PRIORITIZATION OF REPAIR/REPLACEMENT OF AGED GRAY CAST IRON PIPELINES BASED ON RISK ASSESSMENT

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Gray cast iron (GCI) is one of the old pipe materials used for low pressure natural gas distribution pipelines. The GCI pipes were installed from 1885 to the 1970s in the Tokyo metropolitan area, because the GCI pipes were believed to have sufficient strength in those days. However, due to its small elongation, generally less than 1%, and high susceptibility to corrosion, the aged GCI pipelines often break and cause gas leakage. Because the amount of leaking gas due to a break in a GCI pipe is relatively high, the gas could flow into a building through the ground, and possibly cause an accident. To efficiently reduce the risk induced by the breaks in the GCI pipelines and improve their safety level, the authors have developed a method for assessing the risk of each GCI pipeline using a geographic information system (GIS). This paper describes the method for the risk assessment in order to prioritize the repair or replacement of the aged GCI pipelines. The risk of the GCI pipelines is the likelihood of breaks multiplied by the consequence of the accidents induced by the gas leakage. To calculate the likelihood of a break for each GCI pipeline, a likelihood model was established based on the break mechanism of the GCI pipes. As a result of the likelihood calculation, a good correlation was observed between the calculated likelihood and the past break rate for the GCI pipelines. To calculate the consequence of the accident for each GCI pipeline, a consequence model was also established and improved with site surveys at more than 100 sites. The risk calculation enables us to prioritize the repair or replacement of the GCI pipelines; the GCI pipelines having a higher risk can be repaired or replaced prior to those having a lower risk. Thus, the total cost, that is, the sum of the total risk and the total investment for the repair or replacement, can be minimized.
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1. INTRODUCTION

Tokyo Gas (TG) has been supplying natural gas to over 9,000,000 customers in the Tokyo metropolitan area of Japan, using 50,000 km of distribution pipelines. Gray cast iron (GCI) is one of the old pipe materials used for low pressure gas distribution pipelines. The GCI pipes were installed from 1885 to the 1970s, because the GCI pipes were believed to have sufficient strength in those days. However, due to its small elongation, generally less than 1%, and high susceptibility to corrosion, the aged GCI pipelines often break and cause gas leakage. Because the amount of leaking gas due to a break in a GCI pipe is relatively high, the gas could flow into a building through the ground, and possibly cause an accident.

To reduce the risk induced by the breaks in the GCI pipelines and improve their safety level, TG has been conducting a program to repair or replace the GCI pipelines with liners or polyethylene pipes [1]. In order to efficiently reduce the risk of the GCI pipelines, the authors have developed a method for assessing the risk of each GCI pipeline using a geographic information system (GIS) [2] [3]. This paper describes the present method for the risk assessment in order to prioritize the repair or replacement of the aged GCI pipelines.

2. METHOD OF RISK ASSESSMENT

Figure 1 shows a flow sheet for the risk assessment for the GCI pipelines [2] [3].

![Flow sheet for the risk assessment](image-url)
The GCI pipes have risk induced by the breaks. In this paper, the risk of the GCI pipeline is defined as a potential cost, which equals “the probability of the break in the pipeline (likelihood)” multiplied by “the estimated cost for the break and the subsequent gas leakage (consequence)”.

For each GCI pipeline, a “likelihood model” provides the likelihood of a break using the detailed data of the pipeline and the environment. On the other hand, a “consequence model” provides the consequence of an accident for each GCI pipeline using the detailed data of the environment. Details of the likelihood model and the consequence model are described in the following chapters.

Figure 2 schematically shows the relationship of the total risk, the total investment for the repair or replacement, and the total cost. The total risk is the sum of the risk of all the GCI pipelines. The total investment is the sum of the costs for the repair or replacement of the GCI pipelines. In Figure 2, as the length of the repair or replacement increases, the total investment linearly increases, and the total risk decreases as shown by the dashed lines.

When the risk of each GCI pipeline is calculated, the GCI pipelines having a higher risk can be repaired or replaced prior to those having a lower risk. Therefore, the total risk rapidly decreases in the early stage of the repair or replacement, and the total risk curve changes as shown by the solid line (A). As a result, the total cost, that is, the sum of the total risk and the total investment for the repair and replacement, can be reduced as shown by the solid line (B). The total cost curve (B) then has a minimum value. This indicates that an optimum point for the investment can be obtained.
3. LIKELIHOOD ASSESSMENT

3.1 Procedure for the Likelihood Assessment

Figure 3 shows the procedure for the likelihood assessment in this study. (a) Survey at the sites where the GCI pipes have broken and a laboratory investigation clarified the break mechanism of the GCI pipes (how the GCI pipes break). (b) The likelihood model was then established based on the break mechanism. (c) The established model calculates the likelihood of a break in each GCI pipeline. (d) To verify the likelihood model, the calculated likelihood was compared with the data from breaks in the past.

(a) Clarification of the break mechanism

(b) Establishment of the likelihood model

(c) Calculation of the likelihood

(d) Verification

Figure 3: Procedure for the likelihood assessment in this study

3.2 Clarification of the Break Mechanism

To clarify the break mechanism of the GCI pipes, site surveys and laboratory investigations were conducted for the broken GCI pipes. Table 1 shows the contents of the site survey and the laboratory investigation.

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Table 1: Contents of the site survey and the laboratory investigation

Figure 4 shows a typical site survey and laboratory investigation. The site surveys provided environmental data, such as the amount of the ground subsidence, and the deformation of the pipes. Finite element (FE) analyses were then conducted to evaluate the stress based on the results of the site surveys and the laboratory investigations.
3.3 Establishment of the Likelihood Model

In addition to the site surveys and the laboratory investigations, the data from past breaks in the GCI pipelines were analyzed. The data include the diameter, wall thickness, depth of corrosion (metal loss), chemical composition, age, etc. These studies clarified the break mechanism and the important factors that affected the breaks in the GCI pipes. The likelihood model, which can calculate the probability of a break in each GCI pipeline, was then established on the basis of the break mechanism.

3.4 Calculation of the Likelihood

The likelihood model provides the likelihood of the breaks in each GCI pipeline using pipe data, such as the diameter, strength, and manufacturing process, and environmental data, such as ground subsidence, ground subsurface condition, and history of construction work, using the following formula.

\[
\text{Likelihood}_i = f (P_{i1}, P_{i2}, P_{i3}, \ldots, E_{i1}, E_{i2}, E_{i3}, \ldots)
\]

In this formula, \(P_{i1}\) represents the diameter, \(P_{i2}\) represents the strength, and \(P_{i3}\) represents the manufacturing process, of the pipeline \(i\), while \(E_{i1}\) represents the ground subsidence, \(E_{i2}\) represents the ground subsurface condition, and \(E_{i3}\) represents the history of the construction work of the pipeline \(i\).
Our study showed that the amount of the ground subsidence is one of the most important factors affecting the break mechanism. Based on the result of this study, the ground subsidence was obtained for the likelihood calculation using PSInSAR technology [4]. Figure 5 schematically shows the evaluation of the ground subsidence using the PSInSAR technology. Satellites measure the change in the wavelength of the reflected microwaves each year. This change indicates the change in the ground surface level, that is, the speed of the ground subsidence. Figure 6 shows an example of the ground subsidence using the PSInSAR technology. In Figure 6, red points represent locations where the speed of the ground subsidence was high.

The likelihood model calculated the likelihood of a break for each GCI pipeline. Figure 7 shows the relationship between the calculated likelihood and the break rate per unit length of the GCI pipelines in the past. Figure 7 indicates that there exists a good correlation between the calculated likelihood and the past break rate. The result indicates that the present likelihood model is applicable for predicting breaks in the GCI pipelines.
4. CONSEQUENCE ASSESSMENT

4.1 Procedure for the Consequence Assessment

Figure 8 shows the procedure for the consequence assessment in this study. A consequence model was initially established. The consequence model consists of (a) an event tree type model which can calculate the probability of accidents induced by the break of the GCI pipeline, and (b) a cost calculation model which can calculate costs incurred by the accidents. After the establishment of the consequence model, (c) the site surveys improved the consequence model. (d) The consequence of an accident for each pipeline was then calculated using the improved consequence model.

Figure 8: Procedure for the consequence assessment in this study

4.2 Establishment of the Consequence Model

Figure 9 schematically shows the consequence model. The consequence model consists of the “event tree” type model and the “cost calculation” model.

Figure 9: The consequence model
The event tree type model assumes the scenarios of the accidents induced by the breaks in the GCI pipelines. In this study, the event tree type model calculated the probability of each accident using the results of past accidents.

The cost calculation model provides not only the direct costs, such as the repair or replacement costs of the broken pipes and the compensation for injured people and damaged buildings, but also indirect costs, such as the loss in revenue due to a reduced gas demand and change in the regulatory policy. The cost incurred by each accident shown in Figure 9 depends on the environment around the GCI pipelines. For example, a high population density area has a large consequence induced by a break. Therefore, the cost calculation model employed (1) cost data, such as repair or replacement costs, traffic insurance [5], loss of buildings induced by fire [6], and employment statistics [7], and (2) environmental data, such as population density [8], traffic density [9], and land use [10], to evaluate the cost incurred by a break in each GCI pipeline.

4.3 Improvement of the consequence model by site surveys

To improve the consequence model, more than 100 sites were surveyed in our pipeline network. Additional information was collected at each site, such as the number of pedestrians, types of buildings, and traffic density. The important factors, which have not been included in the original consequence model [2], were clarified using this additional information. Based on the results, the original consequence model was then improved.

5. RISK CALCULATION

The risk of each GCI pipeline is the calculated likelihood multiplied by the calculated consequence. Figure 10 shows a typical result of the risk calculation for the GCI pipelines. In Figure 10, the red lines denote a higher risk, the yellow ones denote an intermediate risk, and the green ones denote a lower risk. The risk calculation enables us to prioritize the repair or replacement of the GCI pipelines; the GCI pipelines having a higher risk can be repaired or replaced prior to those having a lower risk.

Figure 10: Typical result of the risk calculation
6. CONCLUSION

This paper describes a method for a risk assessment in order to prioritize the repair or replacement of aged GCI pipelines. The risk of the GCI pipelines is the likelihood of the breaks multiplied by the consequence of the accidents induced by the gas leakage.

The site surveys and the laboratory investigations clarified the break mechanism of the GCI pipes. The likelihood model was established on the basis of the break mechanism of the GCI pipes. The likelihood model then calculated the likelihood of the break in each GCI pipeline using the data for the pipeline and the environment. As a result of the likelihood calculation, a good correlation was observed between the calculated likelihood and the past break rate of the GCI pipelines.

The consequence model, which can calculate the consequence of an accident for each GCI pipeline, consists of the “event tree” type model and the “cost calculation” model. The site surveys on more than 100 sites improved the consequence model. The improved consequence model calculated the consequence induced by the break for each GCI pipeline using the environmental data.

The risk of each GCI pipeline is the calculated likelihood multiplied by the calculated consequence. The risk calculation enables us to prioritize the repair or replacement of the GCI pipelines; the GCI pipelines having a higher risk can be repaired or replaced prior to those having a lower risk. Thus, the total cost, that is, the sum of the total risk and the total investment for the repair and replacement, can be minimized.
REFERENCES


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