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Diagnosis and renewal decision making of water mains using 3D scanning data

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ABSTRACT

The aging water infrastructure is one of the emerging issues for sustainable water supply. The renewal priority has been a concern for the operators of waterworks and decided by risk and residual life. The thickness of corrosion is measured using a pit depth gauge which is hard to read every detail of pipe surface roughness. 3D scanner, however, scans the three-dimensional surface of a pipe with high accuracy. The 3D analysis could be also used to analyze corrosion area, maximum corrosion depth, and tensile strength simulation. Using 3D scanning results, a modified method for residual life prediction was developed combining 3D scanning data analysis with conventional direct and indirect methods. In this study, a method was developed to perform numerical simulation for a tensile test from 3D scanning data. Although the simulation method was not verified with physical examination, tensile strength simulation showed a potentiality to supplement physical test after the accumulation of kinetic parameters.

Keywords: Aged pipe; Residual life; Pipe corrosion; Renewal decision making; 3D scanning

1. Introduction

The aging water infrastructure is one of the emerging issues for sustainable water supply in South Korea [1]. The total length of the South Korean water distribution pipe network was estimated to be 185,000 km in 2016 [2]. The proportion of pipeline aged more than 20 years after burial is about 30% in South Korea. Due to the aged pipeline, water loss is inevitable during water distribution [3]. The loss of water caused by leakage and burst of aged pipe was about 400 million USD/year or more [4]. In addition, the leaked water flow from a pipe may erode the soil around the pipe and thus cause various problems such as sinkholes [5].

Aged water distribution pipelines should be renewed continuously with a tight budget. The renewal priority has been a concern for the operators of waterworks and decided by risk and residual life of water distribution pipe [6]. Researches on the prediction of pipe residual life have relied on mainly statistical or economic approaches based on accumulated pipe accident histories which are key for this approach [7]. They accumulate data, however, are rare and incomplete [8]. The renewal priority of a pipe often was decided by indirect methods based on pipe material, diameter, thickness, installation year, surface load, and soil environment data [9,10]. Direct methods could be used to compensate for the disadvantages of the indirect method [11]. The direct method is to take a pipe sample with hot tapping from a buried pipe or to observe the inside of the pipe through a CCTV apparatus. Collected pipe samples are used for thickness measurement and tensile strength tests. Residual thickness after corrosion is a critical factor for predicting the residual life of a pipe [12]. The thickness of corrosion is measured using a pit depth gauge which is hard to read every detail of pipe surface roughness. 3D scanner, however, scans the three-dimensional surface of pipe with high accuracy. 3D analysis could be used to analyze corrosion area, maximum corrosion depth, and tensile strength simulation. 3D scanner technologies require tools to process

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roughness data from enormous vector data (i.e., mesh generated from 3D scanning) [13]. In this study, a method was developed to measure surface roughness from 3D scanning data using software.

The tensile strength test is labor and time-consuming since a special size and shape sample must be crafted. If numerical analysis could replace the tensile test, it could reduce difficulties to predict the residual life of the aged pipe. A method was developed to perform numerical simulation for a tensile test from 3D scanning data. Since the condition of the pipe and its environment also influenced the residual life, a modified analysis method was developed by combining the conventional indirect method and tensile strength. In this study, a modified method for residual life prediction was developed using conventional direct and indirect methods combined with 3D scanning data processing and numerical tensile strength analysis.

2. Material and methods

2.1. Pipe 3D scanning and rendering

Samples of pipes were taken from two cities in South Korea. A donut-shaped pipe sample was taken using the hot tapping method and then scanned using a handheld scanner (Fisher, Thunk3D, Beijing). The scanned image was further processed into 3D vector data by a process of polygonation using 3D viewer (Microsoft, Seattle, USA), FreeCAD (non-commercial free software), and Solid Works software programs (3DS, Waltham, USA). With the Solid Works software, the mesh was constructed from data obtained through 3D scanning. The FreeCAD program was used to measure the depth of corrosion and surface roughness. The 3D viewer was used to observe three-dimensional pipe conditions in general. The polygon data was used for tensile stress analysis later. The data process schematics are shown in Fig. 1.

2.2. Pipe condition rating with direct and indirect methods

The pipe condition rating criteria using the direct and indirect method are shown in Tables 1 and 2, respectively [14].

Overall pipe condition rating is calculated by a weighted average method using Eq. (1) [15]. A weighting factor ranges from 0.0 to 1.0.

$$\text{Evaluation score} = \frac{\sum_{i=1}^{n} w_i p_i}{\sum_{i=1}^{n} w_i} = \frac{w_1 p_1 + w_2 p_2 + \cdots + w_n p_n}{w_1 + w_2 + \cdots + w_n} \quad (1)$$

w_i = weighting factor; p_i = condition value by evaluation using Table 1 and 2; n = number of items.

2.3. Modified method for predicting the residual life of pipe sample

The process of the modified method for predicting the residual life of a pipe is shown in Fig. 2. The major improvement involves corrosion depth and tensile strength simulation by computing the change rate of allowable stress and comparing the initial wall thickness of a pipe with the maximum corrosion depth using 3D scanning data.

Table 1
Direct assessment factor and condition rating

Factor	Classification range	Condition value
External corrosion thickness	Over than 20%	0.00
	20%–15%	0.25
	15%–10%	0.50
	10%–5%	0.75
	Lower than 5%	1.00
External coating peeling	Over than 80%	0.00
	80%–60%	0.25
	60%–40%	0.50
	40%–20%	0.75
	Lower than 20%	1.00
External corrosion perimeter	Over than 80%	0.00
	80%–60%	0.25
	60%–40%	0.50
	40%–20%	0.75
	Lower than 20%	1.00
Internal corrosion thickness	Over than 20%	0.00
	20%–15%	0.25
	15%–10%	0.50
	10%–5%	0.75
	Lower than 5%	1.00
Internal coating peeling	Over than 80%	0.00
	80%–60%	0.25
	60%–40%	0.50
	40%–20%	0.75
	Lower than 20%	1.00
Internal corrosion perimeter	Over than 80%	0.00
	80%–60%	0.25
	60%–40%	0.50
	40%–20%	0.75
	Lower than 20%	1.00
Water pressure (kg/cm^2)	Over than 7.0	0.00
	7.0–6.0	0.25
	6.0–5.0	0.50
	5.0–4.0	0.75
	Lower than 4.0	1.00

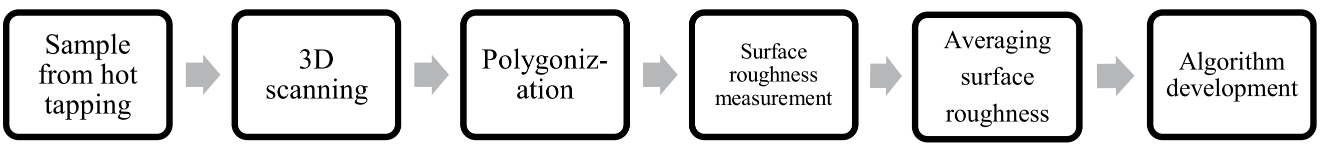


Fig. 1. Schematic diagram for algorithm development.

Table 2
Indirect assessment factor and condition rating

Factor	Classification range	Condition value
Type of pipe	CIP, GSP	0.00
	PVC, PE	0.25
	SP, PC, PCC	0.50
	DCIP	0.75
	STS, PFP	1.00
Diameter of pipe (mm)	Lower than 150	0.00
	150–350	0.20
	350–600	0.40
	600–1,000	0.60
	1,000–2,000	0.80
	Over than 2,000	1.00
Internal coating	None	0.00
	Epoxy	0.50
	Coal tar enamel	0.75
	Asphalt	0.75
	Cement coal tar	1.00
External coating	None	0.00
	Coal tar enamel	0.75
	Asphalt	1.00
Burial year	Over than 25	0.00
	20–25	0.25
	15–20	0.50
	10–15	0.75
	Lower than 10	1.00
Type of soil	Clay	0.00
	Clay + Gravel, Silt	0.25
	Sand + Gravel, Loam	0.50
	Sand	1.00
Connection method	Flange, socket	0.25
	Sleeve coupling	0.25
	Heat plate bonding	0.50
	Mechanical, push-on	1.00
	Post weld paint	1.00
Fault and civil appeals history	Over than 5 times	0.00
	3–5 times	0.25
	1–3 times	0.50
	None	1.00
Soil pH	Over than 8	0.00
	5–7	0.50
	Lower than 5	1.00
Sulfide concentration	Lower than 200	0.00
	200–500	0.50
	Over than 500	1.00
Soil resistance	Over than 1,500	0.00
	1,000–1,500	0.50
	Lower than 1,000	1.00

3. Results and discussions

3.1. Pipe sample 3D scanning

The 3D scanning was carried out with a donut-shaped sample taken from hot tapping of a pipe. The 3D scanning image was stored in vector data and could be seen with the 3D viewer (Microsoft, Seattle, USA). Fig. 3 illustrates the representative three-dimensional shape of a specimen. The first and second figures are the front and rear sides of the sample, respectively. The third figure shows meshes for finite element analyses which is a polygonal form. The fourth figure shows a certain surface of the specimen in a magnified form.

Table 3 is a three-dimensional rendering image to determine the degree of corrosion by analyzing the surface roughness using the data obtained by 3D scanning. The data obtained by 3D scanning of the pipe specimen are rendered using the FreeCAD and Solid Works programs to show the degree of corrosion of a specimen. Each color refers to a 'curvature' depending on the depth of corrosion. The green color represents the light degree of corrosion while dark blue severe corrosion state. The boundary between the normal and corroded surfaces is colored in red and yellow. The results of the analysis of three steel pipe (SP) and three ductile cast iron pipe (DCIP) show the corrosion of a pipe and help operators to understand its condition.

The maximum corrosion depths, initial thickness, and thickness reduction rate are shown in Table 4. The corrosion rate of SP ranged from 1.67% to 5.00%. And the corrosion rate of DCIP ranged from 3.34% to 15.00%.

3.2. Results of analysis using direct and indirect methods

A modified analysis method was applied to specimens obtained from a city in South Korea. The data for the direct evaluation of pipe condition are shown in Table 5 at Area 1 and Area 2. Table 6 shows data for indirect evaluation for Area 1 and 2. The initial thickness of the pipe was 80.0 mm for both direct and indirect methods.

Based on the data shown in Tables 5 and 6, the condition rating is obtained by applying the condition rating formula as shown in Table 7. If the evaluation score of the direct method is 0.75 or below, replacement and renewal are required for the pipe by the Korean field guideline. If the evaluation score is 0.8 or higher, the condition of the pipe is good. If the evaluation score is between 0.75 and 0.80, the replacement or renewal is considered depending on the condition of the pipe. If the evaluation score of the indirect method is less than 0.45, replace and renewal is required for the pipe. If the evaluation score is 0.6 or higher, the condition of the pipe is good. If the evaluation score is between 0.45 and 0.60, the pipeline should be assessed after site excavation and then a detailed assessment should be performed with an expert's advice by the Korean law.

Assessment of soil corrosion was also carried out with ANSI/AWWA's evaluation method as shown in Table 8. The results for Area 1 and Area 2 are shown in Tables 9 and 10, respectively. The evaluation results were 16 and 11 for Area 1 and Area 2, respectively. The soil was corrosive and recommended to be replaced by non-corrosive soil.

Fig. 2. Modified process for the prediction of residual life of aged pipe through tensile strength simulation and conventional method.

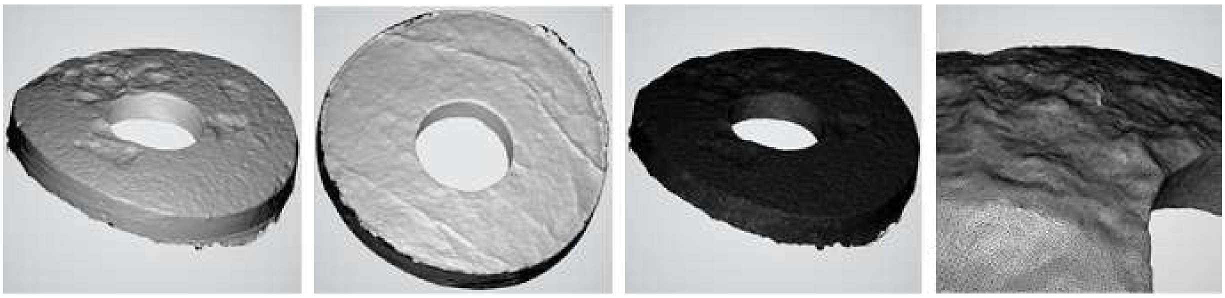


Fig. 3. Representative 3D scanning image and polygonal form of a pipe specimen.

Table 3
Surface roughness rendering for corrosion depth measurement with the 3D scanning data

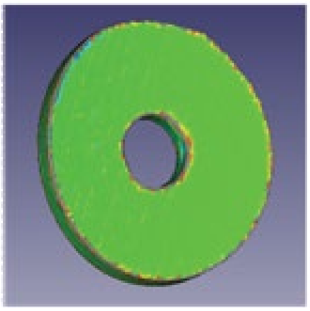
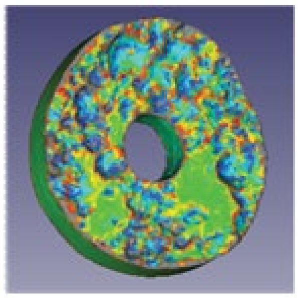
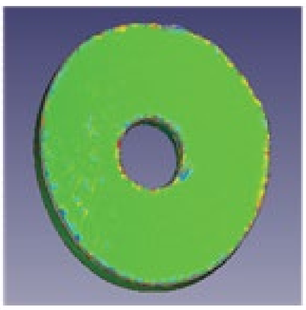
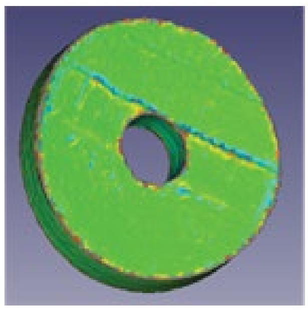
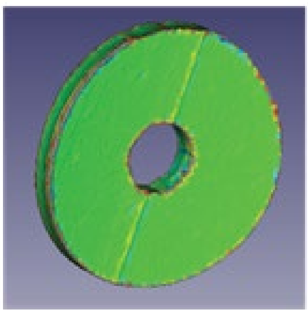
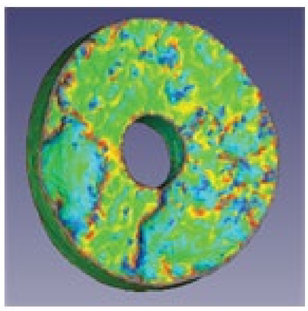
Number	Figure	Number	Figure
1 (SP)		4 (DCIP)	
2 (SP)		5 (DCIP)	
3 (SP)		6 (DCIP)	

Table 4
Maximum corrosion depth measurement using 3D scanning

Number (Type of pipe)	Maximum corrosion depth (Initial sample thickness)	Number (Type of pipe)	Maximum corrosion depth (Initial sample thickness)
	Thickness reduction rate		Thickness reduction rate
1 (SP)	59 mm 60 mm 1.67%	4 (DCIP)	85 mm 100 mm 15.00%
2 (SP)	53 mm 55 mm 3.64%	5 (DCIP)	87 mm 90 mm 3.34%
3 (SP)	57 mm 60 mm 5.00%	6 (DCIP)	87 mm 100 mm 13.00%

Table 5
Analysis data using direct method at Area 1 and 2

Factor	Area 1	Area 2
Maximum corrosion depth (mm)	5.4	3.9
Internal mean corrosion thickness (mm)	0.6	0.5
Internal corrosion perimeter (%)	Lower than 7	Lower than 8
Internal coating peeling (%)	Lower than 14	Lower than 19
External corrosion depth (mm)	5.4	3.9
Water pressure (kg/cm^2)	5.3	5.5

Table 6
Analysis data for indirect method at Area 1 and 2

Factor	Area 1	Area 2
Type of pipe	SP	SP
Diameter (mm)	900	900
Internal coating	Epoxy	Epoxy
External coating	Coal tar enamel	Coal tar enamel
Burial year	32	32
Type of soil	Sand + Gravel	Sand + Gravel
Connection method	Post weld paint	Post weld paint

3.3. *Allowable stress change rate analysis using 3D scanning date based*

When assessing the aged pipes by the direct and indirect method, the allowable stress change rate and tensile strength due to the reduction of residual thickness of pipes have not been involved so far. The corroded surface, however, is a starting point where leaks or bursts occur. Note that a problem occurs where the pipe has a minimum residual thickness. Therefore, the allowable stress change rate and tensile strength were calculated with the residual thickness data obtained by 3D scanning. The results were arranged to reflect evaluation ratings in addition to the direct and indirect methods.

Pipe samples taken from Area 1 and Area 2 were used to compute the rate of allowable stress change due to the reduction of residual thickness. It is assumed that the downside of the pipe sample was crafted for the small fragment (i.e., 1.0mm in thickness). The initial thickness of the pipe was 80.00mm and the rate of change of allowable stress (F) could be calculated by substituting it for the tensile strength formula as Eq. (2).

$$\text{Tensile strength} = \frac{F}{A} \tag{2}$$

F = Force (allowable stress)
A = Area

The allowable tensile strength of SP in the Korea Standard (KS) is 30 kg/cm^2 or 2,940 N/mm^2. Since the sectional area of A was 80 mm^2, the calculation of allowable stress of the pipe before installation could be expressed as Eq. (3).

$$\frac{2{,}940\text{N}}{\text{mm}^2} \times 80\text{mm}^2 = 235{,}200N \tag{3}$$

The thickness of the aged pipe was 74.6 mm (thickness reduction rate was 6.75%) and 76.1 mm (thickness reduction rate: 4.88%) for Area 1 and Area 2, respectively, so the allowable stresses could be expressed as Eqs. (4) and (5), respectively.

$$\frac{2{,}940\text{N}}{\text{mm}^2} \times 74.6\text{mm}^2 = 219{,}324N \tag{4}$$

Table 7
Analysis results using direct and indirect methods

Evaluation method	Area	Score	Results
Direct	Area 1	0.719	Replacement or renewal
	Area 2	0.731	Replacement or renewal
Indirect	Area 1	0.345	Replacement or renewal
	Area 2	0.345	Replacement or renewal

Table 8
Rating value of soil corrosivity with ANSI/AWWA evaluation method

Factor	Classification range	Score
Soil specific resistance (Ω–cm)	<1,000	10
	1,001–2,000	8
	2,001–5,000	5
	5,001–10,000	2
	>10,001	0
pH	0–2	5
	2–4	3
	4–6.5	0
	6.5–7.5	0
	7.5–8.5	0
	>8.5	3
Redox potential (mV)	>100	0
	50–100	3.5
	0–50	4
	–	5
Water contents	More than 20%	2
	10%–20%	1
	Lower than 10%	0
Oxide (chloride/sulfide)	More than (+)100 mg/kg	3.5
	Lower than 100 mg/kg	2
	None	0

$$\frac{2,940\text{N}}{\text{mm}^2} \times 76.1\ \text{mm}^2 = 223,734N \quad (5)$$

The allowable stress change rate could be calculated as expressions shown as Eqs. (6) and (7).

$$\frac{23,5200 - 219,324}{235,200} \times 100(\%) = 6.75\% \quad (6)$$

$$\frac{235,200 - 223,734}{235,200} \times 100(\%) = 4.88\% \quad (7)$$

The allowable stress change rate for the two samples were reduced by 6.75% and 4.88%, respectively. The allowable stress change rates could be added to the conventional direct assessment method with the classification and condition values shown in Table 11, which was suggested by authors. Since the classification value of Table 11 ranged from 4.50% to 6.00% for Area 1 and more than 6.00% for Area 2, the condition values were 0.25 and 0.00, respectively. Adding the change rate of allowable stress as a factor for direct assessment could increase accuracy by reflecting the physical conditions of a pipe.

3.4. Simulation of pipe tensile strength

Fig. 4 is the result of simulating tensile strength by virtually creating an 80 mm thick sample of SP, binding on one

Table 11
Assessment classification range and condition value for allowable stress change rate

Factor	Classification	Condition value
Allowable stress change rate	0%–1.50%	1.00
	1.50%–3.00%	0.75
	3.00%–4.50%	0.50
	4.50%–6.00%	0.25
	More than 6.00%	0.00

Table 9
Evaluation result of soil corrosivity for Area 1

	Soil specific resistance	pH	Redox potential	Water contents	Concentration of sulfur	Concentration of chlorine	Result
Value	801 Ω–cm	6	313.9	65%	24.62 mg/kg	30.12 mg/kg	Corrosive soil
Score	10	0	0	2	2	2	16

Table 10
Evaluation result of soil corrosivity for Area 2

	Soil specific resistance	pH	Redox potential	Water contents	Concentration of sulfur	Concentration of chlorine	Result
Value	2,910 Ω–cm	6	348.0	65%	1.02 mg/kg	29.76 mg/kg	Corrosive soil
Score	5	0	0	2	2	2	11

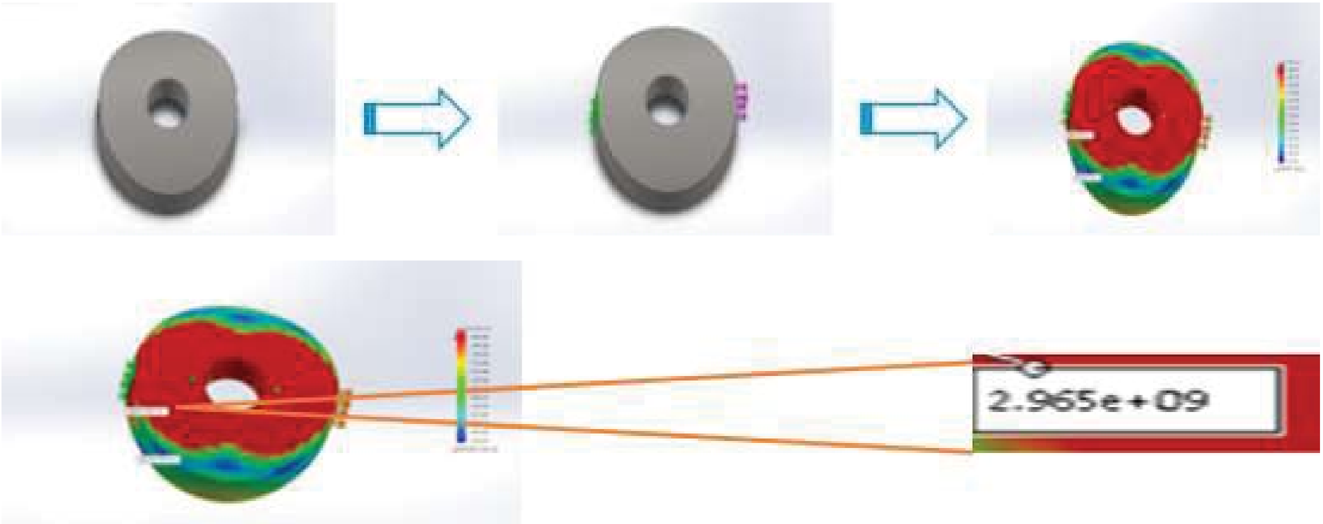


Fig. 4. Results of tensile strength simulation of virtual pipe sample.

side and generating a pull force on the other. As previously stated, the allowable tensile strength of the pipe in the SP material of KS standard is 30 kg/cm^2 (or 2,940 N/mm^2). In the tensile strength simulation, the maximum value of tensile strength was 2.96 × 10^9 N/m^2 (or 2,960 N/mm^2), indicating an inconsistency of 0.675%. The aged pipe needs to be renewed to satisfy the Korean Standard. Although the simulation method was not verified with a physical examination, tensile strength simulation showed the potential to supplement physical test after the accumulation of kinetic parameters.

4. Conclusions

The residual life of the aged pipe has been assessed with direct and indirect methods to evaluate the pipe condition, which lacks the actual conditions and sufficient reflection of the buried environment. This study developed a method to measure surface roughness using a 3D scanner by calculating the maximum corrosion depth from 3D scanning data using FreeCAD and Solid Works. The corrosion rate of SP ranged from 1.67% to 5.00%. And the corrosion rate of DCIP ranged from 3.34% to 15.00%. We developed a method to improve the accuracy and reliability for making optimal decisions on the replacement or renewal of a pipe by adding analysis results obtained from 3D scanning along with the condition assessment of pipes using the existing direct and indirect methods. Based on the data obtained through 3D scanning, tensile strength simulation was also carried out and found that it lacks 0.675% from the Korean Standard of pipe. Although the simulation method was not verified with physical examination, tensile strength simulation showed a potentiality to supplement physical tests after the accumulation of kinetic parameters.

Acknowledgment

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