case study covers 40 pipelines and 10 planning periods, the combinations of pipeline rehabilitation are approximately $2.5 \times 10^{120}$ ($N$: amount of pipelines $\times$ planning periods). Estimating the appropriate investment for so many combinations cannot be handled by the IP method. Assumptions applied in the case study are the following.

- Figure 5 shows the water demand and population assumed for the case study. As can be seen, water demand and population forecast in the planning period are assumed to decrease because it is the trend in many provincial cities in Japan.
- Budget limit for pipeline rehabilitation is assumed to be 3% of the revenue of the water supply of each period due to the water demand forecast shown in Figure 5.
- The damage rate of asbestos cement pipes and ductile iron pipes, which are used in the distribution network of the model case, are assumed as Figure 4.
- Since the durability of the water main is generally longer than 20–30 years, each pipe is prevented from being replaced twice in a planning period of 50 years.

According to the results of the case study, shown in Figure 6, pipelines selected for replacement in the early periods are comparatively nearer to the reservoir. Moreover, pipelines chosen for replacement before third planning period are pipelines that had been used for more than 30 years. Therefore, it can be said that the results estimated are appropriate for the phased renewal of pipes from the viewpoints of experience and common sense. Thus, the proposed MCS method is found to be both convenient and practical for the planning of pipeline rehabilitation.

![Figure 4](image1.png)

**Figure 4** Damage rates of pipes used for the model case. The two curves are drawn based on the following references; Kobayashi (1988), Japan Water Works Association (1988), Kawakita (1986) and Hosoi et al. (1988)

![Figure 5](image2.png)

**Figure 5** Forecast of the water demand and population in the distribution region

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Conclusion

This study focused on pipeline rehabilitation because it is a big problem in many cities. The benefits of using new piping have been quantified in order to plan rehabilitation in terms of cost-effectiveness. Next, pipeline rehabilitation to maintain the water supply on an optimal basis with a limited budget was considered after comparing Integer Programming and Monte Carlo simulation models. As a result of this study, the Monte Carlo simulation was found to be both a convenient and a practical method for the appropriate investment of pipeline rehabilitation planning.

References

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