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Comprehensive Evaluation Modeling of Water Distribution Network by Using Statistical Analysis

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Abstract

A score evaluation method is the most common deterioration evaluation technique used in Korea for the efficient maintenance of the water distribution network which is a major society-based facility. This study carried out modeling for complementing the limitations of the existing score evaluation method.

Keywords: *Residual life, Water distribution systems, Leakage, Corrosion rate, Shot-Blasting*

1. Introduction

Water distribution network is major infrastructure reliably supplying water, a substance necessary for living to everyone. The water distribution network, which should maintain the function of a facility while maintaining proper water quantity, water quality and water pressure, requires systematic maintenance and administrative operations for deterioration management.

In Korea, various methods have been developed for the deterioration evaluation of a water distribution network but the score evaluation method is a technique which is the most commonly used at present. In order to conduct the score evaluation method, excavation work for collecting pipes to be evaluated are accompanied and the collected data are classified into indirect evaluation factors composed of the basic information of a target pipe and direct evaluation factors composed of detailed information. Indirect evaluation factors consist of the factors that can be obtained without collecting a pipe directly and most information is determined at the time of laying the pipe. Related evaluation factors include pipe type, pipe diameter, inner sheath type, outer sheath type etc. and these indirect evaluation items are used as base data that can infer the deterioration state of the target pipe based on the advantage that information collection is easy.

Direct evaluation factors consist of the information that can be obtained by directly taking a pipe and then, using equipment or tools. Related evaluation items include actually measured bore, pipe thickness, external corrosion depth, pipe sediment thickness etc. and deterioration progress can be evaluated more accurately because they are information collected by directly taking the pipe to be evaluated.

Although being used in the most representatively in Korea at present, however, the score evaluation method reveals a few problems. The first is a problem about the item measurement method and criteria. Direct evaluation items measure the

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information by using a variety of tools. However, the exact criteria for the measuring method are not prepared and there are only a few experts for measurement. The next is a problem about the evaluation procedures. In the case of deterioration evaluation using the existing score evaluation method, about 22 items should be measured in order to carry out indirect and direct evaluation. A lot of time and money are required because outage and excavation work should be accompanied in order to measure 12 direct evaluation items among them.

Therefore, this study carried out modeling to alleviate these problems. It proposed a modified deterioration evaluation technique that can not only streamline the same methods and procedures as the existing deterioration evaluation but ensure the minimum reliability. The existing indirect evaluation secured the minimum reliability by simplifying the procedures and adding new evaluation items. The direct evaluation carried out only simplification task for the number of existing items without adding new evaluation items. Also, the comparison and analysis of existing results were carried out by conducting the comprehensive evaluation, the final step of the existing score evaluation method with modified indirect evaluation and simplified direct evaluation. And the deterioration status prediction curve of water distribution was derived by using pipe data by pipe diameter and buried year collected from each region and the modified score evaluation method.

2. Materials and Method

2.1. Data Table

A sheet compatible with the program was produced for the statistical analysis using the collected information on 339 pipes. It was created by using the Excel program and classified into a sheet composed of indirect evaluation factors and comprehensive evaluation results and direct evaluation factors and comprehensive evaluation results. Also, information was digitized by referring to the item-specific score translation criteria for program application. The following is the part of a sheet summarizing the collected data according to the purpose.

Table 1. Collected Data of Pipe for Modeling Ⅰ

No.	Age	Material	Diameter	Inner coating	Outer coating	Soil	Road
1	26	0.75	100	1	1	0.5	0.75
2	28	0.75	100	1	0.5	0.5	0.75
3	28	0.75	100	1	1	0.5	0.75
4	14	0.75	100	1	1	0.5	0.75
5	28	0.75	100	1	1	0.5	0.75
6	14	0.75	100	0	0	0.5	0.5
7	14	0.75	100	1	1	0.5	0.75
8	27	0.75	100	1	1	0.5	0.75
9	20	0.75	100	1	1	0.5	0.75
10	27	0.75	75	0	1	0.5	0.75
11	28	0.75	150	1	1	0.75	0.5
12	28	0.75	150	1	1	0.75	0.5
13	28	0.75	150	1	1	0.5	0.25

14	31	0.75	100	1	1	0.5	0.75
15	23	0.5	100	0.5	0.5	0.5	0.75
16	27	0.75	200	1	1	0.5	0.75
17	24	0.75	100	1	1	0.5	0.75
18	24	0.75	100	1	1	0.5	0.75
19	18	0.75	100	1	1	0.75	0.5
20	20	0.75	100	1	0	0.75	0.75
21	17	0.75	100	1	1	0.75	0.75
22	28	0.75	100	0.5	1	0.5	0.75
23	19	0.75	100	1	1	0.75	0.5
24	25	0.75	150	1	0	0.5	0.75
25	23	0.75	150	1	0	0.5	0.75
26	25	0.75	150	1	0	0.5	0.75
27	23	0.75	150	1	0	0.5	0.75
28	27	0.75	150	1	0	0.5	0.75
29	7	0.75	150	1	0	0.5	0.75
30	14	0.75	150	1	0	0.5	0.75

Table 2. Collected Data of Pipe for Modeling Ⅱ

No.	Joint	Break history	Complain history	Indirect	Direct	Comprehensive 1	Comprehensive 2
1	1	0.25	0	0.49	0.79	2	1
2	1	0.25	0	0.4	0.62	3	2
3	1	0.25	0	0.4	0.74	3	2
4	1	0.25	0	0.4	0.67	3	2
5	1	0.25	0	0.4	0.61	3	2
6	0.25	0.25	0	0.39	0.61	3	2
7	1	0.25	0	0.68	0.81	1	1
8	1	0.25	0	0.4	0.55	3	2
9	1	0	0	0.57	0.77	2	1
10	1	0.5	0.5	0.45	0.56	3	2
11	1	0.25	0.25	0.41	0.67	3	2
12	1	0.25	0.25	0.41	0.64	3	2
13	1	0.25	0.25	0.4	0.74	3	2
14	1	0.5	0.5	0.45	0.68	3	2
15	1	0.5	0.5	0.43	0.46	3	2
16	1	0.5	0.25	0.44	0.6	3	2
17	1	0.5	0	0.51	0.78	2	1
18	1	0.5	0	0.51	0.53	2	1

19	1	0.75	0.75	0.67	0.81	1	1
20	1	0.25	0.25	0.6	0.84	1	1
21	1	0.25	0	0.59	0.76	2	1
22	1	0.5	0.25	0.44	0.59	3	2
23	1	0.5	0.25	0.61	0.82	1	1
24	1	1	1	0.78	0.861	1	1
25	1	0	0	0.41	0.73	3	2
26	1	1	1	0.55	0.777	2	1
27	1	1	1	0.55	0.803	2	1
28	1	1	1	0.55	0.809	2	1
29	1	1	1	0.78	0.82	1	1
30	1	0	0	0.56	0.86	2	1

2.2. Indirect Evaluation Modeling Reflecting Soil Properties

A correlation analysis was carried out by classifying factors into existing evaluation factors and added soil properties factors. As a result, in the case of the existing evaluation factors, a correlation between leakage and breaks history and complaints history by water quality, water pressure was found to be the highest. Also, in the case of soil properties factors, a correlation for soil resistivity and oxidation·reduction potential was found to be the highest. In the case of some areas, however, the average value was used without directly measuring soil resistivity and hence, a correlation associated with soil resistivity secures a relatively low reliability. Therefore, if excluding the results of soil resistivity, a correlation between oxidation·reduction potential and soil corrosiveness comprehensive evaluation results can be determined to be the highest. It was found that if adding soil properties factors to the existing indirect evaluation through these results, oxidation reduction potential is essential information.

(1) Liner regression analysis

A regression analysis was carried out by adding 5 soil properties factors to existing indirect evaluation factors and as a result, the results shown in Table 3 could be derived. This modeling analyzed deterioration evaluation results by pipe diameter targeting DCIP and therefore, evaluation factors for pipe type and pipe diameter among existing indirect evaluation factors were excluded.

Table 3. Simple Regression Analysis Adding Items on Soil Properties

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.08625	0.095536	8.230	6.70e-07
Age	-0.01348	0.010897	-2.062	0.0570
Outer coating	0.285015	0.0696121	3.538	0.00154
Inner coating	0.01652	0.0390834	0.042	0.96712
Soil	0.08446	0.1006391	0.150	0.88180
Joint	-0.07845	0.080738	0.212	0.7268

		1		0
Road	0.036651	0.0575953	0.917	0.36774
Breaks history	0.064248	0.0446630	1.311	0.20118
Complaints history	0.081293	0.0435065	1.860	0.07420
Ohm-cm	-0.0278	0.0288462	-1.170	–0.25255
pH	0.003841	0.0096528	0.251	0.80407
ORP-mV	0.231573	0.2773913	0.981	0.33575
Moisture content	0.041699	0.0157818	2.769	0.01024
CL_SO	-0.00082	0.0151158	-0.225	0.82344
Residual standard error		0.0071 on 15 degrees of freedom		
Adjusted R-squared		0.6198		
F-statistic		3.796		
p-value		0.02735		

13 factors except for evaluation factors for pipe type and pipe diameter were analyzed and as a result, R2 meaning the rate of variation of the dependent variable showed the value of 0.6198. R2 is expressed as a value between 0 and 1 and higher values are considered to be highly significant with the model. And p-value representing the probability that the independent variable is not significant in the dependent variable was found to be 0.02735.

This modeling result expressed as R2 value of 0.6198 and 0.02735 of p-value can be summarized in the following equation.

$$\begin{aligned} Evaluation\,grade &= w_0 + w_1 p_1 + w_2 p_2 + \dots + w_n p_n \\ &= -0.08625 - 0.1348 p_1 + 0.285015 p_2 + 0.01652 p_3 \\ &\quad + 0.08446 p_4 - 0.07845 p_5 + 0.036651 p_6 + 0.064248 p_7 \\ &\quad + 0.081293 p_8 - 0.02781 p_9 + 0.003841 p_{10} + 0.231573 p_{11} \\ &\quad + 0.041699 p_{12} - 0.00082 p_3 \end{aligned}$$

However, this modeling has more items than the existing evaluation. And if analyzing the score difference from existing evaluation results from the burial time to 50 years, the average residual was found to be high, from minimum 0.02896 to maximum 0.03506. The magnitude of this residual is 0.01 difference and is a value that cannot obtain sufficient significance due to the characteristics of the indirect evaluation with changing deterioration rating. Therefore, it is necessary to ensure a higher significance by selecting highly influential items among 13 evaluation items with the stepwise selection method.

(2) Indirect evaluation modeling using the stepwise selection method

A stepwise regression analysis was carried out to complement the above modeling results.

Table4. Indirect Evaluation Modeling using Stepwise Regression Analysis

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	0.790672	0.095536	8.230	6.70e-07
Age	-0.01269	0.010897	-2.062	0.0570
Breaks history	0.084927	0.011723	2.842	0.0124
Complaints history	0.035985	0.033900	1.510	0.1519
ORP-mV	-0.02125	0.02951	-2.035	0.047888
Moisture content	0.018835	0.013342	4.358	0.00011
Residual standard error		0.02135 on 54 degrees of freedom		
Adjusted R-squared		0.8561		
F-statistic		28.23		
p-value		3.502e-16		

Of 8 existing indirect evaluation factors and 5 soil properties factors, highly influential items were selected by using the stepwise selection method and as a result, 5 items were selected as shown in Table 4.4. And R2 meaning the rate of variation of the dependent variable showed the value of 0.8561. Also, p-value representing the probability that the independent variable is not significant in the dependent variable was found to be 3.502e-16. Through these results, a higher significance could be found than the above simple regression analysis results and implementation efficiency of the indirect evaluation could be also increased by simplifying 13 evaluation items to 5. The indirect evaluation modeling results using the stepwise selection method can be expressed as the following equation.

$$\begin{aligned} Evaluation\,grade &= w_0 + w_1 p_1 + w_2 p_2 + \dots + w_n p_n \\ &= 0.790672 - 0.01269 p_1 + 0.084927 p_2 \\ &\quad + 0.035985 p_3 - 0.02125 p_4 + 0.018835 p_5 \end{aligned}$$

This modeling has fewer items than the previous evaluation and if comparing the difference in the existing evaluation results with previously conducted method, the average residual was found to be minimum 0.00143 to maximum 0.00641. It was found that the residual of this modeling identified as a value of two decimal places is much lower than the residual of the above simple regression analysis. These results can be concluded that the results similar to the existing indirect evaluation can be derived only by using 5 derived evaluation items.

2.3. Direct Evaluation Modeling using Stepwise Selection Method

The direct evaluation modeling using the stepwise selection method was carried out by selecting 9 items, regional common items among existing 12 evaluation items. And unlike indirect evaluation modeling, each modeling was conducted by pipe diameter and new items were not added.

Table 5. Modified Equation of Direct Avaluation

Diameter	Equation	Factor
80mm	$Evaluation\ grade = w_1p_1 + w_2p_2 + \dots + w_np_n = 0.686238 + 0.022471p_1 + 0.033310p_2 + 0.051178p_3 - 0.004676p_4$	p_1 : Thickness p_2 : Thickness of coating p_3 : Depth of corrosion (inner) p_4 : Size of corrosion (inner)
100mm	$Evaluation\ grade = w_1p_1 + w_2p_2 + \dots + w_np_n = 0.53288 + 0.10756p_1 + 0.07714p_2 + 0.03778p_3 + 0.14498p_4 + 0.06006p_5$	p_1 : Inner diameter p_2 : Thickness p_3 : Thickness of coating p_4 : Depth of corrosion (inner) p_5 : Sediment
150mm	$Evaluation\ grade = w_1p_1 + w_2p_2 + \dots + w_np_n = 0.579852 + 0.115047p_1 + 0.064806p_2 + 0.101061p_3 + 0.058147p_4$	p1 : Inner diameter p2 : Thickness p3 : Depth of corrosion (inner) p4 : Sediment

2.4. Derivation of Deterioration State Prediction Curve using Exponential Function

Each pipe diameter-specific deterioration state prediction curve was derived targeting ductile cast iron pipes collected in this study and derived by using direct evaluation information collected through a variety of measurement tasks. And comparison·analysis with the state prediction curve derived based on existing evaluation results were carried out.

(1) ≤80mm

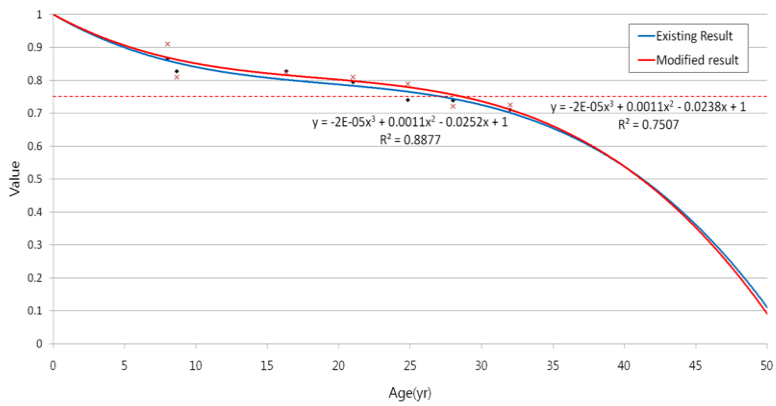

Figure 1. Comparison with State Prediction Curve (≤ 80mm)

(2) 100mm

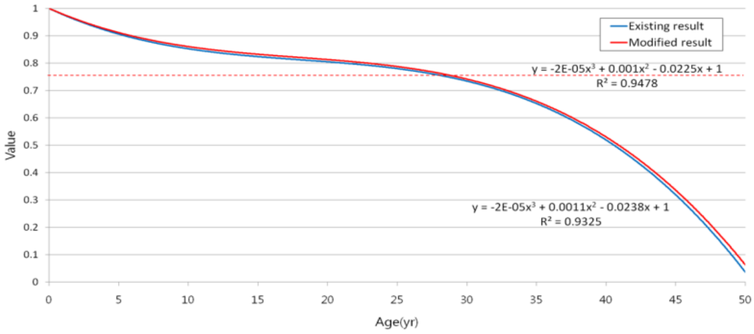

Figure 2. Comparison with State Prediction Curve (100mm)

(3) 150mm

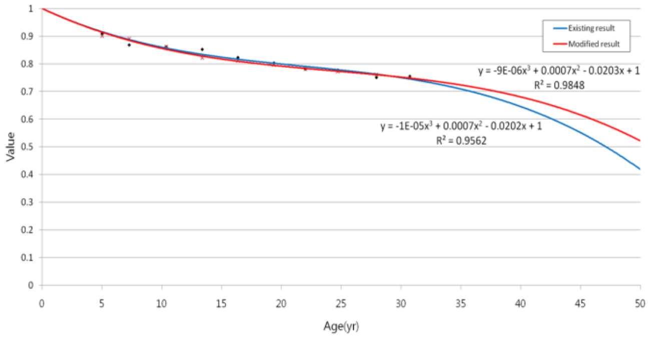

Figure 3. Comparison with State Prediction Curve (150mm)

3. Results and Conclusion

The score evaluation method is the most common deterioration evaluation technique used for the effective maintenance of domestic water distribution network. The score evaluation method classified into the indirect evaluation and direct evaluation calculates final comprehensive deterioration evaluation results based on results from two evaluations. The indirect evaluation consists of 10 evaluation items and direct evaluation consists of 12 evaluation items.

Due to the limitations not considering technical, economic situation of each region, however, improvement plans for field application improvement is required to be provided. In this study, modeling for complementing the limitations of existing score evaluation method was carried out. First, pipe information of each region was collected. The collected information consists of indirect evaluation items and direct evaluation items for conducting the existing score evaluation method and was converted to excel-based data table for conducting modeling for each evaluation. And modeling for increased efficiency of the indirect evaluation and direct evaluation was carried out and then, modified score evaluation method was proposed based on this result.

3.1. Indirect Evaluation Modeling Reflecting Soil Properties

Indirect evaluation modeling reflecting soil properties was carried out for the purpose of improving implementation efficiency and reliability of the indirect evaluation composed of 10 evaluation items. First, soil effects factors of Modified

ANSI were added in order to increase the reliability for three variable factors with relatively smaller number than 7 fixed factors setting the initial value and reduce the proportion for buried year, one of variable factors. As a result, when adding 5 soil effect factors to 10 indirect evaluation items, the average residual by pipe diameter compared to existing indirect evaluation was found to be higher, 0.02896 ~ 0.03506. The magnitude of this residual is a value that cannot secure sufficient significance due to the nature of the indirect evaluation that the deterioration grade is changing by 0.01 difference. Therefore, we carried out modeling that can ensure a higher significance by selecting highly influential items among 15 evaluation items with the stepwise selection method.

Indirect evaluation modeling using the stepwise selection method was carried out for the purpose of selecting only highly influential factors among existing 10 evaluation items and 5 evaluation items. As a result, existing 3 variable factors and oxidation reduction potential, moisture content rate were selected and average residual by pipe diameter was found to be relatively low from minimum 0.00143 to maximum 0.00641. This result could secure higher reliability than the above modeling and reduce 15 evaluation items to 5 and increase implementation efficiency.

3.2. Direct Evaluation Modeling Using Stepwise Selection Method

Unlike the indirect evaluation, the direct evaluation consists of items collecting information about the target pipe through a variety of measurement tasks and hence, sufficient reliability for deterioration evaluation can be secured. Therefore, this study was carried out in the direction of selecting highly influential items among existing 12 evaluation items by using the stepwise selection method.

Unlike indirect evaluation items, direct evaluation items consist of direct information about the pipe such as thickness, inner diameter of a pipe. Therefore, unlike the above indirect evaluation modeling, direct evaluation modeling using the stepwise selection method was conducted by pipe diameter for deriving a more detailed deterioration evaluation equation. As a result, in the case of less than 80mm, 4 items including uncover pipe thickness were selected as important items. And in the case of 100mm, 5 items including actually measured inner diameter were selected and in the case of 150mm, 4 items including actually measured inner diameter were selected. This result has relatively smaller number of items compared to existing direct evaluation and if analyzing a difference from existing evaluation results by pipe diameter, the average residual was found to be minimum 0.00149 to maximum 0.00688. The residual of this modeling identified as the value of two decimal places was found to be much lower than the residual of the above simple regression analysis. Through this result, it can be concluded that the results similar to those of existing direct evaluation can be derived only by using 4～5 evaluation items derived by pipe diameter.

3.3. Deterioration State Prediction Curve Derivation

A deterioration state prediction curve was derived by using the results for the direct evaluation conducted based on direct information about pipes. And if applying the criteria of the score evaluation method to the prediction curve derived by pipe diameter, in the case of ductile cast iron pipe of less than 80mm, the state prediction curve by the existing evaluation method shows 24.30 years and state prediction curve by modified evaluation method shows 28.64 years as the time to consider replacement or repair work. Also, 100mm showed 26.64 years, 27.57 years and 150mm showed the replacement or repair time of 29.64 years, 30.06 years. However, the values calculated by each evaluation method mean when the state of the target pipe should be checked and do not necessarily mean when to carry out replacement or repair. Therefore, the exact life for the target pipe cannot be expected through the state prediction. However, a rough state can be predicted by using the state prediction curve derived in this study if the comprehensive deterioration evaluation cannot be carried out because of insufficient information of the target pipe.

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