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Developing residual life estimation method for DCIP/CIP pipes

Ji-Hoon Choi, Gyeong-soo Kim, Dooil Kim*

Civil and Environmental Engineering, Dankook University, 152, Jukjeon-ro, Suji-gu, Yongin-si, Gyeonggi-do, 16890, Korea, Tel. +82 31 8005 3610; Fax: +82 31 8021 7213; email: dikim21@dankook.ac.kr (D. Kim)

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ABSTRACT

When rehabilitating aged water pipes, the deterioration of pipes should be estimated for prioritization of management. The scoring deterioration is becoming more important as asset management is introduced. In the past, the scoring deterioration was performed using indirect methods. Recently, a technique has been developed to predict the survival of water pipes using the fuzzy method. In this study, after the deterioration of pipes was determined using the fuzzy method, the mathematical relationships for deterioration over time was created using the non-linear regression technique of the Box-Cox statistical package. The validity of this mathematical model was obtained using a statistical package. The increased rate of deterioration was obtained using its derivative function from which the probability of accidents occurring at the cast iron pipe was obtained. Probability of occurrence of more than the target number of accidents was derived through Poisson probability distribution. The point of renewal was determined at the time when the accident probability exceeded 0.6321. As a result, the remaining expected lives of CW-01, CW-03, and CW-07 pipes were 10.2, 10.1, and 10.8 years, respectively. Also, those for CW-02, GM-01, GJ-01, GM-02, GJ-03, GM-03, GJ-05, and GM-04 were 11.1, 5.1, 15.2, 6.5, 12.8, 15.6, 11.4, and 13.3 years, respectively.

Keywords: Asset management; Aged water pipe; Deteriorated water pipe; Fuzzy method; Residual life estimation

1. Introduction

The aging process of water supply network increases the risk of pipe failure [1,2]. Water pressure is always applied to the inside of the pipeline, so there is always a risk of leakage due to the failure. Pipe networks are buried underground and have difficulties in terms of technology for maintenance. Aged and defected pipe networks should be replaced [3]. Continuous rehabilitation and replacement using qualitative and quantitative evaluation results on pipes are essential [4]. It is very important to predict the residual life of the network in order to replace it because not only the timely repair and replacement of pipes meet the expectations of water supply consumers, but it will also greatly help in improving and prioritizing the replacement of pipelines by predicting future deterioration levels [3,5–7].

Four elements that can evaluate the function of water pipes are physical strength, water quality, hydraulic conditions, and water leakage [1,4]. Structural integrity is a measure of how much internal and external loads can be sustained on a pipe and depends on the thickness of the tube material, dimensions, and pipe material [8]. Water quality in a pipe indicates the degree of variation in the water quality in the pipe while being supplied to the consumers from the water purification plant [9]. Hydraulic condition indicates the extent to which adequate pressure is applied to supply sufficient water to all areas within the water supply zone, and evaluation of water pressure is useful in determining the degree of deterioration in the pipeline. Leakage causes economic losses as well as washing out the supporting soil around the pipe resulting in the bending of the pipe and promoting corrosion of outer wall [10–12].

* Corresponding author.

Evaluation of pipe deterioration is largely divided into indirect and direct assessment methods [1–3]. Indirect assessment method is divided into regression and scoring methods. While most of the current information on pipes were not sufficiently accumulated, accurate results could be obtained through a regression model based on historical data if the historical data of pipes is consistently collected along with the introduction of the asset management system in the water supply [13]. For the prediction of damage on pipes using statistical techniques, three main methods may be used. First, there is a relatively simple deterministic method for predicting the frequency of pipe breakages [14], and a method for deriving the probability of failure and survival of the pipe using mathematically complex probabilistic methods [15], and a method to predict the timing of failure rate and failure occurrence of the damage [16,17]. These methodologies are intended to implement preventive maintenance through prediction of damage incidents and to achieve cost savings through efficient operation and maintenance [13,18].

fuzzy-based models mimic logical human thought systems, providing a better model for uncertainty and inaccuracy [19,20]. Therefore, it is possible to deal with complex problems that cannot be explained by the physical model [21]. Despite the advantages of some artificial intelligence, the ability to identify obvious causality is limited. Also, these methods have disadvantages that require a lot of data and a large computational system [22]. Fuzzy theory was first introduced in 1965 by Professor Zadeh at the University of Berkeley as a way of expressing the uncertainty of the natural phenomenon [19]. Fuzzy theory includes the fuzzy set, the fuzzy logic, the fuzzy number, etc. to make the ambiguous data useful [19]. Fuzzy theory involves fuzzification to change a real scalar value into the fuzzy data. This does not limit to only two cases in the set theory in which assigning 0 and 1 in binary system and deciding if an element belong to a particular set or not [19]. Depending on the degree of truth, the element of [0,1] in the closed period responds to corresponding real number and models the entire uncertainty, initiating common-sense inference in decision-making [23].

In general, it would be easiest to apply a linear model of these variables without any conversion if you consider the statistical model for the dependent variables. In this case, a normality test for an error must be accompanied [24]. If it is difficult to verify normality for errors, there is a method through non-parametric analysis, but the method has limitations that can be performed up to the group's comparison. An alternative method of non-parametric analysis to address these limitations is the parametric conversion method [25]. The variable conversion method is a method of statistical analysis for the variables whose combined distribution of variables follow a multivariate normal distribution [26]. Box-Cox transformation is one of the ways in which analysis for variable transformation is made possible, using variable transformed X^{λ} instead of variable X. Generally, values of λ are recommended from –2, –1, 0, 1, 2 [25].

In this study, the fuzzy method was used, non-linear regression analysis, and Poisson probability distribution for the purpose of determining the date of renewal and replacement of old water pipes.

2. Methods

2.1. Pipes status from water mains

The 14 pipes analyzed in this study consist of a pipe with diameter 300 to 2,200 mm. There are six CIP pipes and eight DCIP pipes. We collected installation year, pipe material, pipe diameter, internal and external coating, connection method, historical leakage and burst data, surrounding soil types, and surrounding road conditions. Table 1 is a summary of field data collected from 14 pipes studied.

2.2. Selection of the factors for the evaluation of deterioration rate

The expected life was determined based on a total of 9 parameters for 10 indirect assessment parameters, which are installation year, pipe material, pipe diameter, internal and external coating, connection method, historical leakage and burst data, surrounding soil types, and surrounding road conditions. Pipe material is rated in five grades (Good, Adequate, Fair, Poor, Bad), diameter in six grades (Excellent, Good, Adequate, Fair, Poor, Badexternal coating in three grades (Good, Fair, Bad), installation year in five grades (Good, Adequate, Fair, Poor, Bad), surrounding soil in four grades (Excellent, Adequate, Poor, Failed), surrounding road in five grades (Good, Adequate, Fair, Poor, Bad), connection method in five grades (Good, Adequate, Fair, Poor, Bad), leakage and burst data in four grades (Excellent, Adequate, Poor, Failed) [1]. The weighting factors of aged pipes were cited from the manual [1] and converted so as for a sum of them to be unity. The ratings and weights for each parameter are shown in Table 2. Table 3 shows status evaluation results by this score system.

2.3. Rating deterioration with the fuzzy method

The membership value of the trigonometric function to calculate the fuzzy deterioration rate of each pipe is determined using Eq. (1):

$$\text{Membership value} = \omega \times h \tag{1}$$

where ω is weighting factor and h is evaluated score. For example, the membership set of the GM-01 pipe is calculated by multiplying the weights of (0.22, 0.11, 0.08, 0.02, 0.2, 0.06, 0.06, 0.02, 0.23) and corresponding status score. As a result, the membership set of GM-01 is determined to be (0, 0, 0.06, 0.096, 0.295, 0.1, 0) and expressed in Fig. 1. Table 4 is a summary of the membership values of each pipe.

Fuzzy inference result is calculated in the form of membership value of trigonometry and the defuzzification process using the center of gravity method [19]. The results obtained are then converted to scalar or Crisp values to obtain a clear inference value [27]. The center of gravity of the polygon is obtained using Eq. (2) and is illustrated in Fig. 1. The resulting center of gravity is the fuzzy deterioration rate of the corresponding pipe:

$$R = \frac{\sum m_i r_i}{\sum m_i} \tag{2}$$

where R is center of gravity, m_i is area of polygon, r_i is center of polygon.

Table 1
Field data collected from pipes

Pipe ID	Material	Diameter (mm)	Inner coating	Outer coating	Year installed	Soil	Traffic type	Connection method	Leakage and failure recording (times/5 year-50 km)
CW-01	CIP	400	No	No	1982	Sand-Gravel	>4 lane road	Mechanical	2.61
CW-02	DCIP	700	No	No	1978	Clay	>4 lane road	Mechanical	2.61
CW-03	CIP	700	No	No	1975	Clay	>4 lane road	Mechanical	2.61
CW-04	CIP	600	No	No	1975	Sand	>4 lane road	Mechanical	2.61
GM-01	DCIP	400	No	No	1979	Clay-Gravel	2 lane road	Mechanical	4.23
GJ-01	DCIP	300	Coaltar mortar	No	1995	Clay-Gravel	>4 lane road	Mechanical	2.44
GM-02	DCIP	350	Coaltar mortar	No	1996	Clay	>4 lane road	Mechanical	4.23
GJ-02	CIP	350	No	No	1979	Clay-Gravel	2 lane road	Mechanical	2.44
CW-06	CIP	700	No	No	1975	Sand	>4 lane road	Mechanical	2.469
CW-07	CIP	500	No	No	1982	Sand-Gravel	>4 lane road	Mechanical	2.469
GJ-03	DCIP	450	No	No	1979	Clay	Footway	Mechanical	2.156
GM-03	DCIP	600	Coaltar mortar	No	1997	Sand	>4 lane road	Mechanical	2.156
GJ-05	DCIP	300	No	No	1979	Clay-Gravel	>4 lane road	Mechanical	2.469
GM-04	DCIP	500	No	No	1982	Sand-Gravel	>4 lane road	Mechanical	2.156

2.4. Box-Cox model

In this study, the Box-Cox transformation method was used as an alternative to non-parametric analysis to ensure better statistical significance with relatively small number of data. For regression analysis of cast iron pipes, the independent variable was set to the age of pipe and the dependent variable was set to be the fuzzy deterioration rate as shown in Table 5. Box-Cox variable conversion was done with 'powerTransform' and 'testTransform' tool named 'car' package in the program 'R' [26]. The program R is the programming language specialized in statistics and open source software [25]. In this study, the Box-Cox transformation method converts independent and dependent variables into statistically significant variables and performs regression analysis on converted variables. A nonlinear regression equation derived from the above process is consequently modeled by historical data and can predict changes in deterioration over time.

2.5. Poisson model

Poisson probability distribution was applied to draw probability of accident for the pipes over time. When an event occurs at random within a unit time or space, the Poisson probability distribution is for the number of times the event occurs [28]. The probability density equation of the Poisson distribution is shown as follows:

$$P\left(X_i = x_i\right) = \frac{e^{-\lambda} \times \lambda^x}{x!} \qquad x_i = 0,1,2,... \tag{3}$$

where $P(X_i = x_i)$ is the probability of occurrence of events x_i in interval i, λ_i is average number of occurrences of an event per hour. The results of this study are expressed as Eq. (4):

$$P\left(\mu_t\right) = \frac{e^{-\mu_t} \times \mu_t^{\mu_{\text{Target}}}}{\mu_{\text{Target}}!} \tag{4}$$

where $P(\mu_t)$ is the probability of an accident occurring when the average number of accidents occurred in the time is μ_t. μ_{Target} is the basis for the number of accidents that need to be considered for renewal or replacement as the target pipe is considered to have been used over expected life. In this study, μ_{Target} was determined to be the number of accidents at least once a year for every 50 km pipe based on the indirect assessment method [2]. However, it is difficult to determine the point of renewal or replacement at a particular point only with the result of probability, so the mean time of renewal or replacement of the pipe is determined through the mean recurrence time. The probability of events occurring within the mean recurrence time is in a reciprocal relationship. The probability that no event will occur within the reoccurrence period is expressed with Eqs. (5) and (6):

$$P\left(\text{Not occurred during } \bar{T}\right) \simeq e^{-\bar{T}_p} = e^{-1} = 0.3679 \tag{5}$$

$$P\left(\text{Occurred during } \bar{T}\right) \simeq 1 - 0.3679 = 0.6321 \tag{6}$$

Table 2
Indirect assessment index table

No	Item	Weight	Classification	Grading	Grading	No	Item	Weight	Classification	Grading	Grading
1	Pipe	0.22	CIP, GSP	1.00	Bad	6	Soil	0.06	Clay	1.00	Failed
			PVC, PE	0.75	Poor				Clay+Gravel, Silt	0.50	Poor
			SP, PC, PCC	0.50	Fair				Sand+Gravel, Loam	0.25	AdequateExcellent
			DCIP	0.25	Adequate				Sand	0.00	Bad
			STS, PFP	0.00	Good						
2	Pipe diameter	0.11	Less than 150 mm	1.00	Bad	7	Roads	0.06	Highway	1.00	Bad
			150–350 mm	0.80	Poor				>4 lane road	0.75	Poor
			350–600 mm	0.60	Fair				2 lane road	0.50	Fair
			600–1,000 mm	0.40	Adequate				Local road	0.25	Adequate
			1,000–2,000 mm	0.20	Good				Footway	0.00	Good
			Larger than 2,000 mm	0.00	Excellent					1.00	
3	Internal coating	0.08	No	1.00	Bad	8	Connection	0.02	Sleeve coupling	1.00	Bad
			Epoxy	0.75	Poor				Flange, socket	0.50	Poor
			Coaltar enamel	0.75	Fair				Heat anastomosis	0.25	Fair
			Asphalt	0.50	Adequate				Mechanical, push-on J.	0.25	Adequate
			Cement mortar	0.00	Good				Coating after welding	1.00	Good
4	External coating	0.02	No	1.00	Bad	9	Leakage history	0.23	>5 times/5 year-50 km	1.00	Failed
			Coaltar enamel	0.75	Fair				3–5 times/5 year-50 km	0.50	Poor
			Asphalt	0.00	Good				1–3 times/5 year-50 km	0.25	Adequate
									No	0.00	Excellent
5	Installation year	0.20	More than 25 years	1.00	Bad						
			20–25 years	0.75	Poor						
			15–20 years	0.50	Fair						
			10–15 years	0.25	Adequate						
			less than 10 years	0.00	Good						

Table 3
Status evaluation result by evaluation score system

Pipe ID	Material	Diameter (mm)	Inner coating	Outer coating	Year installed	Soil	Traffic type	Connection method	Leakage and failure recording (times/5 year-50 km)
CW-01	Bad	Fair	Bad	Bad	Poor	Adequate	Poor	Adequate	Adequate
CW-02	Adequate	Adequate	Bad	Bad	Poor	Failed	Poor	Adequate	Adequate
CW-03	Bad	Adequate	Bad	Bad	Bad	Failed	Poor	Adequate	Adequate
CW-04	Bad	Fair	Bad	Bad	Bad	Excellent	Poor	Adequate	Adequate
GM-01	Adequate	Fair	Bad	Bad	Poor	Poor	Fair	Adequate	Poor
GJ-01	Adequate	Poor	Good	Bad	Good	Poor	Poor	Adequate	Adequate
GM-02	Adequate	Poor	Good	Bad	Good	Failed	Poor	Adequate	Adequate
GJ-02	Bad	Poor	Bad	Bad	Poor	Poor	Fair	Adequate	Adequate
CW-06	Bad	Adequate	Bad	Bad	Bad	Excellent	Poor	Adequate	Adequate
CW-07	Bad	Fair	Bad	Bad	Poor	Adequate	Poor	Adequate	Adequate
GJ-03	Adequate	Fair	Bad	Bad	Poor	Failed	Good	Adequate	Adequate
GM-03	Adequate	Fair	Bad	Bad	Good	Excellent	Poor	Adequate	Adequate
GJ-05	Adequate	Poor	Bad	Bad	Poor	Poor	Poor	Adequate	Adequate
GM-04	Adequate	Fair	Bad	Bad	Poor	Adequate	Poor	Adequate	Adequate

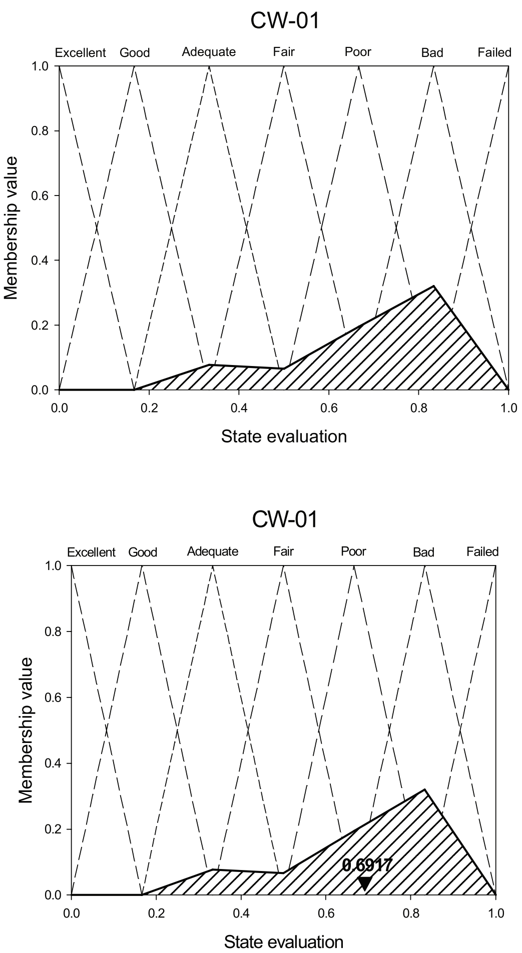

Fig. 1. Membership function value based on status evaluation (CM-01) and estimation results of defuzzifier (CW-01).

Table 4
Membership value for each pipe

Pipe ID	Membership value
CW-01	(0, 0, 0.0775, 0.066, 0.195, 0.32, 0)
CW-02	(0, 0, 0.1615, 0, 0.195, 0.32, 0)
CW-03	(0, 0, 0.1065, 0, 0.045, 0.52, 0.06)
CW-04	(0, 0, 0.0625, 0.066, 0.045, 0.52, 0)
GM-01	(0, 0, 0.06, 0.096, 0.295, 0.1, 0)
GJ-01	(0, 0, 0.1175, 0, 0.163, 0.02, 0)
GM-02	(0, 0, 0.1175, 0, 0.133, 0.02, 0.06)
GJ-02	(0, 0, 0.0625, 0.03, 0.268, 0.32, 0)
CW-06	(0, 0, 0.0775, 0.066, 0.195, 0.32, 0)
CW-07	(0, 0, 0.0775, 0.066, 0.195, 0.32, 0)
GJ-03	(0, 0, 0.1175, 0.066, 0.15, 0.1, 0.06)
GM-03	(0, 0, 0.1175, 0.066, 0.045, 0.1, 0)
GJ-05	(0, 0, 0.1175, 0, 0.313, 0.1, 0)
GM-04	(0, 0, 0.1325, 0.066, 0.195, 0.1, 0)

The probability that an event occurs within that reoccurrence period is always 0.6321 for a relatively rare event defined as $\overline{T}$. Therefore, the average time of recurrence theory determined the point at which the probability of one or more accidents taking place per 50 km of time was 0.6321.

3. Results and discussion

3.1. Fuzzy deterioration rate

The fuzzy inference result is calculated in the form of the membership value of the trigonometry as shown in Eq. (1). The results obtained are then converted to scalar Crisp values to obtain a clear inference value [27], and the defuzzification

Table 5
Relationship between independent and dependent variables (CIP/DCIP)

Age (X)	Deterioration (Y)
6	0.549592
7	0.605623
8	0.587125
21	0.737003
21	0.737003
21	0.657160
24	0.686346
24	0.689961
24	0.682571
24	0.749943
25	0.675054
28	0.751485
28	0.745734
28	0.742864

Table 6
Comparison results of D_s and D_p of each pipeline

Pipe ID	D_s	D_p
CW-01	0.7085	0.6917
CW-02	0.5665	0.6074
CW-03	0.7315	0.7515
CW-04	0.6935	0.7457
GM-01	0.601	0.6316
GM-02	0.4805	0.5752
CJ-01	0.4145	0.4674
GJ-02	0.7305	0.7071
CW-06	0.6715	0.7429
CW-07	0.7085	0.6917
GJ-03	0.5435	0.6124
GM-03	0.4285	0.5647
GJ-05	0.5805	0.6243
GM-04	0.5435	0.5887

process in this study used a weight method such as shown in Eq. (2). The center of gravity of the polygon is illustrated in Fig. 1 for the fuzzy deterioration rate of the corresponding pipe. For example, the center of gravity of CW-01 in the figure was calculated to be 0.6917 as shown in Fig. 1. The whole membership graphs are shown at Fig. 2.

The fuzzy deterioration was calculated through the fuzzy theory for water supply pipes. In general, the deterioration of an aged pipe depends on the traditional evaluation method, resulting in problems with over or underrating the current state of the pipe. In the case of the fuzzy theory, decision-making could be made to be more reasonable [16]. The degree of deterioration (D_s) by the existing evaluation method and deterioration (D_p) using the fuzzy method for the target pipes are shown in Table 6.

3.2. Box-Cox model for CIP and DCIP

If the simple regression model is performed with data from Table 6 and the normal distribution is tested, the variables do not follow the normal distribution. Therefore, the above simple regression does not represent well the relationship between x and y. Relationship between two variables for CIP/DCIP is shown in Fig. 3. To deal with this problem, the relationship between x and y is determined through variable transformation. The Box-Cox transformation method, based on a statistical analysis, was used to find suitable form of variable transformation. The estimated coefficient is the form of x and y^{λ}, in which λ can be –2, –1, 0, 1, and 2 [25].

As the λ of the x (year) variable and the λ of variable y (deterioration), found through the Box-Cox transformation method, is 1.6017 and 1.4179, respectively, the closest value of 1.5 is adopted for both variables. By applying λ as 1.5 to the x and y, respectively, the p-value is 0.9827. Therefore, two variables may be subject to the null hypothesis of normal distribution. The regression model was constructed by designating the converted variable Y as a dependent variable and X as an independent variable.

From the result of the linear regression model of X and Y, the estimate of the Y intersection, β_0, is 0.4226747 and the p-value is less than 0.05, which is acceptable. The estimate of the slope, β_1, is also 0.0014843 and the p-value is less than 0.05, which is also acceptable. Additionally, since R^2 is 0.7586, the derived regression model is sufficient to represent the trend of the data. The above results are summarized in a formula as Eq. (7).

$$Y = 0.4226747 + 0.0014843\,X \tag{7}$$

X and Y are converted by the independent variable of year (x) and the deterioration ($y = D_f$) as shown in Eqs. (7) and (8). The calculated results using Eq. (9) are shown in Table 7.

$$Y^{1.5} = 0.4226747 + 0.0014843x^{1.5} \tag{8}$$

$$y = (0.4226747 + 0.0014843x^{1.5})^{1/1.5} \tag{9}$$

The normality test of residuals using the Normal Q-Q graph for the above regression model is shown in Fig. 4. From the Normal Q-Q graph, the residuals in the regression model appear to be relatively consistent with the 45° line, which means that it is consistent with the standard normal distribution although some outliers appear to exist. Therefore, it is necessary to re-test the normal distribution of residuals using the Shapiro–Wilk Test [25,26]. If the residuals do not show normality, then a modification to the regression model is necessary. Normality analysis of residuals was conducted with Shapiro–Wilk Test [26]. As a result of the Shapiro–Wilk Test, the p-value value for the residual normality of the main steel model data was derived to be 0.156. Since the p-value value is greater than 0.05, the null hypnosis, the residual of the regression model follows the normal distribution, is adopted and the rest of the regression model was constructed to represent the normal distribution. Therefore, the above regression model reflects that the relationship of data is compliant.

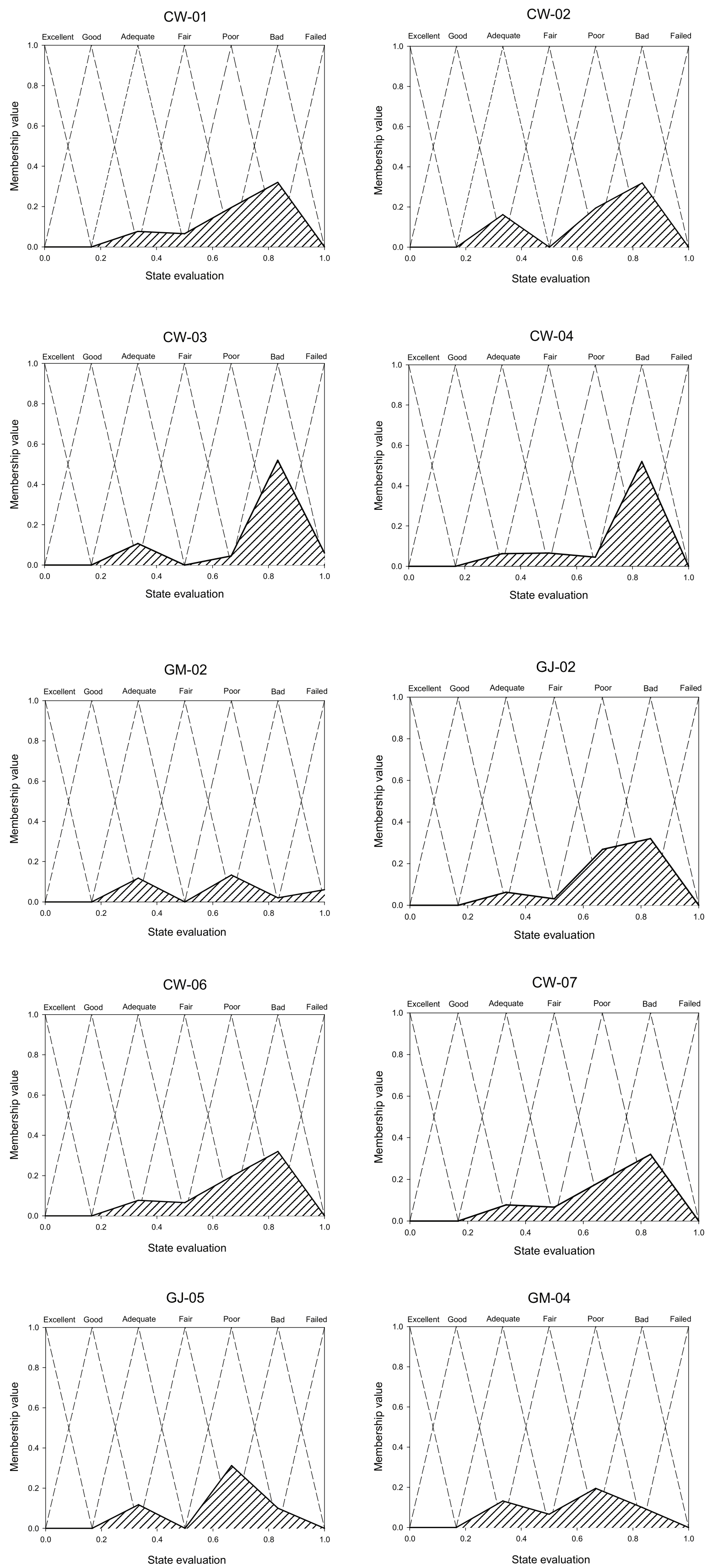

Fig. 2. Calculation result of membership value.

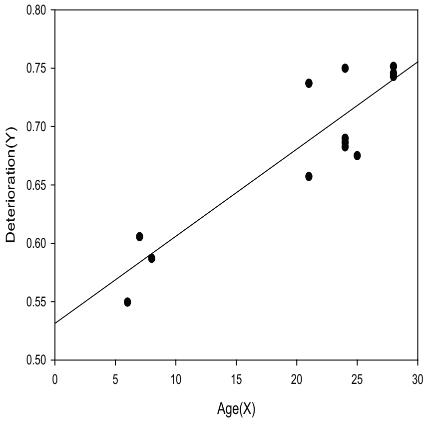

Fig. 3. Relationship between independent and dependent variables (CIP/DCIP).

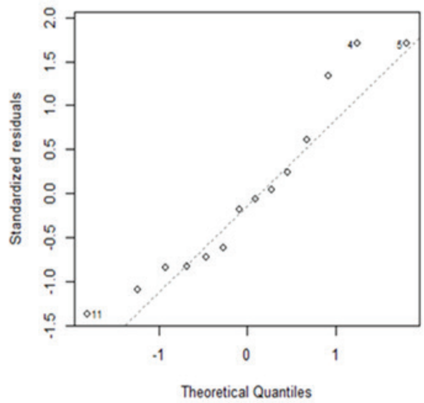

Fig. 4. Result of normalization of residuals.

Table 7
Modeling results of the fuzzy deterioration over year

Year	D_p	Year	D_p	Year	D_p
1	0.5645	17	0.6501	33	0.7863
2	0.5668	18	0.6576	34	0.7957
3	0.5699	19	0.6653	35	0.8052
4	0.5735	20	0.6731	36	0.8148
5	0.5775	21	0.6811	37	0.8245
6	0.5820	22	0.6892	38	0.8342
7	0.5868	23	0.6974	39	0.8440
8	0.5920	24	0.7058	40	0.8539
9	0.5974	25	0.7143	41	0.8639
10	0.6032	26	0.7230	42	0.8739
11	0.6092	27	0.7317	43	0.8840
12	0.6155	28	0.7405	44	0.8941
13	0.6220	29	0.7495	45	0.9043
14	0.6287	30	0.7586	46	0.9145
15	0.6357	31	0.7677	47	0.9248
16	0.6428	32	0.7770	48	0.9352

Table 8
Comparing actual D_p, calculated D_p, actual age, and corrected age

Pipe ID	Actual D_p	Calculated D_p	Actual age (year)	Calculated age (year)
CW-01	0.6917	0.6811	21	22.3
CW-02	0.6074	0.7143	25	10.7
CW-03	0.7515	0.7405	28	29.2
CW-04	0.7457	0.7405	28	28.6
GM-01	0.6316	0.7058	24	14.4
GJ-01	0.5474	0.5920	8	0
GM-02	0.5752	0.5868	7	4.43
GJ-02	0.7071	0.7058	24	24.1
CW-06	0.7429	0.7405	28	28.2
CW-07	0.6917	0.6811	21	22.3
GJ-03	0.6124	0.7058	24	11.5
GM-03	0.5647	0.5820	6	1.1
GJ-05	0.6243	0.7058	24	13.3
GM-04	0.5887	0.6811	21	7.4

In this study, we predicted the 14 deterioration of the cast iron pipes. Actual deterioration of cast iron pipes may differ from those of the above models depending on the surrounding environment or management conditions. Therefore, corrections according to the current state of the pipes are required. For example, for CW-02 pipes, the service life was 25 years from the point of installation. If you look at calculated D_p from Table 8, the value of the cast iron pipe is 0.7143. However, the actual D_p of CW-02 pipes was calculated as 0.6074. This indicates that CW-02 pipes have operated in a better environment than normal cast iron pipes or that adequate maintenance has been performed. Therefore, although the service life of CW-02 pipes is actually 25 years, the current state of the pipe is equivalent to a pipe with a service life of approximately 10.7 years. Table 8 below shows the results by reflecting the current conditions based on the deterioration of pipes.

3.3. *Estimation of failure probability of CIP and DCIP*

The pipes are aging due to internal and external factors over time. As the aging progresses, the durability of the pipes will be weakened, which will result in large and small leaks or accidents [3]. In order to predict the probability of accident on the pipes, the rate of yearly aging increase (d_v) of the pipes must be known first. The increase rate of deterioration (d_v) can be obtained by the derivative of the D_p as shown in Eq. (10):

$$d_v = \frac{\mathrm{d}D_p}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(0.4226747 + 0.0014843t^{1.5}\right)^{\left(\frac{1}{1.5}\right)} = \frac{2}{3}\left(0.4226747 + 0.0014843t^{1.5}\right)^{-\left(\frac{1}{3}\right)}\left(0.00222645\sqrt{t}\right) \quad (10)$$

By multiplying the time (Δt) and adding a correction constant (C) to the formula, the predicted number of accidents occurring in the present (μ_t) can be computed from the previous time (μ_{t-1}).

$$\mu_t = (d_v \times \Delta t + C)(\mu_{t-1}) \tag{11}$$

Here C is a constant to represent the number of accidents occurring at the beginning of the period in which indirect assessment was performed. The predicted number of accidents in the pipes is as shown in Fig. 5 and Table 9. The Poisson probability distribution was applied to predict the probability of accident for each pipe. The number of accidents that were targeted in applying the Poisson probability distribution was the number of accidents occurring in 1 year per 50 km of pipe, based on the national criteria for leakage and damage occurrence in the water supply network [2]. If the probability occurring within the reproducibility period exceeds 0.6321, it means that the average number of accidents is already more than one. The time for renewal or replacement is defined to be when the number of average accidents exceeds one (i.e., when the probability of accident exceeds 0.6321). Fig. 6 represents the life remaining from the present point to the time of renewal or replacement.

The average expected life of the pipes was derived from 32.3 years after estimating the residual life of the target pipe through the accident probability. In case of CW-01, CW-03, and CW-07 mains, it was estimated that the deterioration was more progresssed compared with the results of

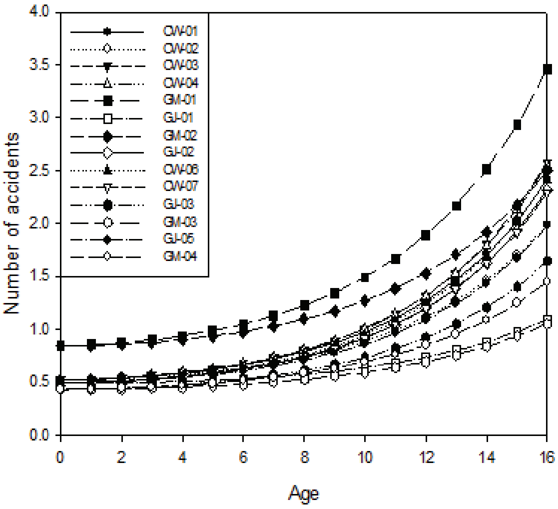

Fig. 5. Prediction of accident occurrence number of CIP/DCIP.

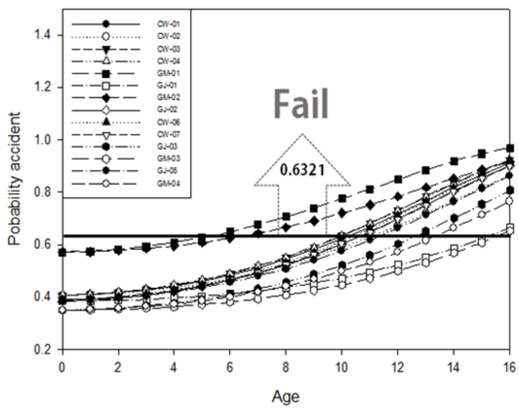

Fig. 6. Prediction of accident occurrence probability of each pipe.

Table 9
Predicted accident occurrence probability of each pipeline

Year	Accident occurrence probability													
	CW-01	CW-02	CW-03	CW-04	GM-01	GJ-01	GM-02	GJ-02	CW-06	CW-07	GJ-03	GM-03	GJ-05	GM-04
0	0.407	0.407	0.407	0.407	0.571	0.386	0.571	0.386	0.390	0.390	0.350	0.350	0.390	0.350
1	0.410	0.410	0.410	0.410	0.575	0.387	0.573	0.390	0.393	0.393	0.353	0.351	0.393	0.352
2	0.417	0.415	0.418	0.418	0.582	0.388	0.578	0.397	0.401	0.400	0.358	0.354	0.399	0.357
3	0.428	0.424	0.430	0.429	0.593	0.391	0.585	0.408	0.412	0.411	0.366	0.357	0.408	0.364
4	0.443	0.436	0.445	0.445	0.608	0.396	0.595	0.422	0.427	0.425	0.377	0.363	0.420	0.373
5	0.462	0.452	0.465	0.465	0.627	0.403	0.608	0.441	0.446	0.443	0.392	0.371	0.436	0.386
6	0.485	0.471	0.489	0.489	0.649	0.412	0.624	0.464	0.470	0.466	0.409	0.380	0.456	0.401
7	0.512	0.494	0.518	0.518	0.676	0.423	0.643	0.491	0.498	0.493	0.431	0.393	0.480	0.420
8	0.545	0.522	0.552	0.551	0.706	0.436	0.666	0.523	0.531	0.525	0.456	0.408	0.508	0.442
9	0.582	0.553	0.591	0.590	0.739	0.453	0.691	0.560	0.570	0.561	0.486	0.425	0.540	0.468
10	0.623	0.589	0.634	0.633	0.775	0.472	0.720	0.602	0.612	0.603	0.520	0.446	0.577	0.499
11	0.669	0.629	0.681	0.680	0.812	0.495	0.751	0.648	0.660	0.648	0.559	0.471	0.618	0.533
12	0.718	0.672	0.732	0.730	0.849	0.522	0.784	0.698	0.710	0.698	0.602	0.499	0.664	0.572
13	0.768	0.719	0.784	0.782	0.885	0.552	0.818	0.751	0.763	0.749	0.650	0.531	0.712	0.616
14	0.819	0.768	0.835	0.833	0.919	0.586	0.853	0.804	0.816	0.802	0.701	0.567	0.762	0.663
15	0.868	0.817	0.882	0.881	0.947	0.623	0.886	0.855	0.867	0.853	0.754	0.608	0.813	0.713
16	0.911	0.863	0.924	0.923	0.969	0.664	0.917	0.901	0.911	0.899	0.807	0.652	0.862	0.765

the deterioration model based on indirect evaluation data. Remaining service life of 10.2, 10.1, and 10.8 years were derived, respectively. CW-02, GM-01, GJ-01, GM-02, GJ-03, GM-03, GJ-05, and GM-04 pipes are estimated to have been managed relatively well compared with the average cast iron pipes. The expected remaining service life estimates were 11.1, 5.1, 15.2, 6.5, 12.8, 15.6, 11.4, and 13.3 years, respectively.

4. Conclusions

In this study, we developed a method to predict the remaining service life of cast iron pipes through the probability of accident. We adopted the fuzzy method and Box-Cox model to consider complex surrounding environment of underground pipe with limited field data. The remaining life prediction can be a technical basis for prioritizing maintenance such as repair and rehabilitation of pipes. After the deterioration of pipes was determined using the fuzzy method, the mathematical relationships for deterioration over time were successfully calculated using the nonlinear regression technique of the Box-Cox statistical package. The validity of this mathematical model was acceptable after running 'R' statistical package. The increase rate of deterioration was obtained using its derivative function from which the probability of accidents occurring at the cast iron pipe was obtained. Probability of occurrence of more than the target number of accidents was derived through Poisson probability distribution. The point of renewal was determined at the time when the accident probability exceeded 0.6321. As a result, the remaining expected lives of CW-01, CW-03, and CW-07 pipes were 10.2, 10.1, and 10.8 years, respectively. Also, those for CW-02, GM-01, GJ-01, GM-02, GJ-03, GM-03, GJ-05, and GM-04 were 11.1, 5.1, 15.2, 6.5, 12.8, 15.6, 11.4, and 13.3 years, respectively.

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