



Deterioration Prediction Model of Water Pipes Using Fuzzy Techniques

퍼지기법을 이용한 상수관로의 노후도예측 모델 연구

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ABSTRACT

Pipe Deterioration Prediction (PDP) and Pipe Failure Risk Prediction (PFRP) models were developed in an attempt to predict the deterioration and failure risk in water mains using fuzzy technique and the markov process. These two models were used to determine the priority in repair and replacement, by predicting the deterioration degree, deterioration rate, failure possibility and remaining life in a study sample comprising 32 water mains. From an analysis approach based on conservative risk with a medium policy risk, the remaining life for 30 of the 32 water mains was less than 5 years for 2 mains (7%), 5-10 years for 8 (27%), 10-15 years for 7 (23%), 15-20 years for 5 (17%), 20-25 years for 5 (17%), and 25 years or more for 2 (7%).

Key words: Fuzzy, Remaining life, Risk analysis, Water pipe deterioration prediction model

주제어: 퍼지, 잔존수명, 리스크 분석, 노후도예측 모델

1. Introduction

With the quantitative growth in water supply pipes in Korea, pipes made of various kinds of materials have been introduced. However, non-systematic repair/maintenance management on networked pipes has led to shorter lifespans than in advanced foreign countries. Furthermore, negative side-effects have arisen

such as rust due to weak durability and functionality in pipes, in addition to economic loss caused by water leakage. Therefore, the conditions of water mains must be evaluated for sustainable management targeted at more stable and safer water distribution.

Specially, as deterioration and pipe failure in such large-scale water mains pose great potential risk in the case of water leakage, the development of preventive countermeasures would be beneficial, rather than post-accident repair, for example, by putting into action plans to replace deteriorated pipes.

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The factors of considering the prediction of the deterioration of water pipe can be divided with three types such as the physical factor, environmental factor, operational factor (Al-Barqawi et al., 2006). There are the pipe material, pipe, wall thickness, pipe age, pipe diameter, type of connection, pipe lining, the form of lining materials, dissimilar metals as the physical factor. As the environmental factor, there are the types of soil, ground-water, climate, type of backfill, stray current, seismic activity etc. There is the water pressure in the pipe, the water pressure, leakage, water quality, velocity, maintenance activities as the operational factors. Those factors cannot be easily measured or quantified. The prediction of deterioration of water pipe by examining the relations between the factors is more difficult task.

Before the prediction of the deterioration of water pipe, the most common and typical concept about the pipeline life is the "Bathtub Curve" about the pipeline life cycle. The Bathtub Curve means the early burst and the frequency of accidents due to the high failure probability by the initial problems such as the design errors, materials, operating, and the low failure probability is continuously maintained by the stabilization of pipe, but when the years of pipe laying progress increase, in other words, the increase of failure probability due to the end of the life of pipeline, as a result, it shows the direction of increase of the frequency of accidents of pipeline. The management of preventive maintenance before the accident due to the deterioration of the water pipe can extend the life of pipeline (Kleiner et al., 2001).

The methods of prediction of deterioration of water pipe can be divided with two types. First, there is method of using the physical model, second, there is method of using the statistical model. The method of using the physical model is to examine the directness pipe status (presence of scale, degree of corrosion et al.), the scientific basis has the strong point of securely and widely available, but there is limit of the available data and it takes the data research costs. On the other hand, there are the method of supposing the exponential

function or the linear function with correlation and the method of supposing the already established model such as the regression analysis model, markov process model, Poissons model, cohort living model as the methods of using the statistical model, and it has the strong point to collect the data with the low cost and to be used variously but it has the weak point as the unclear scientific basis.

As the method of using the physical model for the prediction of deterioration of water pipe, there are various study cases such as the deterioration prediction of the steel pipe by Pandey (1998), PVC pipe deterioration prediction by Davis et al.,(2007), and the cast-iron pipe deterioration prediction by Moglia et al.,(2008). And there are the various cases such as the exponential function by Walski(1987), the linear function by Jacob and Karney(1994), markovian process by Kleiner(2001), cohort model by Kropp and Baur(2005), fuzzy technique and markov process by Kleiner(2006), the logistic regression analysis by Park (2008), the random fuzzy technique by Lim(2010), and the artificial neural network by Lee(2010) in the models of using the statistical method.

Especially, the case of studies by Kleiner(2006) case of studies suggested the deterioration prediction model of the water supply pipeline by using the fuzzy technique and markov process, so the subjective and vague deterioration related indicators of water pipe and the objective and quantitative deterioration state can be shown by using the fuzzy technique, and the deterioration transition of the water pipe can be predicted by using markovian process, so in this regard, it is judged as the most effective deterioration prediction model.

But although the various water pipe deterioration prediction method theories, it is difficult to develop the reliable water pipe deterioration prediction model due to the lack of data and inaccuracies of data in Korea.

Therefore, this study aims to develop the water pipe deterioration prediction model using the fuzzy technique and markov process by Kleiner(2006) and to examine its applicability.



2. Methods

2.1 Procedure

Based on Kleiner (2006)'s development of a reliable decision-making tool for the repair and replacement of deteriorated pipes based on fuzzy technique and the markov process, the present study used the PDP and Pipe Failure Risk Prediction (PFRP) models via the following three-stage process.

In the first stage, the degree of deterioration was determined in 32 large mains of multi-regional waterworks using the indirectness assessment factor, while deterioration factors and their weighting factors were identified.

In the second stage, the PDP model was developed by using fuzzy deterioration to estimate the fuzzificated degree of deterioration in the above first stage, as well as the markov process and pipe ages. The values in deterioration velocity and remaining lifetime of the targeted 32 mains were calculated by controlling the PDP model in such a way as to minimize the summed value of the square of the difference between the predicted value and the actual measured value against fuzzy deterioration.

In the third stage, the PFRP model capable of determining pipe failure risk finalized by using the failure possibility identified by the PDP model and "predicted failure

consequences." The PFRP model was used to determine the degree of failure risk generated as output values through fuzzy algorithm based on such input values as failure possibility and "predicted failure consequences." The model application was successful in determining the in-time period of rehabilitation and readjustment for pipes of water supply system by calibrating the susceptibility of the failure risk to age. Fig. 1 shows the brief procedure followed in developing the PDP and PFRP models.

2.2. Target data

The deterioration of 32 water mains pipelines was assessed using data obtained from the analysis and investigation of multi-regional waterworks and industrial waterworks with respect to facility data, burial environment, pipe state, outer state, inner state, soil corrosivity, microbial characteristics, construction state, management state, historical data, physical strength, chemical composition, and water corrosion. Among these factors, deterioration assessment was carried out with pipelines and assessment indices that showed relatively suitable results and were readily assessable.

The 32 pipelines were largely used for conveying raw water, treated water, or industrial water. The pipe material was CIP, DCIP, SP, or PC, and they were mostly large pipes with diameters ranging from 300mm to 2,200mm.

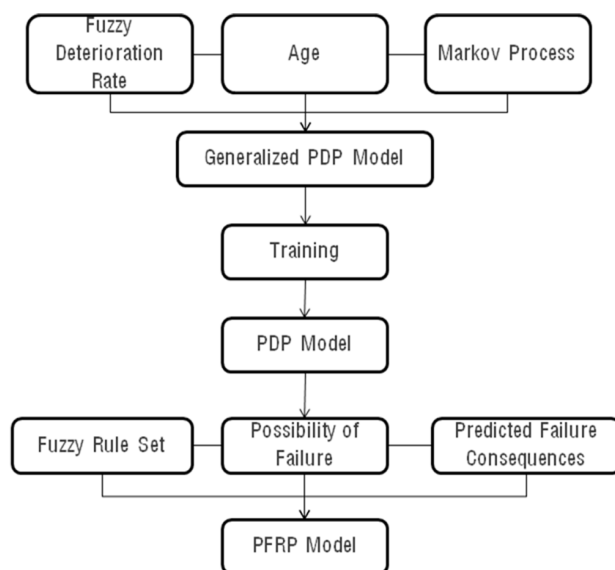


Fig. 1. Method of PDP and PFRP Modeling.

2.3 Deterioration assessment

The local 'Manual for Diagnosing Water Supply Piping Network' requires such assessment items as indirect evaluation factors, direct evaluation factors, and corrosion-impacting factors to determine more about structural safety. Indirect evaluation factors were mainly adopted owing to easier accessibility and better accuracy to related data, which detailed as pipe material, pipe diameter, inner coating, outer coating, age of use, type of soil, traffic type, connection type, leakage and failure recording, and occurrences of claim-petitioning such as water quality/pressure. The nine aforementioned subfactors were incorporated in the study by excluding the last subfactor of occurrences of claim-petitioning due to statistical insufficiency.

Table 1. Indirectness assessment index and classification scope

Index	Classification scope	Value	State	Index	Classification scope	Value	State
1. Material	CIP, GSP	1.00	Bad	6. Soil	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	Adequate
	DCIP	0.25	Adequate		Sand	0.00	Excellent
	STS, PFP	0.00	Good				
2. Diameter	<=150mm	1.00	Bad	7. Traffic type	Highway	1.00	Bad
	150 ~ 350mm	0.80	Poor		>4 lane road	0.75	Poor
	350 ~ 600mm	0.60	Fair		2 lane road	0.50	Fair
	600 ~ 1000mm	0.40	Adequate		Local road	0.25	Adequate
	1000 ~ 2000mm	0.20	Good		Footway	0.00	Good
	>2000mm	0.00	Excellent				
3. Inner coating	No	1.00	Bad	8. Connection method	Sleeve coupling	1.00	Bad
	Epoxy	0.75	Poor		Flange, Socket	1.00	Poor
	Coaltar enamel	0.75	Fair		heat anastomosis	0.50	Fair
	Asphalt	0.50	Adequate		Mechanical, Push-on J.	0.25	Adequate
	Cement mortar	0.00	Good		Coating after welding	0.25	Good
4. Outer coating	No	1.00	Bad	9. Leakage and failure recording	>5times/5year-50km	1.00	Failed
	Coaltar enamel	0.75	Fair		3 ~ 5times/5year-50km	0.50	Poor
	Asphalt	0.00	Good		1 ~ 3times/5year-50km	0.25	Adequate
			No		0.00	Excellent	
5. Age	>25year	1.00	Bad				
	20 ~ 25year	0.75	Poor				
	15 ~ 20year	0.50	Fair				
	10 ~ 15year	0.25	Adequate				
	<=10year	0.00	Good				

The 9 deterioration assessment indices are shown in Table 1 Here, the state of deterioration assessment indices is divided into diverse grades of 3, 4, 5 or 6. The state of each assessment index was rated on the following 7-point grade scale to ensure consistent evaluation of the states of deterioration assessment indices: Excellent, Good, Adequate, Fair, Poor, Bad, and Failed.

The indirectness assessment items do not necessarily have the same effects on water main deterioration. Therefore, calculating the deterioration of a water main necessitates calculating the weighting values of indirectness assessment items. Since this study does not examine the weighting values of indirectness assessment items that affect the deterioration of water mains, the existing literature (Deteriorated Water Main Assessment and Management Manual, 2002) was cited. Consequently, the weighting value by indirectness assessment item was determined to be 0.22 for material, 0.11 for diameter,

0.08 for inner coating, 0.02 for outer coating, 0.20 for age, 0.06 for soil, 0.06 for traffic type, 0.02 for connection type, and 0.23 for leakage and failure recording, with the total of the weighting values being 1.

2.4. PDP Modeling

The degree of deterioration was calculated by multiplying the weighting value by the graded subfactor, the result of which was further converted into fuzzy deterioration through fuzzification with 9 membership values. The fuzzy deterioration in case of time t is expressed by Eq. 1 as follows;

$$C_t = \{ \mu_t^{C_1}, \mu_t^{C_2}, \mu_t^{C_3}, \mu_t^{C_4}, \mu_t^{C_5}, \mu_t^{C_6}, \mu_t^{C_7} \} \quad (\text{Eq. 1})$$

where, C_t : Fuzzy deterioration in case of time t

$\mu_t^{C_i}$: Membership value as to time t and triangular membership



In the current state as the water pipe condition the fuzzy deterioration C_t of the pipeline has spread as C_{t+1} by the transition matrix D_t using the markov process as the concept which is influenced on the verge stage. If markov process concept is used sequentially by the time sequence after the water pipe is layed, C_t value about whole life of water pipe can be expressed. In other words, markov process is the tool for prediction C_t of value progress through the transition matrix D_t in the conceptual aspect in the future. It can be expressed by Eq. 2 as follows;

$$C_{t+1} = C_t \otimes D_t \tag{Eq. 2}$$

Eq. 2 has two pre-assumptions: firstly, water mains are not capable of improvement without external intervention as expressed by $D_t^{i,j} = 0$ when all $i > j$. Secondly, pipes suffer relatively slow but continual natural deterioration, thus concluding that triangular membership, i , is processed to deterioration, $i + 1$ if time is in short for deterioration (Kleiner, 2001). Therefore, Eq. 3 is drawn when D_t is formed as a matrix using the above assumptions.

$$\mu_{t+1}^{C_i} = \begin{cases} \mu_t^{C_1} (1 - D_t^{1,2}) & i = 1 \\ \mu_t^{C_{i-1}} D_t^{i-1,i} + \mu_t^{C_i} (1 - D_t^{i,i+1}) & i = (2, 3, \dots, 6) \\ \mu_t^{C_6} D_t^{6,7} + \mu_t^{C_7} & i = 7 \end{cases} \tag{Eq. 3}$$

where, $D_t^{i,j}$ is the deterioration rate when triangular membership, i , in time t is transformed to deterioration, j . For example, $D_t^{1,2}$ means the degree of deterioration rate when triangular membership 1(excellent) in time t is transformed to triangular membership 2(good). Likewise, if $D_t^{i,j}=0.05$, 5% membership value in triangular membership, i , is transformed to triangular membership, $i + 1$ when the deterioration of pipes is transformed from time t to time $t + 1$. In other words, No. i membership value included in C_t spreads No. $i - 1$ membership value by $D_t^{i,j}$, or can be spread as No. $i + 1$ membership value, and it means to calculate C_t using markov process concept by the flow of time of the water pipe.

Eq. 3 shows that the fuzzy deterioration in pipes is gradually absorbed to failed triangular membership. In such cases, however, the analysis is too complicated to be non-realistic because the fuzzy deterioration in pipes shall be expressed only through numerous triangular memberships. Therefore, the threshold value, G_i , is introduced to reduce the distribution of triangular membership to 7 grades, subject to the pipe conditions. G_i acts to control the value of membership when triangular membership i flows to change to $j(i + 1)$ in time t , which means the value of membership in triangular membership i is restricted unless otherwise exceeded by threshold value G_i in a certain time τ prior to t . To represent this, Eq. 4 is formed by introducing G_i to Eq. 3.

$$\mu_{t+1}^{C_i} = \begin{cases} \mu_t^{C_1} (1 - D_t^{1,2}) & i = 1 \\ \mu_t^{C_{i-1}} D_t^{i-1,i} + \mu_t^{C_i} - g_i D_t^{i,i+1} & i = 2 \\ g_{i-1} \mu_t^{C_{i-1}} D_t^{i-1,i} + \mu_t^{C_i} - g_i D_t^{i,i+1} & i = \{3, 4, \dots, 6\} \\ \mu_t^{C_6} + g_i \mu_t^{C_6} D_t^{6,7} & i = 7 \end{cases} \tag{Eq. 4}$$

$$g_i = \begin{cases} 1 & \text{if } \max(\mu_\tau^{C_i}) \geq G_i \text{ for any } \tau \leq t \\ 0 & \text{otherwise} \end{cases}$$

Fig. 2 shows the diagram extracted from Eq. 4.

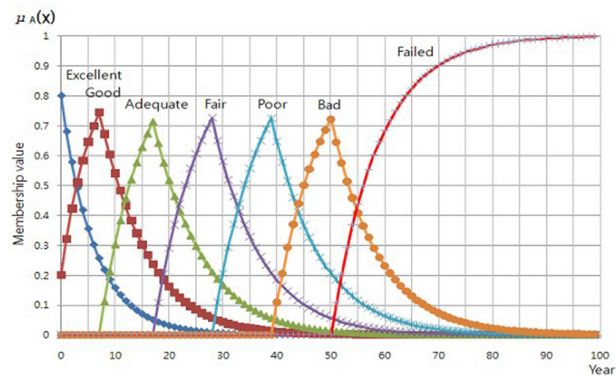


Fig. 2. Deterioration curves with membership thresholds

Therefore, when $D_t^{i,j}$ and G_i in Eq. 4 vary in the deterioration prediction model, the shape of the deterioration curve in Fig. 2 is changed. Using this method, PDP modeling was finalized in the pertinent piping network so as to minimize the summed value of the square of the difference between the predicted value and actual measured value.

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2.5 PFRP Modeling

The pipe failure risk was estimated through fuzzy algorithm using rule-base by setting as input values the failure possibility (frequency) depending on the age of time elapse in the failed curve of PDP the model, as well as the "predicted failure consequences (damaged magnitude)".

2.5.1 Failure Possibility (Frequency)

The failure possibility as in the PFRP model can be extractable from the "failed" curve by the age of time elapse in the PDP model. For example, when Pipe No. CW-01

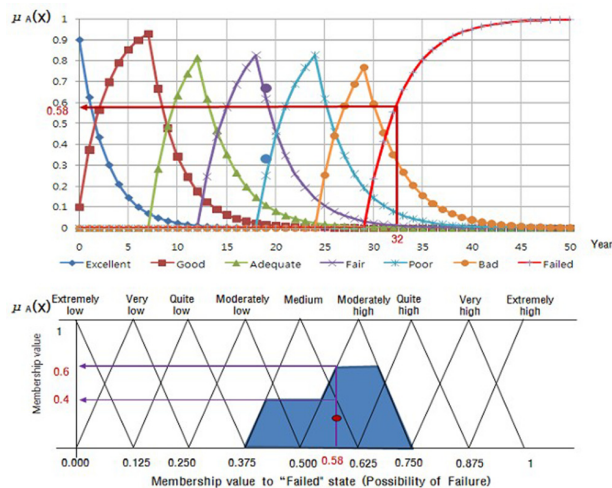


Fig. 3. Re-mapping of membership values in the "Failed" state onto the "Possibility of Failure" fuzzy set

is superannuated with an age of 32 years, the resultant failure possibility is 0.58, which can be expressed following fuzzification by the diagram shown in Fig. 3.

2.5.2 Predicted Failure Consequences (Damaged Magnitude)

"The predicted failure consequences" can be determined according to the water supply connection, pipe diameter and use purpose of the pipe. By focusing on the fact that volumetric water flowability is directly dependant on the size of the pipe diameter, this study adopted a subfactor of pipe diameter as the determinants for "predicted failure consequences"; more specifically, by relying on lost water volume in the case of pipe fracture (failure) and the number of households cut off for water supply by using fuzzy technique based on the 9 grades (from extremely low to extremely severe). For example, the "predicted failure consequences" for the 400mm-pipe can be expressed as shown in Fig. 4

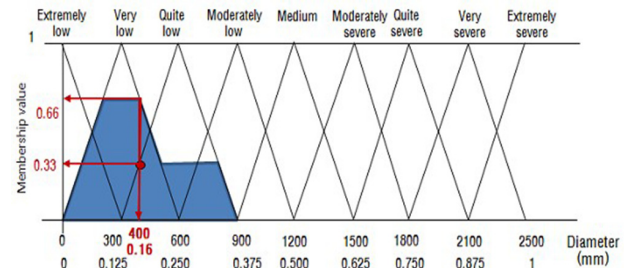


Fig. 4. Fuzzification of predicted failure consequences

Table 2. Fuzzy rule-set for failure possibility and consequence relationship

Possibility of Failure	Predicted Failure Consequences								
	Extremely low	Very low	Quite low	Moderately low	Medium	Moderately severe	Quite severe	Very severe	Extremely severe
Extremely low	EL	EL	VL	VL	QL	QL	ML	ML	M
Very low	EL	VL	VL	VL	QL	ML	M	M	MH
Quite low	VL	VL	QL	QL	ML	ML	M	M	MH
Moderately low	QL	QL	QL	QL	ML	M	M	MH	QH
Medium	QL	ML	ML	ML	M	M	MH	MH	QH
Moderately high	ML	ML	ML	ML	M	MH	MH	QH	VH
Quite high	ML	M	M	M	MH	MH	QH	QH	VH
Very high	M	M	M	M	MH	QH	VH	VH	EH
Extremely high	M	MH	MH	MH	QH	VH	VH	EH	EH

EL : Extremely low, VL : Very low, QL : Quite low, ML : Moderately low, M : Medium, MH : Moderately high, QH : Quite high, VH : Very high, EH : Extremely high



showing that membership values are 0.66 for Very-Low triangular membership, 0.33 for Quite-Low triangular membership, and zero for the remaining grades.

2.5.3 Fuzzy Rule-set

To execute the fuzzy algorithm, with the possibility of failure and "the predicted failure consequences" being the input and the failure risk being as the output, rules that control the input and output values of the fuzzy algorithm are necessary. The fuzzy rule-set consists of the rules that control the input and output values of the fuzzy algorithm, and refers to the failure risk for the possibility of failure and "the predicted failure consequences" at the number of all cases.

This study used a generalized fuzzy rule-set, as shown in Table 2. The proposed fuzzy rule-set, however, is fully modifiable based on empirical grounds. It is deemed that the reliability of the result value will be increased if the fuzzy rule-set is modified and supplemented with optimal values at the stage of utilizing the development result.

3. Results and Discussion

3.1 Deterioration assessment

The deterioration of the 32 pipelines can be determined by applying weighting values of indices to their graded values of indices, as shown in Table 3.

The deterioration of a pipeline has a value between 0 and 1. The nearer to 0 the deterioration, the better the pipeline,

and the nearer to 1 the deterioration, the poorer the pipeline. Pipeline No. GS-01 showed a deterioration of 0.242, and was the best pipe. Pipeline No. CW-03 showed a deterioration of 0.749, and was the poorest pipe. These data on pipeline deterioration, however, are only relative, not absolute, values for determining the degree of deterioration. The current state of a pipeline cannot be determined only with the deterioration of the pipeline, which is judged to be quite insufficient as grounds for deciding at which time in the future the pipeline should be renewed or replaced. Therefore, it is deemed that the deterioration of pipelines calculated in this section has limitations.

3.2. Fuzzy deterioration assessment

To apply the deterioration of pipelines calculated above to the PDP model, it should be converted to the fuzzy deterioration. The results of converting the deterioration of the 32 pipelines to the fuzzy deterioration are shown in Table 4.

Just like the deterioration of the 32 pipelines obtained above, pipeline No. GS-01 shows the best fuzzy deterioration, which may be expressed as (0, 0.54, 0.46, 0, 0, 0, 0); and pipeline CW-03 shows the poorest fuzzy deterioration, which may be expressed as (0, 0, 0, 0, 0.5, 0.5, 0).

3.3. Results of the PDP Model

If the PDF model is trained with the fuzzy deterioration of the 32 pipelines, the threshold values of G_i and $D_t^{i,j}$

Table 3. Deterioration rate analysis result of pipes

Pipe ID	Deterioration rate	Pipe ID	Deterioration rate	Pipe ID	Deterioration rate
CW-01	0.556	GJ-01	0.330	GJ-03	0.421
CW-02	0.408	PH-01	0.571	KG-02	0.407
CW-03	0.749	GM-02	0.420	KG-03	0.415
CW-04	0.731	CJ-01	0.250	US-02	0.392
SD-01	0.472	GJ-02	0.668	NG-05	0.459
GS-01	0.242	NG-04	0.404	NG-06	0.459
GM-01	0.605	US-01	0.512	GM-03	0.313
CW-05	0.477	KG-01	0.447	GJ-04	0.489
NG-01	0.353	YC-01	0.370	GJ-05	0.561
NG-02	0.376	CW-06	0.731	GM-04	0.433
NG-03	0.377	CW-07	0.628		

*Bold letters indicate the maximum and minimum values

Table 4. Fuzzy deterioration rate of pipes

Pipe ID	Fuzzy deterioration rate	Pipe ID	Fuzzy deterioration rate
CW-01	(0, 0, 0, 0.670, 0.330, 0, 0)	NG-04	(0, 0, 0.580, 0.420, 0, 0, 0)
CW-02	(0, 0, 0.550, 0.450, 0, 0, 0)	US-01	(0, 0, 0, 0.930, 0.070, 0, 0)
CW-03	(0, 0, 0, 0, 0.500, 0.500, 0)	KG-01	(0, 0, 0.130, 0.870, 0, 0, 0)
CW-04	(0, 0, 0, 0, 0.620, 0.380, 0)	YC-01	(0, 0, 0.780, 0.220, 0, 0, 0)
SD-01	(0, 0, 0.170, 0.830, 0, 0, 0)	CW-06	(0, 0, 0, 0, 0.620, 0.380, 0)
GS-01	(0, 0.540, 0.460, 0, 0, 0, 0)	CW-07	(0, 0, 0, 0.230, 0.770, 0, 0)
GM-01	(0, 0, 0, 0.370, 0.630, 0, 0)	GJ-03	(0, 0, 0.480, 0.520, 0, 0, 0)
CW-05	(0, 0, 0.130, 0.870, 0, 0, 0)	KG-02	(0, 0, 0.550, 0.450, 0, 0, 0)
NG-01	(0, 0, 0.880, 0.120, 0, 0, 0)	KG-03	(0, 0, 0.520, 0.480, 0, 0, 0)
NG-02	(0, 0, 0.730, 0.270, 0, 0, 0)	US-02	(0, 0, 0.640, 0.360, 0, 0, 0)
NG-03	(0, 0, 0.730, 0.270, 0, 0, 0)	NG-05	(0, 0, 0.250, 0.750, 0, 0, 0)
GJ-01	(0, 0.020, 0.980, 0, 0, 0, 0)	NG-06	(0, 0, 0.250, 0.750, 0, 0, 0)
PH-01	(0, 0, 0, 0.570, 0.430, 0, 0)	GM-03	(0, 0.120, 0.880, 0, 0, 0, 0)
GM-02	(0, 0, 0.480, 0.520, 0, 0, 0)	GJ-04	(0, 0, 0.070, 0.930, 0, 0, 0)
CJ-01	(0, 0.500, 0.500, 0, 0, 0, 0)	GJ-05	(0, 0, 0.630, 0.370, 0, 0, 0)
GJ-02	(0, 0, 0, 0, 0.990, 0.010, 0)	GM-04	(0, 0, 0.400, 0.600, 0, 0, 0)

*Bold letters indicate the maximum and minimum values

Table 5. PDP model training result of pipes

Pipe ID	Age (year)	$D_t^{i,j}$	sum of square deviations	Remaining life(year)	Pipe ID	Age (year)	$D_t^{i,j}$	sum of square deviations	Remaining life(year)
CW-01	19	0.305	0.0207	10	NG-04	13	0.310	0.0225	15
CW-02	23	0.195	0.0118	23	US-01	31	0.180	0.0515	19
CW-03	26	0.305	0.0114	3	KG-01	17	0.325	0.0006	9
CW-04	26	0.295	0.0332	4	YC-01	6	0.550	0.0711	8
SD-01	23	0.240	0.0020	15	CW-06	28	0.280	0.0246	3
GS-01	9	0.280	0.0034	22	CW-07	21	0.325	0.0028	5
GM-01	23	0.280	0.0093	8	GJ-03	24	0.195	0.0093	22
CW-05	37	0.155	0.0053	22	KG-02	19	0.225	0.0186	20
NG-01	13	0.295	0.0340	17	KG-03	19	0.235	0.0132	19
NG-02	13	0.305	0.0288	16	US-02	12	0.350	0.0121	13
NG-03	13	0.305	0.0288	16	NG-05	16	0.310	0.0048	12
GJ-01	7	0.515	0.0240	9	NG-06	16	0.310	0.0048	12
PH-01	22	0.275	0.0122	10	GM-03	6	0.545	0.0001	8
GM-02	6	0.615	0.0084	7	GJ-04	24	0.240	0.0141	14
CJ-01	5	0.515	0.0009	11	GJ-05	24	0.175	0.0236	28
GJ-02	23	0.320	0.0358	4	GM-04	21	0.220	0.0063	19

*Bold letters indicate the maximum and minimum values

have values that minimize the sum of squares of deviation for the measured and predicted values.

Under the assumption that fuzzy deterioration at the time of underground laying was (0.9, 0.1, 0, 0, 0, 0, 0), the critical values G_i in each triangular membership were applied

by (-, 0.9, 0.8, 0.8, 0.8, 0.7, -). Similarly, when fuzzy deterioration was computed for all 32 pipe mains, the $D_t^{i,j}$ values, added values of difference square and remaining lifetime could be determined in each pipe main. The results are shown in Table 5.



Application of the PDP model revealed that GM-02 showed the highest deterioration rate of 0.615, and that CW-05 showed the lowest deterioration rate of 0.155. CW-06 and CW-03 had the shortest remaining life of 3 years, and GJ-05 had the longest remaining life of 28 years. Analysis of the mean deterioration rates by material revealed that CIP had a mean deterioration rate of 0.305, DCIP 0.343, and SP 0.307. In conclusion, combining the results of deterioration rate and remaining life revealed that pipeline Nos. CW-03, CW-04, GJ-02, CW-06, and CW-07 should be given priority for improvement or replacement. Nevertheless, the results from the PDP model need to be applied to the PFRP model in order to predict the deterioration more accurately and logically.

3.4 Results of the PFRP Model

Pipe failure risk was predicted according to the age of pipes by taking full advantage of 'failure possibility', 'predicted failure consequences' and 'rule-set' extracted from the PDP model. Accordingly, the result for CW-01 is shown in Fig. 5, which demonstrates that all other cases are equivalently computable.

The failure risk in the study can be expressed by defuzzified failure risk, conservative failure risk and optimistic failure risk. To strengthen safety in piping, optimistic failure risk may be preferable to conservative failure risk because, even in the case of the same risk, the conservative failure risk has earlier renewal and replacement than the optimistic failure risk.

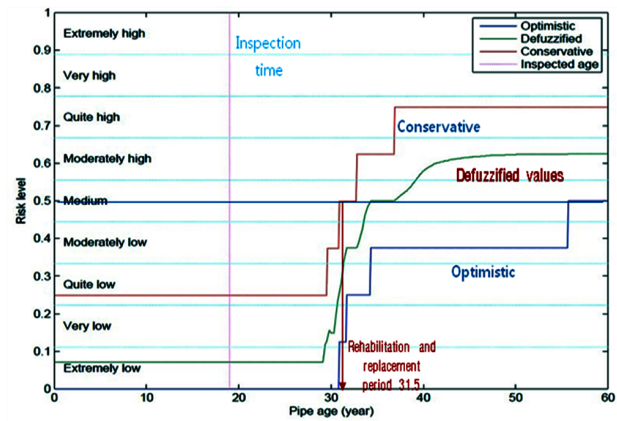


Fig. 5. PFRP model result of Pipe ID CW-01.

Unlike in the PDP model, the remaining life in the PFRP model can be applied flexibly according to failure risk, conservative failure risk or optimistic failure risk. For example, in the event that the conservative failure risk is determined when the risk caused by policy is set as medium, the results through the PFRP model against all 32 mains are made as shown in Table 6 according to the priority in repair and replacement, i.e., the order of remaining life.

From this analysis with a medium level of policy risk and a conservative failure risk, among the 30 pipelines, excluding 2 whose remaining life could not be obtained, 2 pipelines (7%) had a remaining life of 5 years, 8 (27%) of 5-10 years, 7 (23%) of 10-15 years, 6 (20%) of 15-20 years, 5 (17%) of 20-25 years, and 2 (7%) of more than 25 years.

Table 6. Remaining life at medium and conservative risk levels

Pipe ID	Remaining life(year)	Rank	Pipe ID	Remaining life(year)	Rank	Pipe ID	Remaining life(year)	Rank
CW-01	12.5	14	GJ-01	10	10	GJ-03	25.5	29
CW-02	24.5	28	PH-01	10.5	11	KG-02	20.5	24
CW-03	5	2	GM-02	8	6	KG-03	19.5	23
CW-04	5.5	3	CJ-01	11.5	13	US-02	13.5	15
SD-01	-	-	GJ-02	5.5	3	NG-05	13.5	15
GS-01	22.5	26	NG-04	16.5	18	NG-06	13.5	15
GM-01	10.5	11	US-01	-	-	GM-03	9	7
CW-05	23.5	27	KG-01	9.5	9	GJ-04	16.5	18
NG-01	17.5	20	YC-01	9	7	GJ-05	31.5	30
NG-02	17.5	20	CW-06	4.5	1	GM-04	21.5	25
NG-03	17.5	20	CW-07	6.5	5			

*Bold letters indicate the maximum and minimum values

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4. Conclusion

Both PDP and PFRP models were developed in an attempt to predict the deterioration and failure risk in water mains using fuzzy technique and the markov process. These two models were used to determine the priority in repair and replacement, by predicting the deterioration degree, deterioration rate, failure possibility and remaining life of 32 water mains.

Although the PDP model was found to be effective in determining the approximate timing for rehabilitation and replacement, using the model for prediction was difficult when the deterioration was already in process. On the contrary, the PFRP model could be applied flexibly, regardless of ongoing deterioration; hence, this model is likely to be the fittest for determining the timing of repair/replacement when the related data is accumulated. From an analysis approach based on conservative risk with a medium policy risk, the remaining life for 30 of the 32 water mains was as follows: 2 mains (7%) showed a remaining life of less than 5 years, 8 (27%) of 5-10 years, 7 (23%) of 10-15 years, 6 (20%) of 15-20 years, 5 (17%) of 20-25 years, and 2 (7%) of 25 years or more.

Thus, this study calculated the deterioration prediction and remaining life based on only 32 pipeline as subjects. But it is judged that more selections of the analysis case on the water pipe and the verification water pipe of same type should be needed for the reliability improvement of PDP model and PFRP model. Especially, the data which was used for PDP model and PFRP model in this study is the indirectness assessment factor about the pipe deterioration, so the factor which can be changed with time is only the pipe age factor among the indirectness assessment factors. In this case, the measurement of the deterioration by the specific time interval about the same water pipe cannot classify the difference between the actual measurement value and the prediction value by the model definitely. But if the directness assessment factors such as the physical strength of capsule and chemical composition, etc. which is changed with the time are applied to PDP model and PFRP model which was suggested in this study, it is judged that will be used enough as the validation data for the reliability

of this model.

In other words, it can be used enough for the water pipe deterioration of PDP model and PFRP model using the indirectness assessment factor and for the remaining life prediction, and it is judged that will be used more effectively for determining the renewal and replacement priorities and time of aging water pipe by drawing reliable result rather than the case that the directness assessment factor about the water pipe deterioration assessment is managed and used continually in Korea.

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