Study on Replacement Plan with Statistical Analysis for Water Distribution Pipelines

by

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A dissertation submitted for

the degree of Doctor of Engineering

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The Graduate School of Urban Environmental Sciences

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September 2013

Contents

Chapter 1 Introduction

1-1 Progress of Korea's water supply system

Korea has more than 100 years of water purification history since the Plant No. 1 at the "Ttukdo" water reservoir in the "Ttuk-seom" region was established as the first of the water purification plants.[1)] Although water supply facilities and dissemination were extremely inadequate in the early days, water supply and the improvement of water supply facilities showed rapid progress under the economic development policy that started in the late 1970s, and water supply for large cities including Seoul began to meet the demand in the 2000s (**Fig. 1-1-1**).

According to the 2011 waterworks statistics, the water-supply population was 48,937,688 people out of the administrative total population of 51,716,745; while the water supply ratio all over the country and in metropolitan cities were 95.8% and 97.9%, respectively, which means a majority of the people in Korea are now receiving water supply services.

Recently, a waterworks team in Korea has been making an effort to supply high quality water. The city of Seoul especially announced a "five-year plan of waterworks vision" in 2007. It included the supplying of the best water quality and the achievement of competitiveness in order to prepare for the water industry market to open up. The waterworks vision had three major goals, which were to supply the best water quality, to provide the best customer service, and to achieve the highest revenue water ratio in the world. The waterworks team conducted the following to accomplish these goals.

Firstly, in order to produce the best water quality, the waterworks team carried out a consolidated water examination on the achievement of quality water source and advanced water treatment such as membrane system. As a result, advanced water treatment technology is making great contributions not only to the quantitative growth, but also the qualitative growth of water supply. This is particularly owing to the fact that water-supply consumers are seeking high standard water services that correspond to their improved living environment.

Secondly, tap water is fully delivered all the way up to the faucet under the system of service pipes without any deterioration in water quality. The ability of a pipe network system to function greatly affects water supply conditions in terms of quantity and quality. Particularly, the average revenue water ratio of the entire country in relation to the amount of fees collected for the production of water supply facilities, was 83.5% in year of 2011 (**Fig. 1-1-2**). It is reported that this mostly resulted from pipe deterioration and water leakage in the water distribution system. Water leakage is greatly associated with the reduction of function caused by decrepit water distribution pipes (**Fig. 1-1-3**).

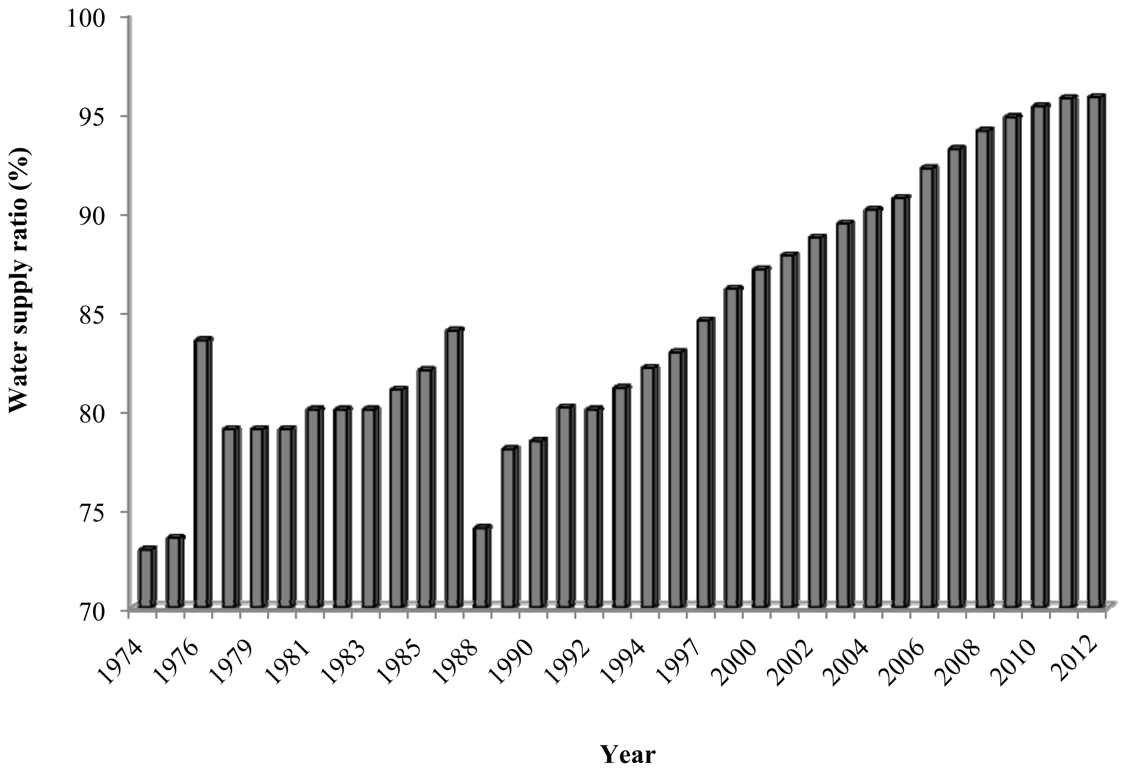

Fig. 1-1-1 Trend of water supply ratio in Korea

(Source: Website of Korean Statistical Information Service)

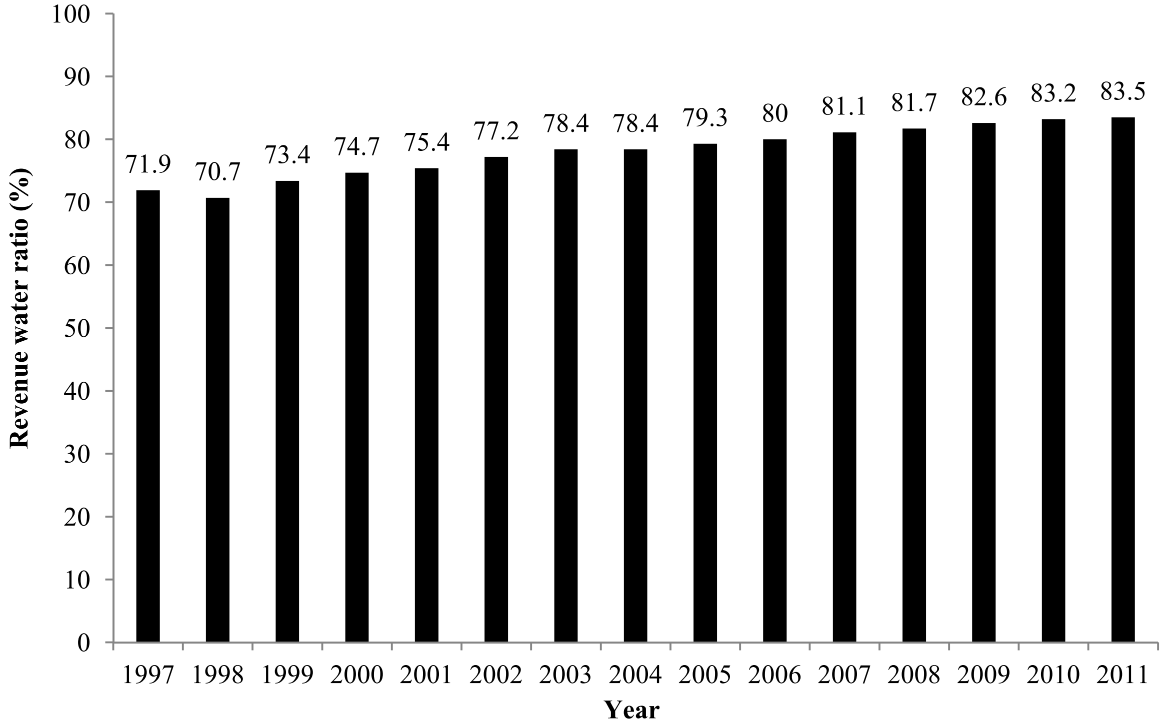

Fig. 1-1-2 Trend of revenue water ratio in Korea (Source: 2011 waterworks statistics)

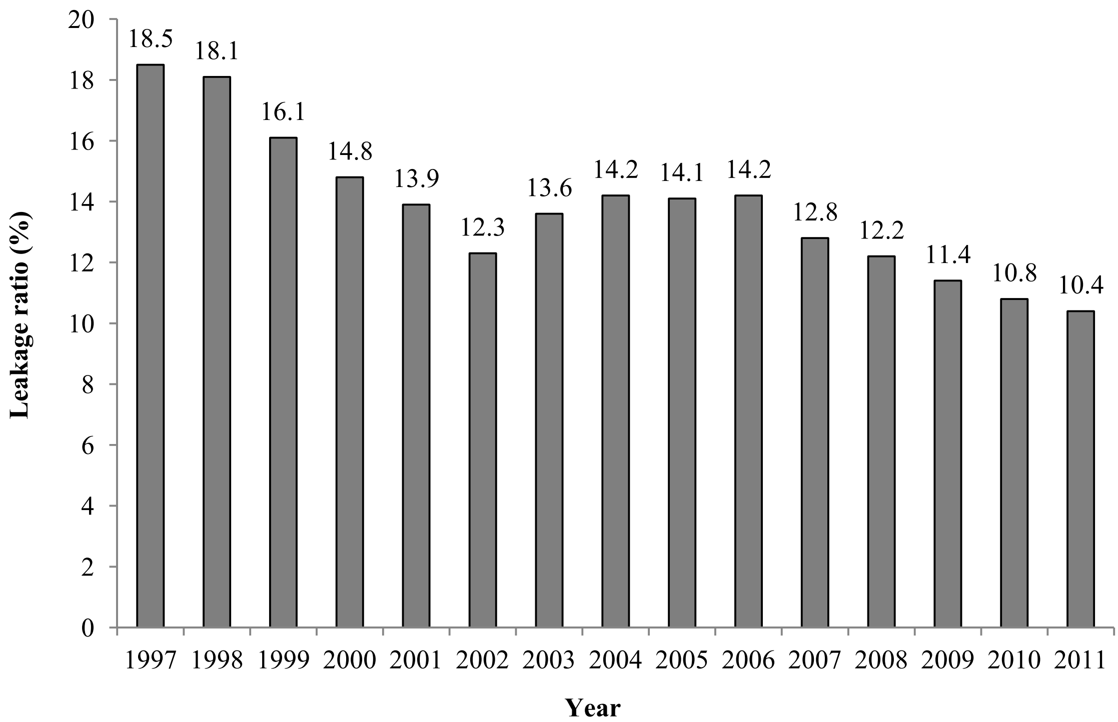

Fig. 1-1-3 Trend of leakage ratio in Korea (Source: 2011 waterworks statistics)

1-2 Leakage and deterioration of distribution pipelines

There are many factors that contribute to leakage and deterioration, and these factors have some kind of correlation between them[2)]. This study looks at four remarkable factors: the pipe material as a physical and chemical factor, the aging as a physical factor, the soil property as a chemical factor, and the replacement as a social factor.

Firstly, the occurrence of leakage and deterioration is substantially different for each pipe material, which includes around 13% PVC and 12% PE pipes (**Fig. 1-2-1**). Particularly among the distribution pipes, 12% are cast iron pipes (CIP). The main disadvantages of CIP are that it is heavy and that it is subject to corrosion from the inside and the outside.[3)] Consequently, as ductile cast iron pipe (DCIP) is stronger and less rigid than CIP, it is mostly used in distribution pipe instead of CIP.

In the case of service pipes, 24.2% and 24.1% of pipelines are PVC and PE, respectively, which are hardly used for pipes to be newly laid or replaced (**Fig. 1-2-2**). PVC and PE pipes are highly valuable in many construction applications as they are thermo resistant and fire retardant, and they serve as high quality water conduits. However, the probability of leakage is high when heat plate bonding and strength is weak.[4)] Nowadays, stainless steel is mostly used in service pipes instead of PVC and PE. As indicated by the 2011 waterworks statistics, there are around 37% of PVC and 14% of PE pipes that are over 21 years in use (**Fig. 1-2-3**). This is the absolute cause of leakage in service pipes.

Table 1-2-1 Information of pipe materials

SP	Steel pipe	**CIP**	Cast iron pipe	**SPPW**	Galvanized Steel Pipes for Water Service	**PVC**	Polyvinyl chloride pipe
DCIP	Ductile iron pipe	**CP**	Copper pipe	**PE**	Polyethylene pipe	**STS**	Stainless steel pipe

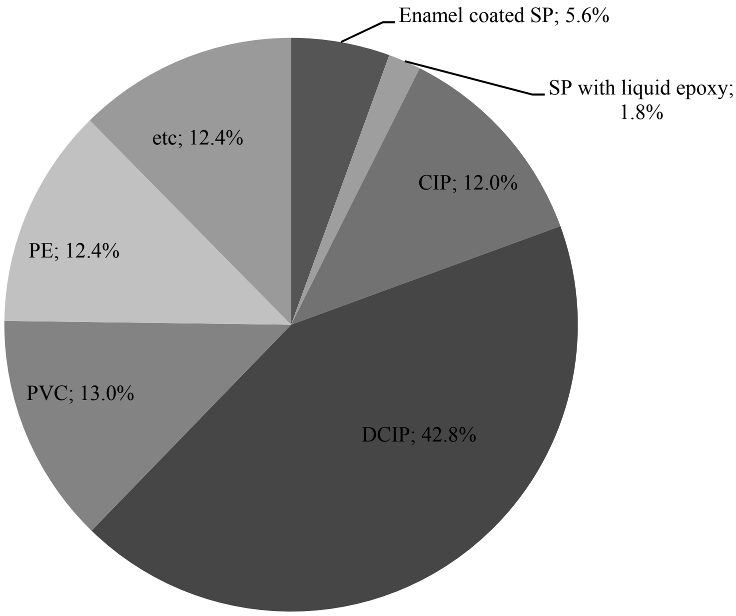

Fig. 1-2-1 Composition of distribution pipe materials

(Source: 2011 waterworks statistics)

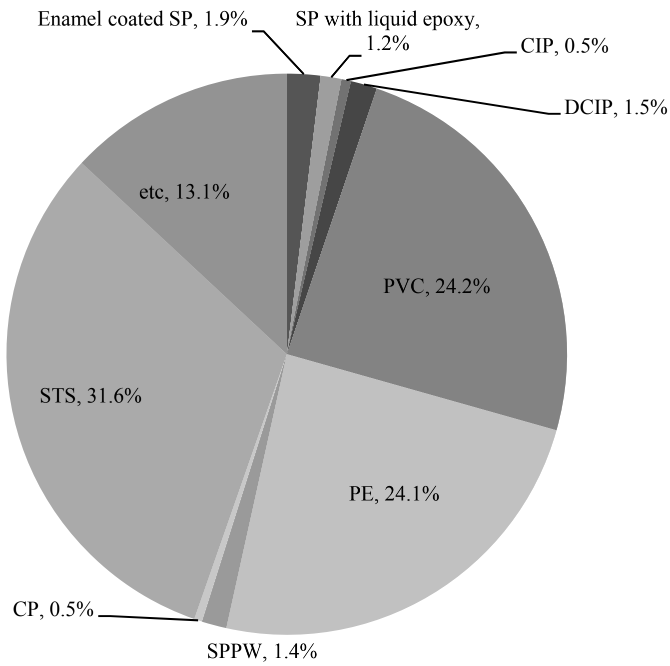

Fig. 1-2-2 Composition of service pipe materials

(Source: 2011 statistics of waterworks)

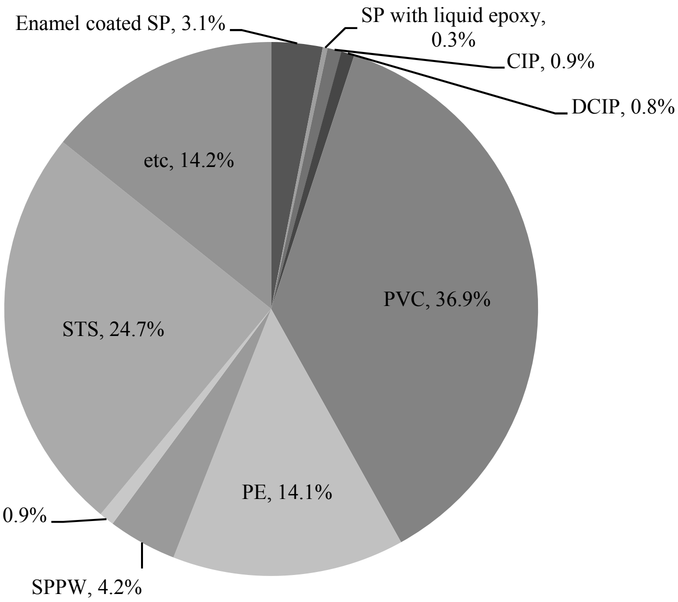

Fig. 1-2-3 Aging ratio according by pipe material (service pipes)

(Source: 2011 waterworks statistics)

Fig. 1-2-4 and **Fig. 1-2-5** show the number of leakages and amount of leakage according to each pipe material. It can be proved that there is a relation between leakage and pipe material. **Fig. 1-2-4** indicates the obtained amount of leakage for each pipe material. The results are in order from the largest to the smallest leakage: PE, PVC, STS, SP and so on. It is noteworthy that the sum of leakage amount in PE and PVC pipes is almost 50% of the total leakage amount.

Meanwhile, **Fig. 1-2-5** shows the results in order from the highest to the lowest number of leakages per pipe length by pipe material. Copper pipe (CP) has the highest number of all, but the length of CP is around 0.2% of the total length of pipes. So it is natural that CP has the highest value among other materials in these results. Excluding the results for CP and Etc., the ranks for the other materials are, in order from the highest to the lowest: STS, PVC, PE, SP, CIP and DCIP. In the case of STS, PVC and PE pipes, these are widely used service pipes, although nowadays many PVC and PE pipes have been replaced by stainless (STS) pipes. In the case of STS pipes, the number of leakage per pipe length is around 20% of the total result, while PVC and PE pipes show almost 16% and 15% of the total result, respectively. On the other hand, CIPs, SPs and DCIPs are used distribution pipes, but CIP and SP pipes have been replaced by DCIPs recently. As expected, CIPs and SPs have a higher probability of leakage than DCIPs.

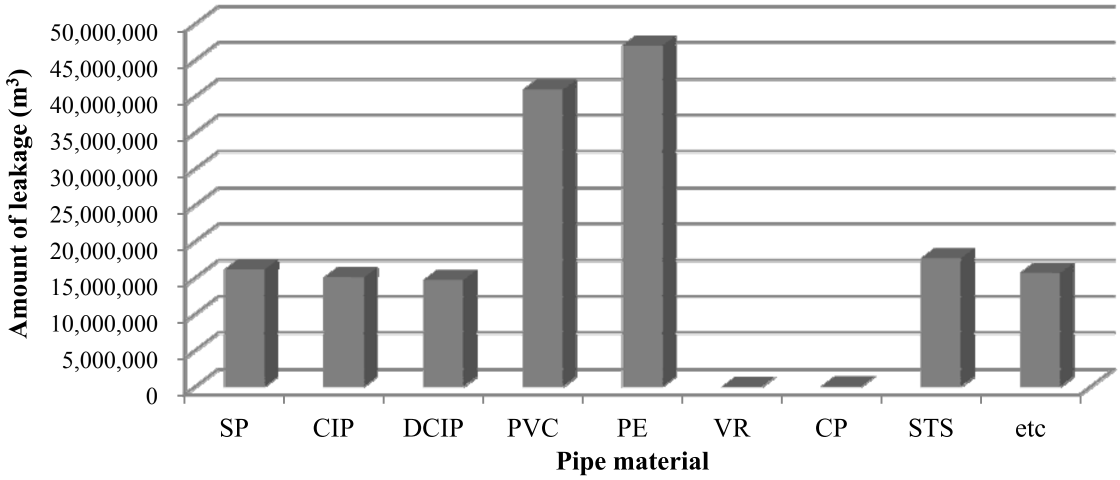

Fig. 1-2-4 Amount of leakage in water distribution system by pipe material
(Source: 2011 waterworks statistics)

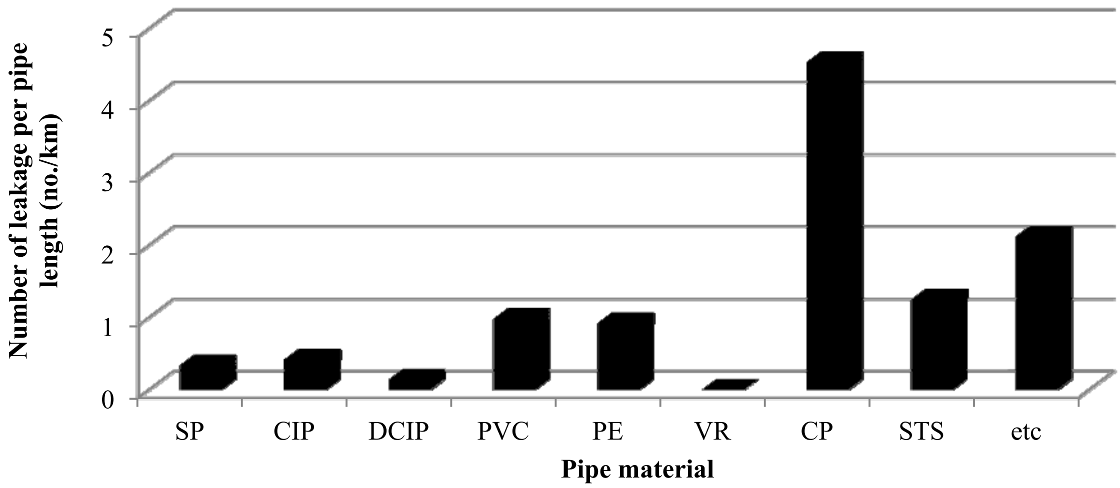

Fig. 1-2-5 Number of leakages per pipe length by pipe material
(Source: 2011 waterworks statistics)

The second remarkable factor is aging. According to the 2011 waterworks statistics, the total length of water distribution pipelines (distribution pipelines + service pipelines) in Korea is nearly 159,039 km, where the total length of aged pipes over 21 years in use is 40,321 km and the aging ratio of the entire pipeline is around 25% (**Table 1-2-2**). Hereupon, pipes of over 21 years in use were regarded as aged pipes

Table 1-2-2 Aging condition of pipelines in Korea (Source: 2011 waterworks statistics)

	Water transmission main (km)	Transmission pipe (km)	Distribution pipe (km)	Service pipe (km)
Total length	3,257	10,718	89,903	69,137
Length of aged pipe	1,212	2,896	18,255	22,066
Aging ratio (%) (over 21 years)	37%	27%	20%	32%

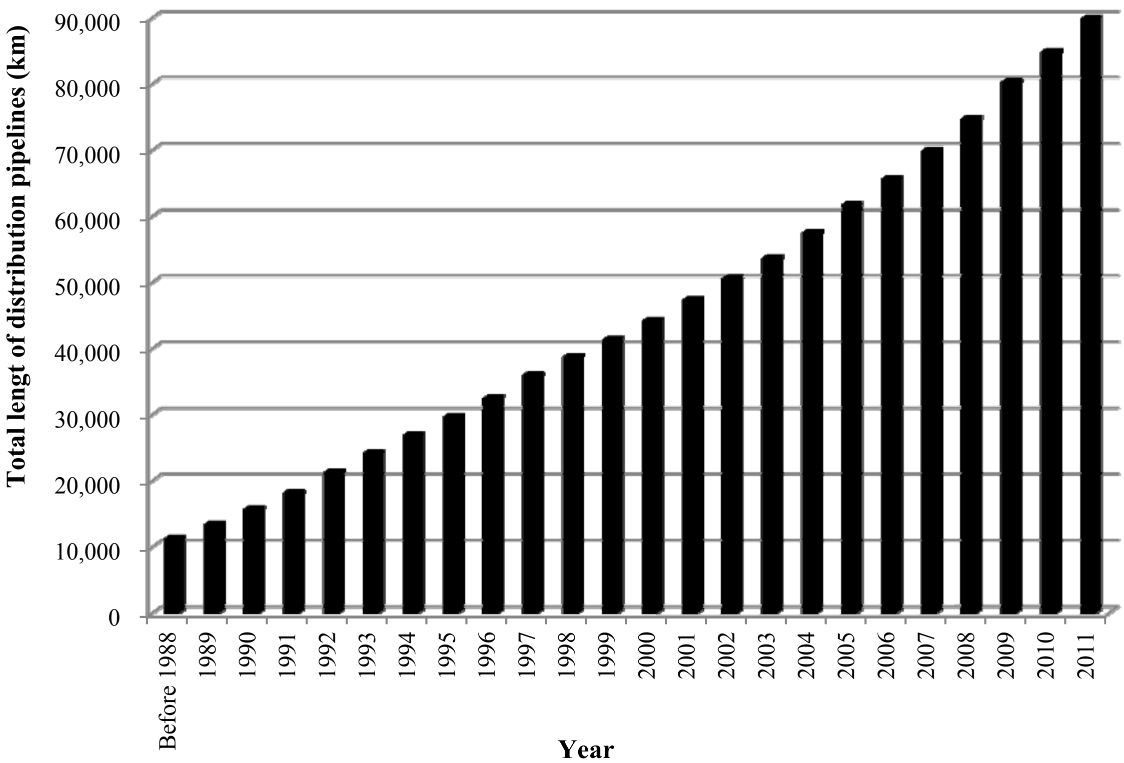

Fig. 1-2-6 Accumulated total length of distribution pipes over the years

(Source: 2011 waterworks statistics)

Fig. 1-2-6 shows the accumulated total length of distribution pipes over the years. Supposing there is no establishment of new distribution pipes for 20 years from now, around 60% distribution pipes will have been in use for over 21 years. As deterioration of pipes is the main cause of pipe accidents (such as leakage, corrosion and burst), it is necessary for the water distribution system to invest in developments such as replacement and maintenance. Despite that, such developments are still lacking compared to that of water treatment technology.

As mentioned above, there are many causes for leakage occurrence, among which unreported leaks are particularly influenced by pipe corrosion. In the case of external corrosion, it is influenced by soil properties such as soil resistivity, pH, moisture, microorganism, and so on.[5)] Thus, the soil property is the third most remarkable factor. However, as it is an extremely difficult task to directly measure the degree of corrosion, it is thus necessary to indirectly measure and assess corrosion in pipes. After assessing pipe corrosion, corroded pipes will need to be replaced in order to prevent leakage.

The fourth most remarkable factor is pipe replacement. According to the 2011 waterworks statistics, there are still a lot of leakage occurrences (**Table 1-2-3**). In addition, only 0.9% of pipelines are replaced per year and there is a shortage of investments in the pipeline replacement project. This is a potential source for water leakage and pipeline accidents. Thus, it is necessary to replace aged pipes and pipe materials that are weak and prone to leakage or accidents.

The International Water association (IWA) defines leakage in two categories: real losses and apparent losses. Real losses (leakage) are the physical escape of water from the distribution system, and include leakage and overflows prior to the point of end use. On the other hand, apparent losses are essentially losses that consist of customer use which is not recorded due to metering error, incorrect assumption of unmeasured use, or unauthorized consumption.[6)] It is worthy of note here that there are much more real losses (leakage) than apparent losses.

Leakage occurs for many reasons such as poor material, pressure transients, corrosion, poor installation, environmental conditions, and so forth.[7)] British leakage management terminology distinguishes reported bursts from unreported leaks.[8)] Reported burst is the main cause of leakage, and it is possible to quickly repair pipes when they burst. However, as it is difficult and time consuming to find leak points in the case of unreported leaks, too much time is wasted before leak points are discovered. Thus, it is necessary to prevent unreported leaks such as through pipe replacement.

Table 1-2-3 Condition of leakage in Korea (Source: 2011 waterworks statistics)

	Transmission	Distribution pipe	Service pipe	Indoor service pipe	Total
Number of leakage (number)	397	20,180	65,255	58,258	144,090
Amount of leakage (m^3)	3,516,366	58,555,140	64,783,391	8,061,730	134,916,627

1-3 Problems with leakage and deterioration

When water leakage and pipeline accidents occur, water can be cut off and cause direct damage to consumers, while affecting others as a result of roads being blocked off and hindered the use of surrounding facilities during pipeline restoration.[9)] Therefore, it is necessary to prevent social losses by changing pipelines in advance to prevent water leakage and accidents. In general, however, the replacement project is focused on pipes that have exceeded a certain period of time in use since installation, rather than considering the present conditions and functional durability. Since deterioration of pipelines and functional reduction are affected by several complex factors such as road load on pipes and the surrounding soil conditions, in addition to the year the pipes were laid, it is necessary to come up with replacement plans that consider these factors.

In developed countries with advanced water supply systems, there have been active and vigorous researches on the improvement and replacement of water distribution pipes, as well as on economic evaluation since several decades ago. Currently, studies in Korea on performance improvement and replacement of faulty pipes are also in progress, but there is difficulty due to a lack of systematic data accumulated over a long period of time. Not only that, even studies that look at economic efficiency are still insufficient. Moreover, water distribution system as a buried structure makes it difficult to check the progress of deterioration and condition, while road excavation and occupation of road facilities increase the burden of social costs.

Consequently, in order to prevent water leakage and suggest how to effectively plan management of water distribution pipelines, this research introduced three methods as follows:

1) To indirectly check and assess the present conditions of pipes through a statistical approach in order to prevent water losses by corrosion;

2) To effectively calculate the replacement rate of pipelines through benefit-cost analysis within the limited budget;

3) To calculate the replacement priority of pipelines by predicting pipeline accidents and the extent of the damages that may happen in the future.

1-4 Composition of this research

This research is composed of three studies about the plan of pipeline replacement. The first study was for evaluating the present pipe condition in an effective way. Pipe corrosion was regarded as a representative factor of pipe condition in this study, as corrosion of pipes cause cracks and bursts that lead to water leakage, pipe repair, and even water quality problems. However, it is difficult to evaluate pipe corrosion, since pipes laid underground are hardly excavated for examination. Pipe corrosion is also related to many factors such as pipe materials, pipe age, surrounding soil conditions, water quality, pipe maintenance and management, among others. Consequently, in order to evaluate pipe corrosion without excavation, a method of indirect evaluation is necessary.

Thus, a statistical approach and a method to evaluate pipe corrosion indirectly were proposed in **Chapter 2**. For this study we focused on external corrosion by firstly searching references on pipe corrosion and then analyzing samples with pipe characteristics and using soil test. During this process, statistical approach applied to this study cause of insufficient data. In particular, discriminant function analysis and regression analysis were applied to the analyses of soil properties and pipe characteristics, respectively. We then developed models applied to the study area for evaluating pipe corrosion. In addition, this study also evaluated future risks by utilizing developed models.

Next, **Chapter 3** deals with the rate of annual replacement of main distribution pipelines. Water pipelines age with time and aged pipelines cause leakages and other water supply problems. Thus, a replacement plan is needed to effectively maintain these pipelines. This study proposes a long-period simulation using an accidental damage occurrence model that handles water pipeline damage contingencies. It involves the calculation for the post-damage maintenance scenario and the preventive maintenance scenario, as well as comparative analyses of the costs and the affected population, ultimately achieving a highly cost-effective replacement plan. Here, as occurrence of failure may be influenced by various contingent factors like random phenomena, the failure probability is calculated using Monte Carlo simulation. Next, the results of the simulation were applied to economic evaluation using benefit–cost analysis. Economic evaluation is necessary because budgets for pipeline replacement are limited. In this study, the benefit is shown as the affected population, while the cost is the sum of total repair cost and total replacement cost. From this we were able to set the annual replacement rate for main distribution pipeline through the simulation model and economic evaluation. In addition to this, the replacement of key pipelines was also introduced.

Finally, in **Chapter 4** we proposed the replacement order for distribution pipelines. Current existing water pipeline replacement plans almost follow the order of aged pipelines, but such plans can be vulnerable to risks. The cause of a pipe's deterioration is not only due to aging but also various other factors. Accidents along important pipelines cause more impact both directly and indirectly on consumers. Thus, this study aims to propose an efficient water pipeline replacement plan by considering risk prevention and factors that cause the deterioration of pipelines.

For this study we attempted to analyze risks through three analyses. The first analysis was for predicting the number of pipeline damages to find out how many times the pipes would be damaged in the future. The second analysis was for estimating the restoration time which represents indirect disadvantages of pipeline damage accidents by pipe repair time. The third analysis was for investigating the direct impact on consumers when a pipeline is intercepted at the damaged point. From these analyses we were able to obtain the quantitative rank of risks in each analysis. As the risk ranking of each analysis is different, it was necessary to find the overall risk ranking. Consequently, in this study we introduced the predicted risk index (PRI) to estimate the overall risk ranking. In conclusion, the highest PRI eminently deserves the utmost priority for pipeline replacement. This study also proves that replacement in order of PRI has an advantage over replacement in order of aged pipes using the simulation model given in **Chapter 3**.

The composition of this research is shown in **Fig. 1-4-1**.

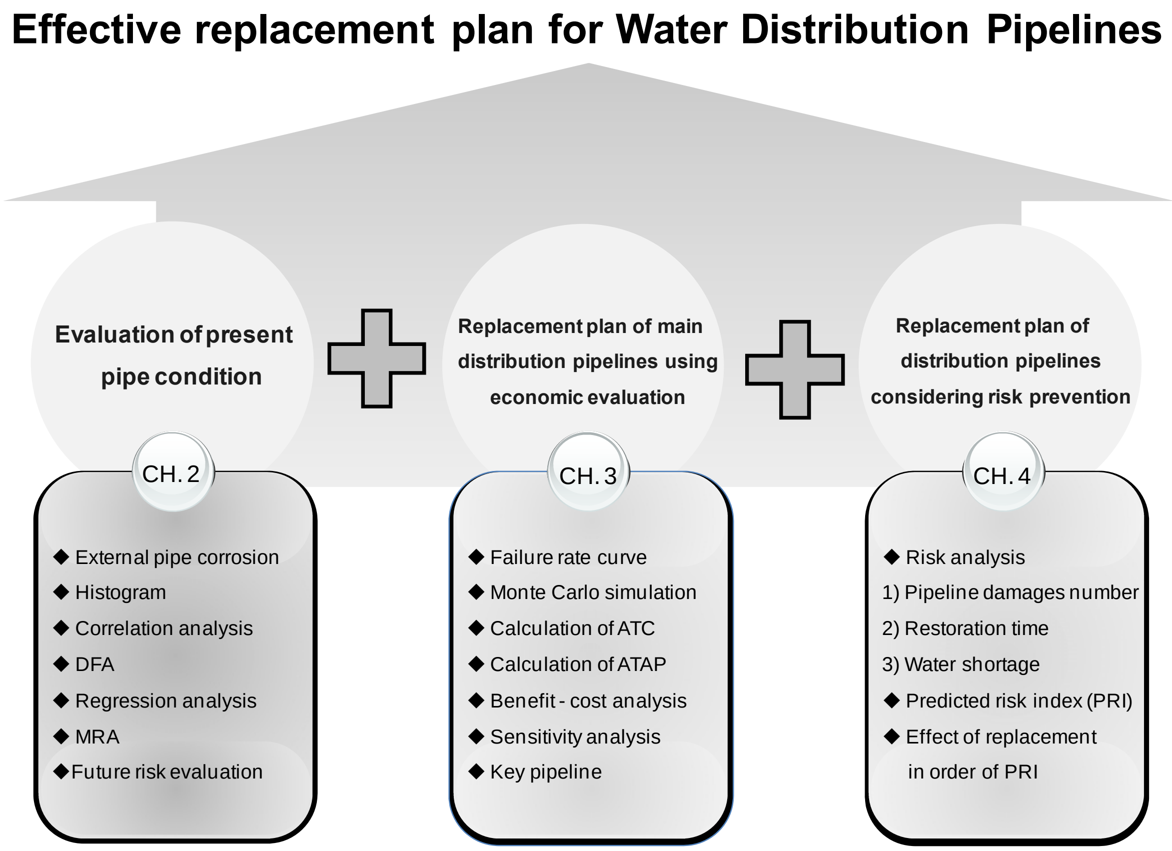

Fig. 1-4-1 Composition of this research

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Chapter 2 Evaluation of present pipes condition

2-1 Introduction

2-1-1 Background and Purpose

Water system plays an important role as a lifeline for our life. It is through pipelines that water is distributed to customers for steadiness and safety without interruption. However, Water pipes tend to be corroded as time goes by. Pipes laid underground are hardly examined without excavation. Some corrosion pipes may cause leakage or damages, resulting in declining or interruption of water supply. In conclusion, pipe corrosion is able to consider pipe condition representative.

Then, in order to maintain customer service at a desirable level, replacement of such old pipelines is considered inevitable. As the replacement of pipelines requires huge costs and time span, it is pressing needs to provide information on how to evaluate the pipe condition in an effective way.

Corrosion of pipes may cause cracks and bursts, resulting in water leakage, pipe repair, and posing even water quality problem so-called 'red water'. Occurrence of the corrosion relates to many factors: pipe materials, pipe age, surrounding soil conditions, water quality, pipe maintenance and management[1), 2)]. It is, therefore, difficult to examine how much extent and where the corrosion is taking place.

Corrosion of outer surface of the metallic pipes occurs mainly due to electrochemical reactions under no homogeneous soil condition. Reaction rate is influenced by soil resistivity, permeability and salty ions existing around the installed pipes[3), 4)].

Most of previous researches dealt with causual analysis of pipe corrosion and prediction of future corrosion for water distribution pipe. Katano et al. (2003) found that the log-normal distribution best fitted their pit data and using regression analysis observed that the environmental factors that were found to be the most significant in determining pit depth included soil type, pH, resistivity, redox potential and sulfate ion[5)]. Kiefner and Kolovitch (2007) developed a Monte Carlo method for determining the corrosion rate distribution in buried pipelines that uses the probability distributions of corrosion depth and initiation time[6)]. Restrepo et al. (2009) employed statistical techniques like cluster analysis to establish the sampling design and later for the data analysis and obtaining a mathematical expression for external corrosion depth as a function of several experimental variables[7)]. In addition, various studies have reported different methodologies used to be able to predict the future trend of corrosion for water pipeline.

Present study has strengths that although data is insufficient, effective evaluation of current condition and prediction model can be obtained clear quantitative model by statistical approach and application is easy in other areas because of high reproducibility. In order to obtain a quantitative model for measuring pipe corrosion, we propose to apply an evaluation index to fuzzy environmental soil conditions of water pipes.

The present study aims at proposing an approach and method to predict intensiveness and probable points of present pipe condition through evaluating pipe corrosion. Base data utilized for the prediction are those sampled at the site. Objectives of the study are referred to:

1) Obtain evaluation indexes for external corrosion reflecting the fuzzy soil nature of installation sites,

2) Develop a multiple regression model to measure the degree of pipe corrosion under the fuzzy soil conditions,

3) Evaluate future risk and timing for decision of pipeline replacement.

2-1-2 Study area and analysis data

The study conducted based on a research project for water distribution network system targeting City S in South Korea from 2009 to 2010[8)]. City S extends to 121.05km^2 with a population of about 1.11 million[9)]. Carrying through this research project, a study on utilization of water network GIS and an investigation concerning pipe corrosions were executed.

Field data on pipe corrosions and soil conditions around pipes were obtained in the previous research project include those of the test pit excavation at 60 random locations along the water distribution pipelines (**Fig. 2-1-1**).

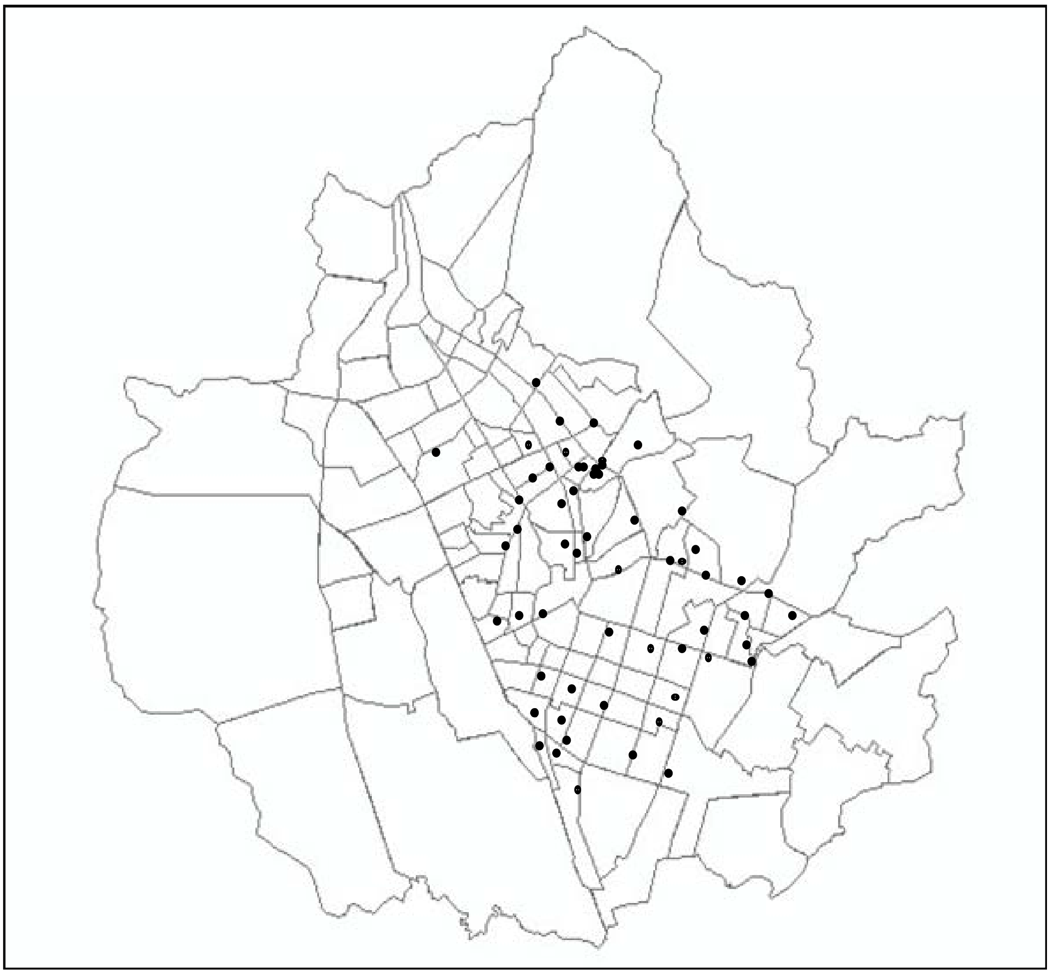

Fig. 2-1-1 Sampling points in City S (n = 60)

And then we can obtain three kinds of information through the test pit excavation. First is degree of external corrosion. Second is characteristics of sample pipe' body. And then last information is results of soil test for sampling points. Specially, the external corrosion is measured by two indexes: external depth of corrosion given as localized corrosion index (Y_d), and corrosion spread on the pipe's surface given as general corrosion index (Y_a). In case of characteristics of sample pipe' body, there is information which is included pipe age, diameter and water pressure. This information is obtained from GIS. And Soil test was analyzed by soil properties around sample pipes[10].

2-2 Basic analysis

2-2-1 Distribution of samples

To begin with, a histogram was created in order to make it easy to understand a distribution of samples. Corrosion conditions are presented in histograms to show cumulative frequency vs. corrosion level (**Fig. 2-2-1** and **Fig. 2-2-2**). As following histograms, no pipe corrosion is found at 47%. This is because the investigation includes pipes that are not corroded due to random sampling.

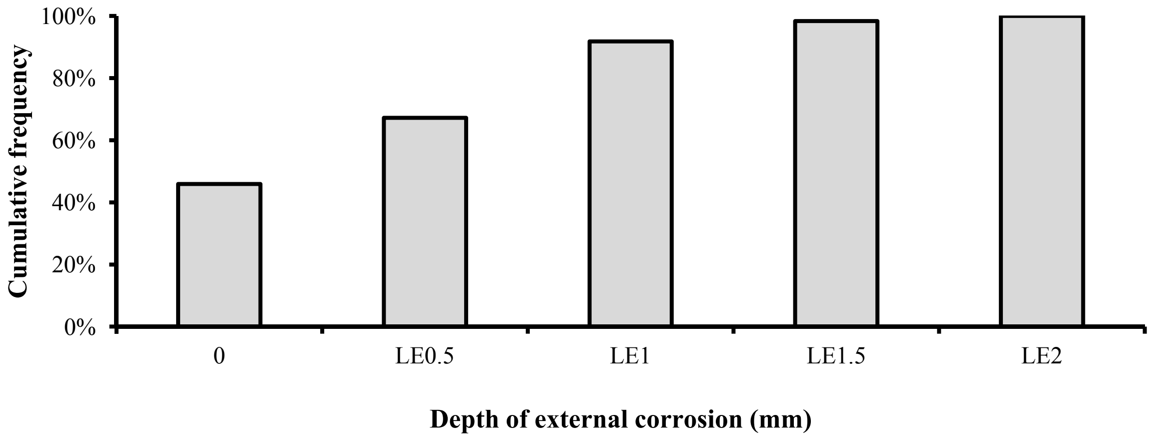

Fig. 2-2-1 Histogram of the depth of external corrosion (Y_d)

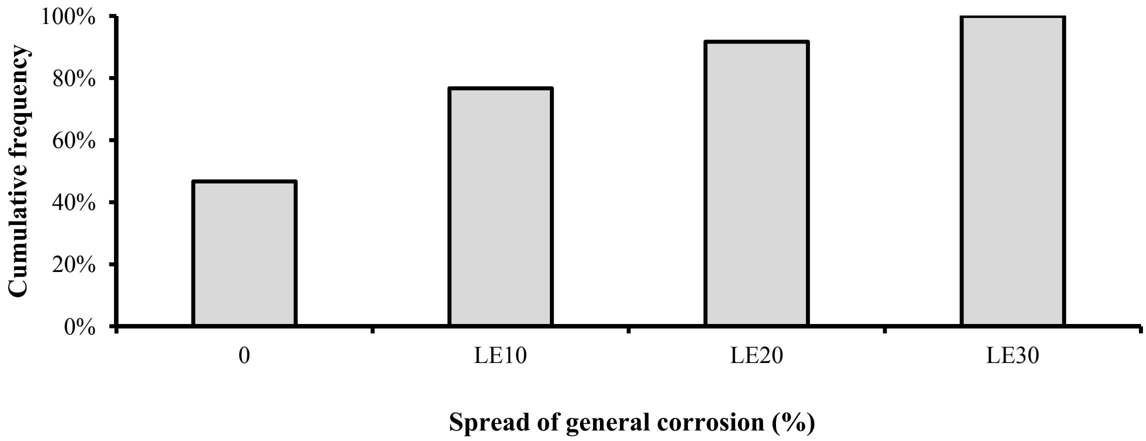

Fig. 2-2-2 Histogram of the spread of general corrosion (Y_a)

Next **Fig. 2-2-3**, **Fig. 2-2-4** and **Fig. 2-2-5** are indicated histograms of pipe characteristics.

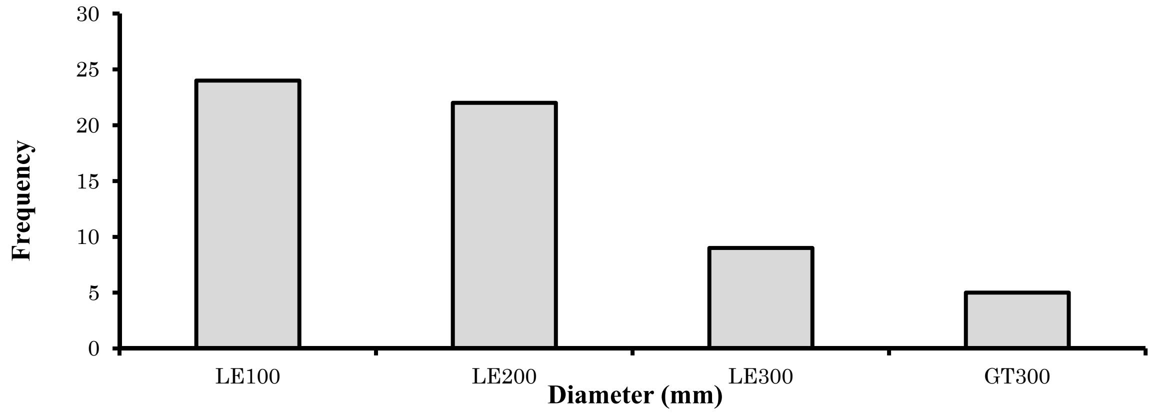

Fig. 2-2-3 Histogram of diameter (X_1)

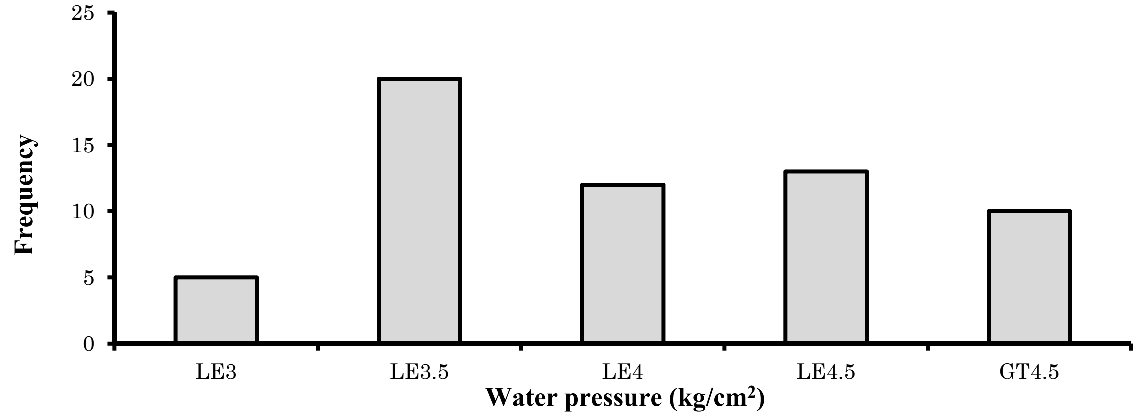

Fig. 2-2-4 Histogram of water pressure (X_2)

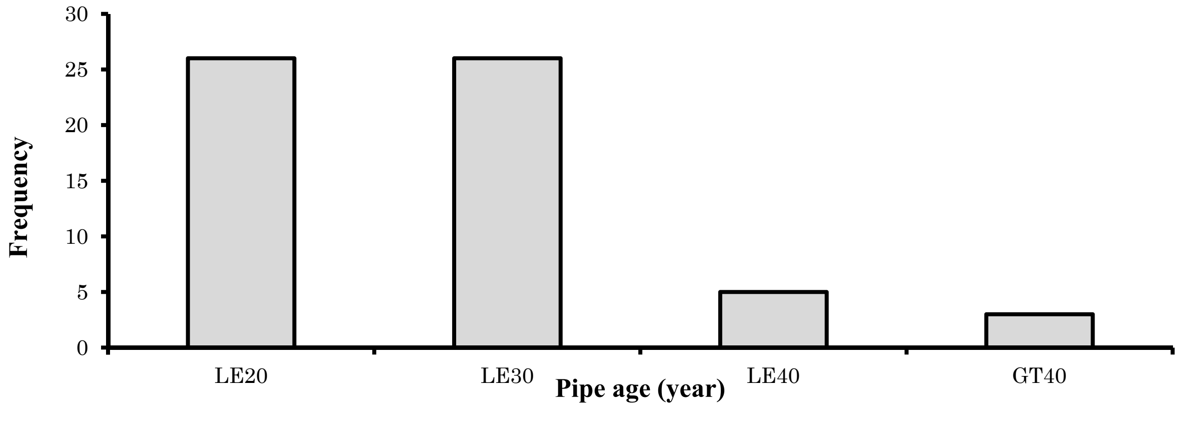

Fig. 2-2-5 Histogram of pipe age (X_3)

This study mainly deals with slender distribution pipes which are lower than 300mm as in **Fig. 2-2-3**. And then the investigation area has rather high water pressure (**Fig. 2-2-4**). According to Korea Waterworks Facility Standards (2004), the standard minimum dynamic water pressure for direct connecting water supply of a 5 storey building is 300~350kPa, and should differ according to topography and dwelling pattern[11)]. Mansion-style dwelling was more common than detached houses in the sampling areas, and due to the high ground levels it can be seen that the water pressure is rather high.

In case of pipe age, the range of distribution is from 12 to 52 years. Despite pipe age of 12 to 52 years, some newer pipes (under 20 years) have deeper and/or wider spread of corrosion than the average. To a contrary, there are some samples which didn't have corrosion found in older (over 40 years) pipes. This tendency is considered to be closely related to characteristics of the surrounding soil conditions and the pipe conditions which are not protected by polyethylene sleeve.

Next histograms show about distribution of soil properties.

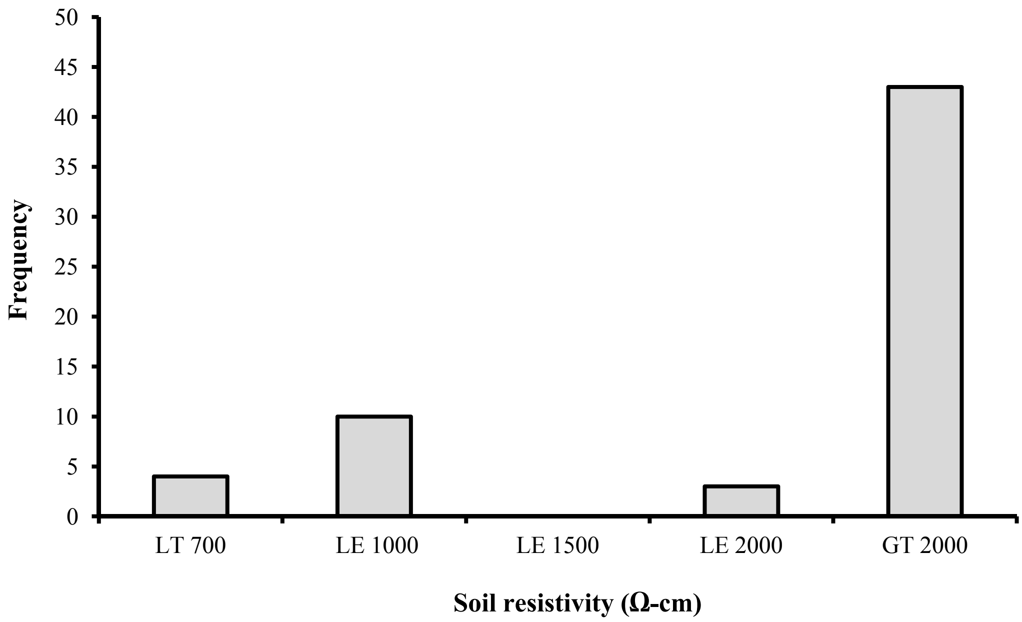

Fig. 2-2-6 Histogram of soil resistivity (X_4)

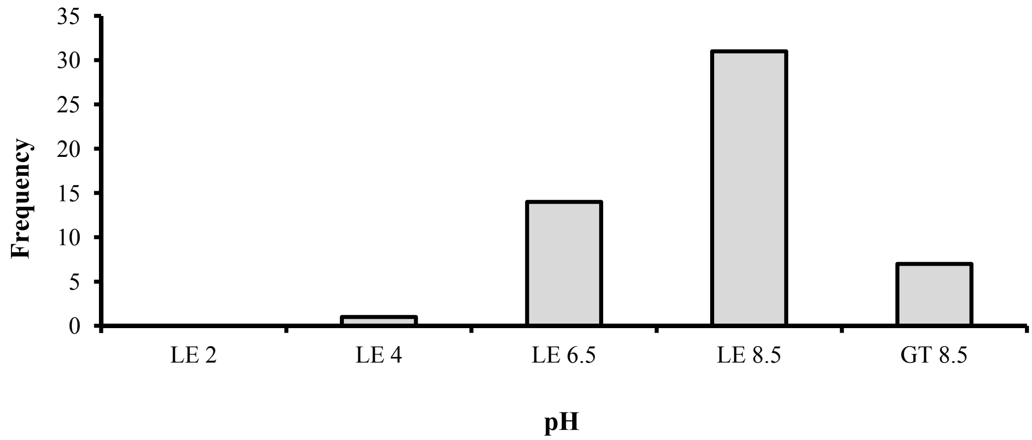

Fig. 2-2-7 Histogram of soil pH (X_5)

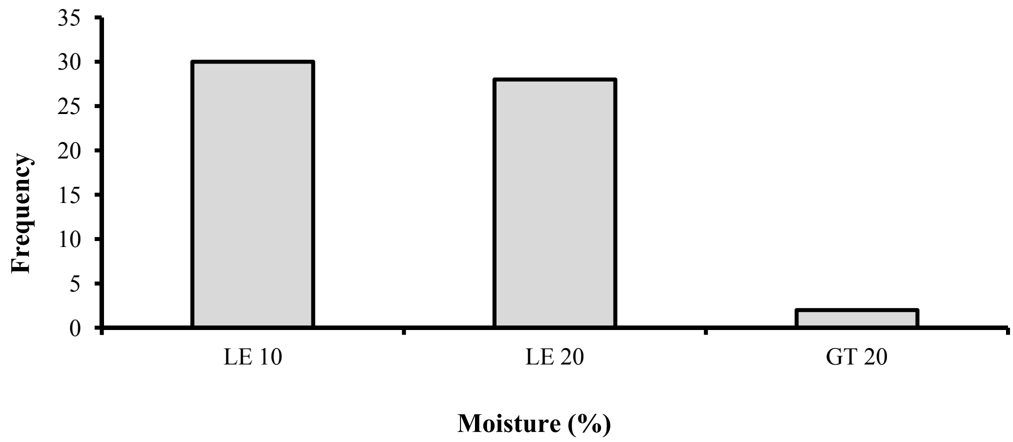

Fig. 2-2-8 Histogram of Moisture (X_6)

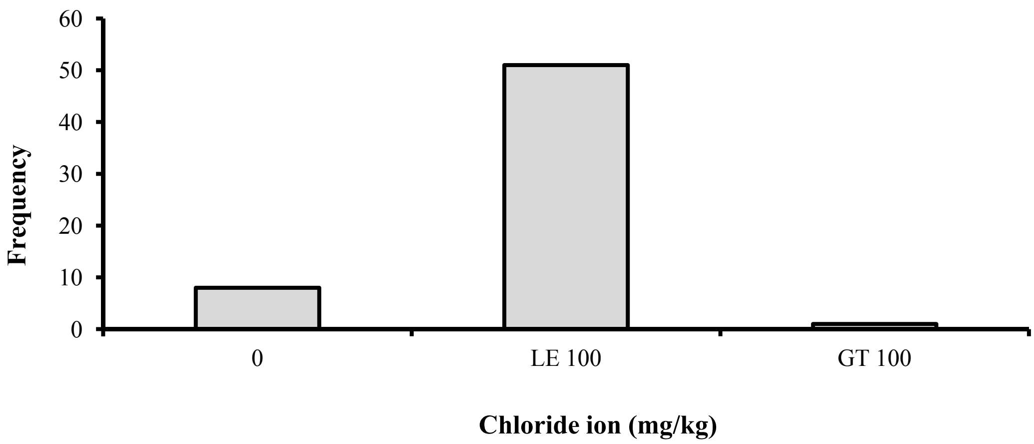

Fig. 2-2-9 Histogram of chlorine ion (X_7)

As the above results, for soil resistivity, it was identified by the ANSI method that only four samples had measurement values below 700 to be under very highly corrosive soil condition, and around 72% of samples indicated values above 2000 to be sampled from extremely low corrosive soil condition. As pH's histogram shows, also, only one sampling point had acidity of less than 4, whereas 7 sampling points were found to have alkalinity of over 8.5. Next, in relation to moisture, exact half of samples are obtained from dry condition (moisture is less than 10%). Lastly, chloride ion was detected from 87% of soil samples. These figures illustrate that the sampling points covered a wide range of soil conditions.

Soil corrosivity assessment was conducted using ANSI index. ANSI index is standard method which is commonly used for assessment corrosivity. **Table 2-2-1** shows valuation basis for corrosivity using modified ANSI. And then **Table 2-2-2** shows ANSI index[12)].

Table 2-2-1 Valuation basis for corrosivity using modified ANSI

Total score (ANSI modified)	Corrosivity	Class
0 ～ 2	Nothing.	1
3 ～ 5	Weak	2
6 ～ 9	Middle	3
Over 10	Strong	4

Table 2-2-2 Assessment table of soil corrosivity by ANSI (modified)

Soil parameter	Range of test result	Assigned points
Soil resistivity (Ω-cm)	<700	10
	700～1,000	8
	1,000～1,200	5
	1,200～1,500	2
	1,500～2,000	1
	>2,000Ω-cm	0
Soil 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 (ORP, mV)	>100	0
	50～100	3.5
	0～50	4
	<0 (-)	5
Moisture (%)	Over 20%	2
	10 ~ 20%	1
	Less than 10%	0
Acid compounds (mg/kg)	Over 100 (+)	3.5
	0 ~100	2
	Negative	0
* If sulfides are present and low or negative redox-potential results are obtained, give 3 points for this range.		

Table 2-2-3 Results of modified ANSI

Total score (ANSI modified)	Corrosivity	Class	Number of samples (n=60)
0 ～ 2	Nothing.	1	6
3 ～ 5	Weak	2	29
6 ～ 9	Middle	3	11
Over 10	Strong	4	14

As the results of modified ANSI method, we can judge that around 42% soil samples have corrosivity.

Also, the relation between the corrosive condition of each soil sample evaluated by ANSI methods and the actually measured external corrosion is shown in **Fig. 2-2-10** and **Fig. 2-2-11**. As the **Fig. 2-2-10** and **Fig. 2-2-11** illustrate, there are samples that actually measured external corrosion depth and spread of general corrosion have low values with the high score of modified ANSI and also have high values with the low score of modified ANSI.

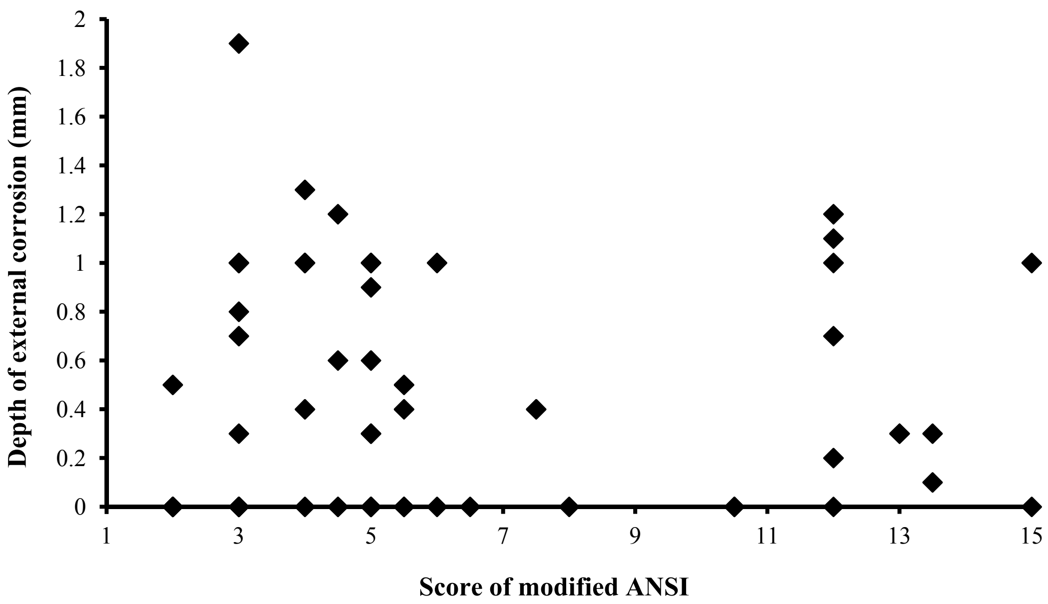

Fig. 2-2-10 Relation between score of modified ANSI and external corrosion depth

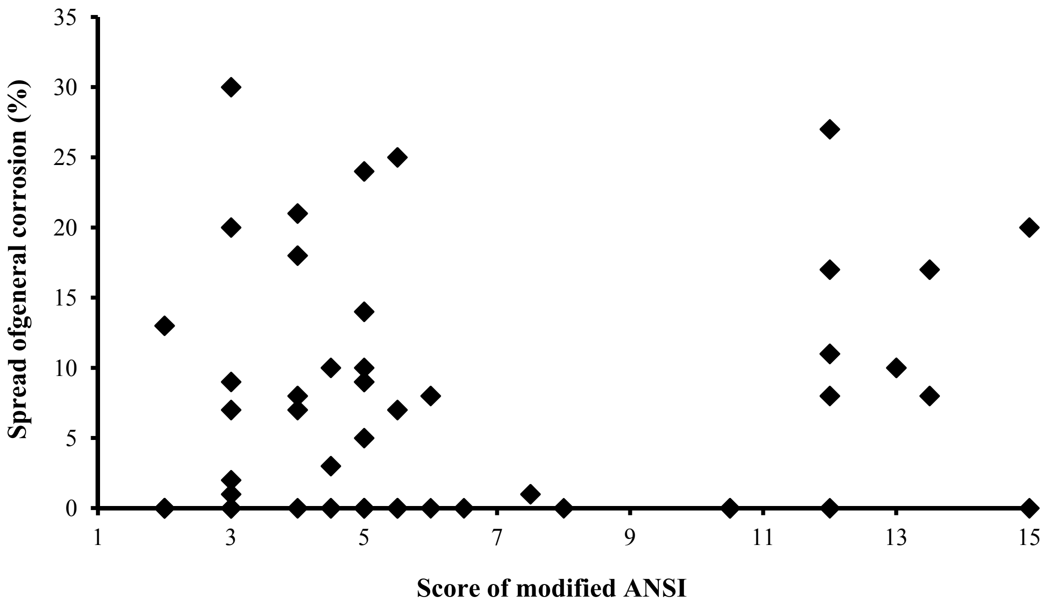

Fig. 2-2-11 Relation between score of modified ANSI and spread of general corrosion

And then, corrosive condition of soil samples was also evaluated using DVGW method which are the most representative methods for evaluation of soil corrosivity. **Table 2-2-4** shows class of corrosivity based on DVGE method[13)]. And then **Table 2-2-5** shows items of DVGE method. As the results, around 88% of soil samples were found to be evaluated as weak corrosivity and 12% soil samples as middle corrosivity using DVGW method (**Table 2-2-6**).

Table 2-2-4 Class of corrosivity based on DVGW method

Estimated value	>0	0 ~ -4	-5 ~ -10	<-10
Corrosivity	Very weak	Weak	Middle	Strong

Table 2-2-5 Assessment table of soil corrosivity by DVGW method

Point	+2	+1	0	-1	-2	-3	-4
Kinds of soil	C, CM, SM, S		S, SL, LM, SA		A, AM, H		T, LS, SA
Groundwater level			No present		Present variable		
Condition of soil			SN S_1		Sr	S_2	
Soil resistivity (Ω-cm)			>10,000	10,000 ~ 5,000	5,000 ~ 2,300	2,300 ~ 1,000	<1,000
Moisture (%)			<20	>20			
pH			>6		<6		
Total acidity (pH7) [mg/kg]			<2.5	>2.5~5	>5		
Redox potential (pH7) [mV]	>400 VS		200~400 VM		0~200 VW		<0 VN
Total alkalinity (pH4.8) [mg/kg]	>1,000	200 ~ 1,000	<200				
Sulphide & Hydrogen sulphide [S^{-2}mg/kg]			No present				Present
Ciders, Cokes			No present				Present
Chloride ion [mg/kg]			<100	>100			
Sulfate ion [mg/kg]			<200	200~500	500~1,000	>1,000	

Table 2-2-6 Results of corrosivity evaluation by DVGW method

Estimate value	>0	0 ~ -4	-5 ~ -10	<-10
Corrosivity	Very weak	Weak	Middle	Strong
Class	1	2	3	4
Number of samples (n=60)	0	53	7	0

Also, the relation between the corrosive condition of each soil sample evaluated by DVGW method and the actually measured external corrosion is shown in **Fig. 2-2-12** and **Fig. 2-2-13**.

Similarly, between actually measured values of external corrosion and absolute values of DVGW score don't have definite relationship as shown in **Fig. 2-2-10** and **Fig. 2-2-11**. These results mean that there are significant differences between the actually measured external corrosion and the corrosive condition evaluated by DVGW method. In conclusion, it is considered that a new evaluation method of corrosivity of soil samples should be developed.

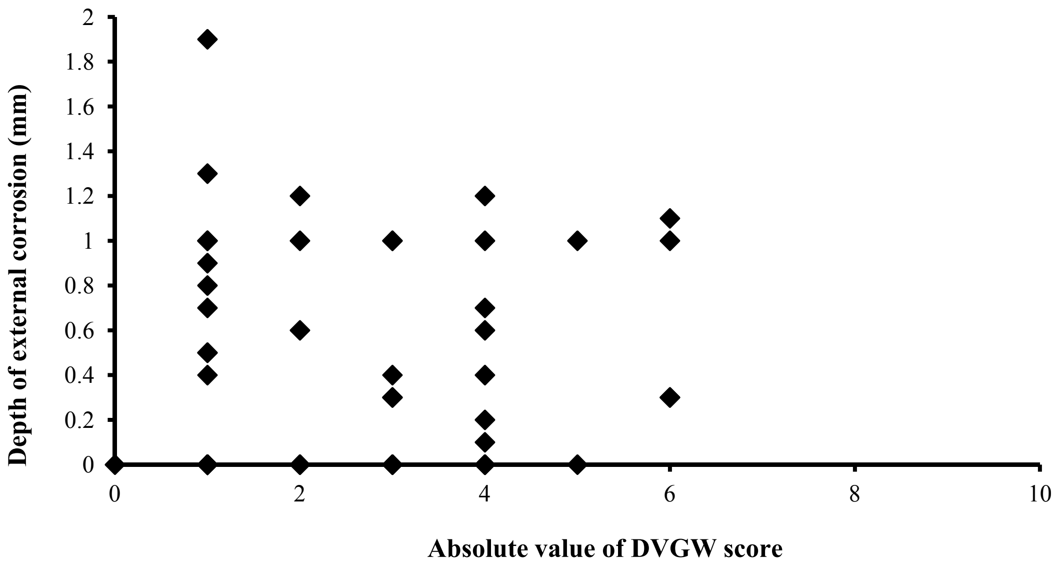

Fig. 2-2-12 Relation between absolute value of DVGW score and external corrosion depth

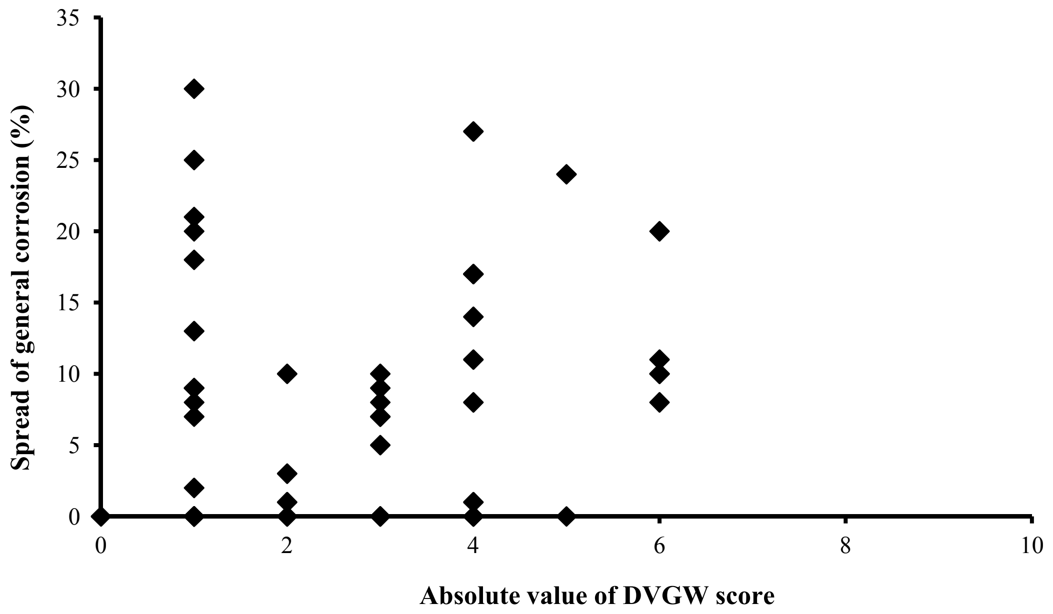

Fig. 2-2-13 Relation between absolute value of DVGW score and spread of general corrosion

2-2-2 Correlation analysis

A correlation analysis is carried out in order to examine the linear correlation between external corrosion and influential factors using scatter diagrams and correlation coefficients. At firstly checked closely at the correlation between depth of external corrosion and spread of general corrosion. The scatter diagram (**Fig. 2-2-14**) reveals that depth of external corrosion has not a definite correlation with spread of general corrosion. Because there are some samples which have big gap between both indexes, the advance on each corrosion index is considered to be helped by different influential factors. Using this result as basis, depth of external corrosion and spread of general corrosion were determined to be treated separately in the following analysis.

Secondly the correlations between external corrosion indexes and characteristics of pipe (pipe age, diameter, material, water pressure) are investigated. The following figures are scatter diagrams of depth of external corrosion with indexes of characteristics of pipe respectively, while the scatter diagrams for general corrosion were skipped because of similarity.

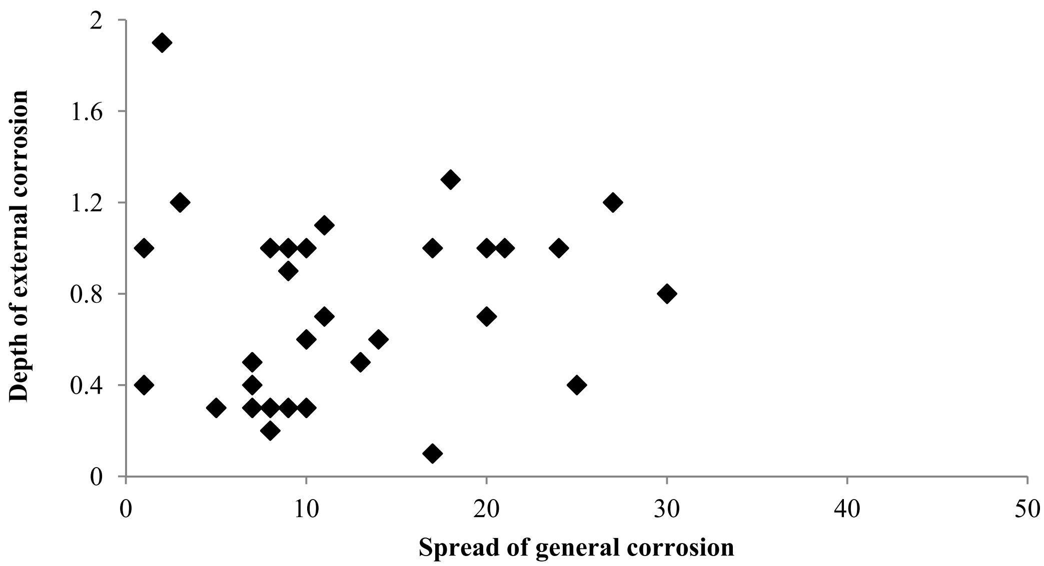

Fig. 2-2-14 Correlation between external corrosion depth and general corrosion

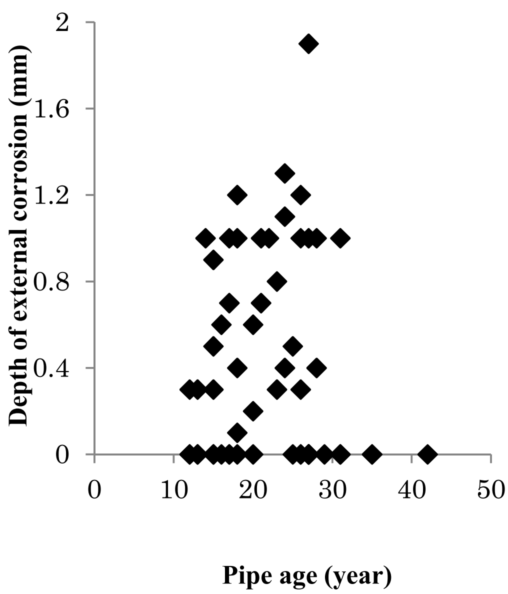

Fig. 2-2-15 Correlation between external corrosion depth and pipe age

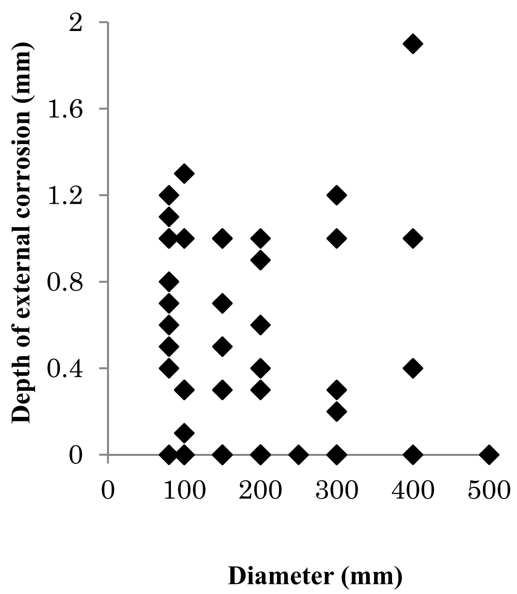

Fig. 2-2-16 Correlation between external corrosion depth and diameter

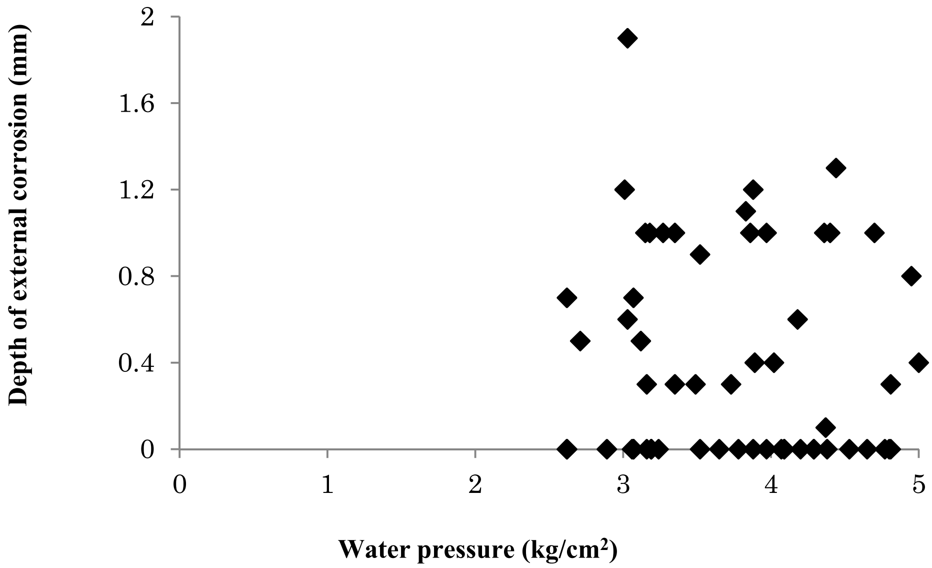

Fig. 2-2-17 Correlation between external corrosion depth and water pressure

And then the next figures are scatter diagrams of depth of external corrosion with indexes of soil properties respectively.

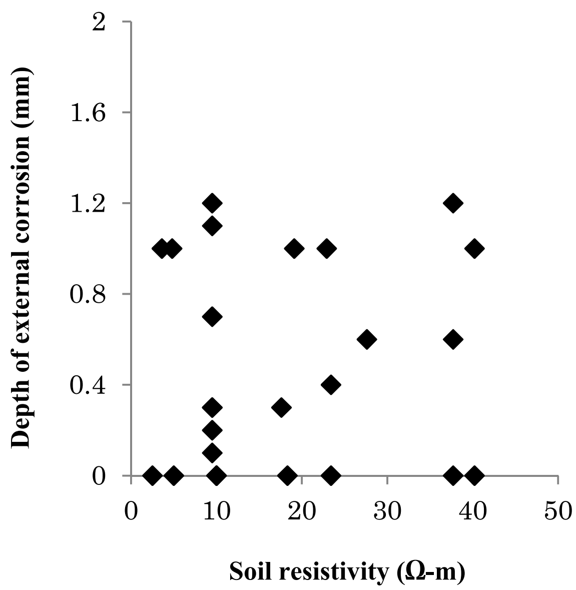

Fig. 2-2-18 Correlation between external corrosion depth and soil resistivity

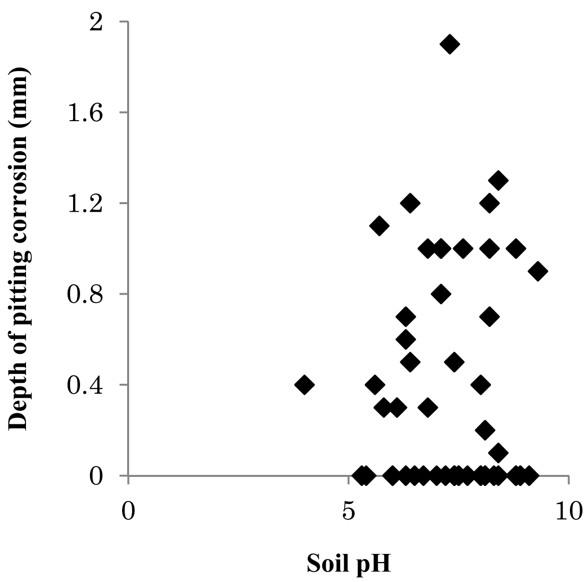

Fig. 2-2-19 Correlation between external corrosion depth and soil pH

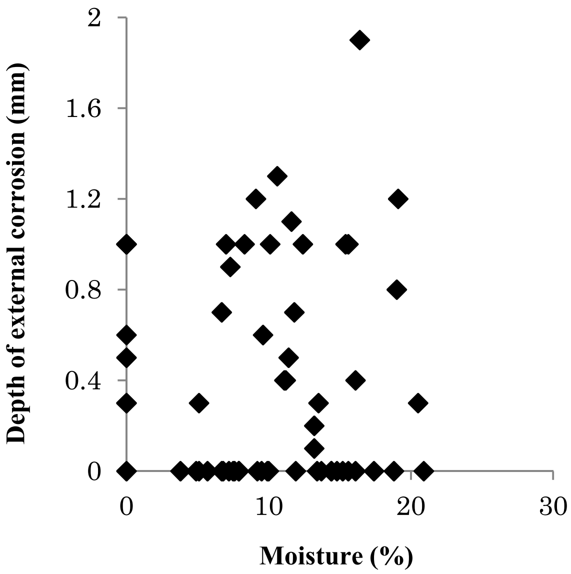

Fig. 2-2-20 Correlation between external corrosion depth and moisture

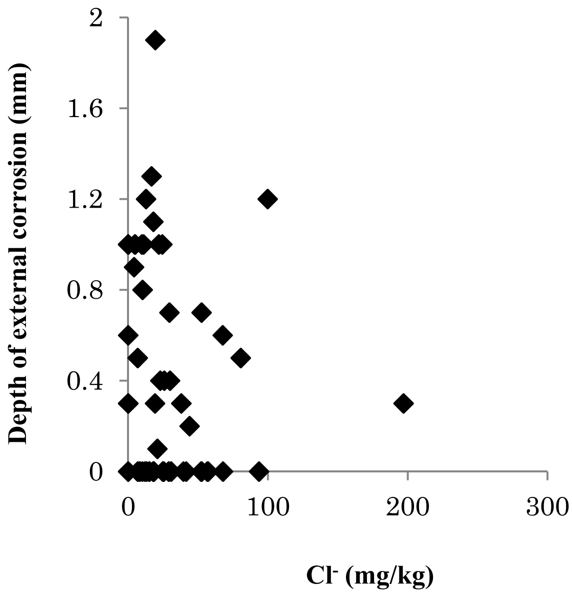

Fig. 2-2-21 Correlation between external corrosion depth and chloride ion

Table 2-2-7 Correlation coefficient between corrosion indexes and influence factors

		Item	Variable	R
Depth of external corrosion (Y_d)	Characteristics of pipe	Diameter (mm)	X_1	-0.03
		water pressure (kg/cm^2)	X_2	-0.08
		Pipe Age (year)	X_3	-0.12
	Soil properties	Soil resistivity (Ω-m)	X_4	-0.09
		Soil pH	X_5	-0.15
		Moisture (%)	X_6	-0.02
		Cl^- (mg/kg)	X_7	-0.12
Spread of general corrosion (Y_a)	Characteristics of pipe	Diameter (mm)	X_1	-0.44
		water pressure (kg/cm^2)	X_2	0.19
		Pipe Age (year)	X_3	-0.25
	Soil properties	Soil resistivity (Ω-m)	X_4	-0.15
		Soil pH	X_5	-0.24
		Moisture (%)	X_6	-0.07
		Cl^- (mg/kg)	X_7	-0.16

As the scatter diagrams, we can find that almost correlations between depth of external corrosion and influence factors have big gap and inverse proportion. To find out more clearly, correlation coefficient was confirmed (**Table 2-2-7**).

It became apparent after correlation analysis that between indexes of external corrosion and influence factors have big gap and non linear relation. This is because around 28 sample pipes don't have external corrosion and some sample pipes have rack of data, so it is difficult to find relation between external corrosion and influence factors.

In order to check relation between external corrosion and influence factors clearly, correlation analysis except for the samples of non-corrosion data and soil properties and/or no soil property data is necessary. So the correlation analysis was performed again without sample pipes which have rack of data and non corrosion. As the results, 26 sample pipes were selected. **Table 2-2-8** shows results of correlation analysis.

Table 2-2-8 Result of correlation by t-distribution ($n = 26$, $r_{0.05} = 0.39$, $r_{0.1} = 0.33$)

Corrosion index	Influence factor		R	$r_{0.05}$	$r_{0.10}$	Logicality
Y_d	Diameter (mm)	X_1	0.21			O
	Water pressure (kg/cm^2)	X_2	-0.16			X
	Pipe age (years)	X_3	0.37		*	O
	Resistivity (Ω-m)	X_4	0.17			X
	Soil pH (-)	X_5	0.24			O
	Moisture (%)	X_6	0.1			O
	Cl^- (mg/kg)	X_7	-0.27			X
Y_a	Diameter (mm)	X_1	-0.77	**		O
	Water pressure (kg/cm^2)	X_2	0.48	**		O
	Pipe age (years)	X_3	-0.3			X
	Resistivity (Ω-m)	X_4	0.11			X
	Soil pH (-)	X_5	0.12			O
	Moisture (%)	X_6	0.13			O
	Cl^- (mg/kg)	X_7	-0.26			X

Next, the correlations among external corrosion (Y_d, Y_a), characteristic of pipe (X_3) and soil properties (X_4, X_5, X_6, X_7) are examined with t-distribution test at 90% and 95% significance level. In here, significance level of reliability is confirmed as results of **Equation 2-2-1**. If correlation coefficients had smaller value than the standard r_α, this means that there is no relation between each influential factor and each corrosion index.

$$r_\alpha = \frac{t_\alpha}{\sqrt{n-2+t_\alpha^2}} \qquad \textbf{(2-2-1)}$$

where, r_a: standard value of correlation coefficient at α-significant level

t_a: t-value at α-significant level (t-distribution test)

n: sample size

As seen in '**' and '*' in **Table 2-2-8**, in case of depth of external corrosion (Y_d), pipe age (X_3) is relevant with 90% significance level. On the other hand, in case of spread of general corrosion (Y_a), diameter and water pressure are relevant with 95% significance level.

In this table, logicality is an indicator illustrating logical relevance within variables. Typically, soil properties except for soil resistivity (X_4) feature that external corrosion accelerates as each element goes up while X_4 has the opposite tendency. According to **Table 2-2-8**, almost all factors cannot pass the t-distribution test and some factors do not have logical relevance. It is likely that the research data is less statistically significant, because the relations among samples with wide range of soil properties (from strongly corrosive soil to non-corrosive soil) are misleadingly vague without classification.

2-3 Discriminant function analysis (DFA)

2-3-1 Purpose of discriminant function analysis

In this study, in order to get more reliable model to predict the degree of pipe corrosion, the relationship between external corrosion and soil property is further looked into by applying DFA. Examining the discriminant function, we quantify the soil environment corrosivity using some combination of variables in which the fuzzy soil property is reflected[14)].

DFA is applied in order to distinguish the corrosive soil environment from the non-corrosive. Common purpose of the DFA is to predict the group membership based on a linear combination of variables using a measure of generalized square distance assuming that each group has a multivariate normal distribution (**Fig. 2-3-1**). Another purpose of DFA is to get an insight into the relationship between the group membership and variables in the prediction model which is given as a discriminant function.

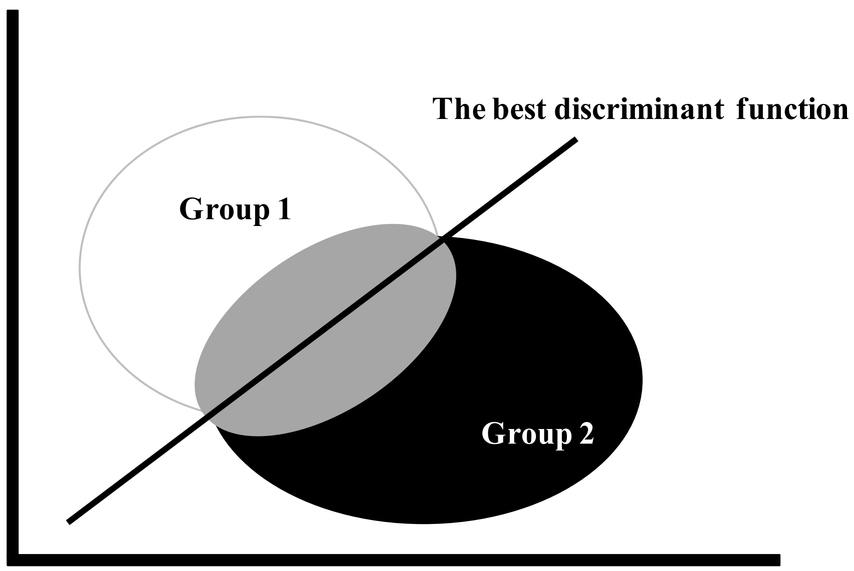

Fig. 2-3-1 Purpose of discriminant function analysis

2-3-2 Set sample condition for BAD and GOOD group

At the beginning of DFA, observations for each group are made including both high-ranking and low-ranking samples reflecting a characteristic of the universe (the population of all samples). In this study, two groups, namely, a corrosive group (named BAD group) and a non-corrosive group (named GOOD group) are considered for each discriminant function corresponding to each corrosion indexes (Y_d and Y_a).

It is normal procedures that DFA focuses merely on data ranked high and low (namely, the first quarter and the last quarter of the sorted sample). In this study, 16 samples (almost the last quarter) which had over 0.6mm of corrosion depth are regarded as BAD group member corresponding to Y_d, and 12 samples with over 10% area corrosion are categorized into BAD group corresponding to Y_a. On the other hand, GOOD group consists of no external corrosion samples both for Y_d and Y_a. As numbers of effective data differs between these groups, a measure to balance sample data is required.

2-3-3 Balance sample size between BAD and GOOD group

To ensure stability of DFA, two groups are preferably equal in data size. The number of samples in GOOD group is greater than sample size of BAD group. As the above the two tables, we can find that the number of GOOD group data is 28. However in case of Y_d, the number of BAD group data is 16. Also in case of Y_a, the number of BAD group data is 12. So, random sampling methods are adopted to select samples for GOOD group. Several sets of samples are arranged so that Good group may have same sample size to BAD group, and then the corresponding models for classification are examined. In this part, 5 random sampling methods were adopted like below **Fig. 2-3-2**.

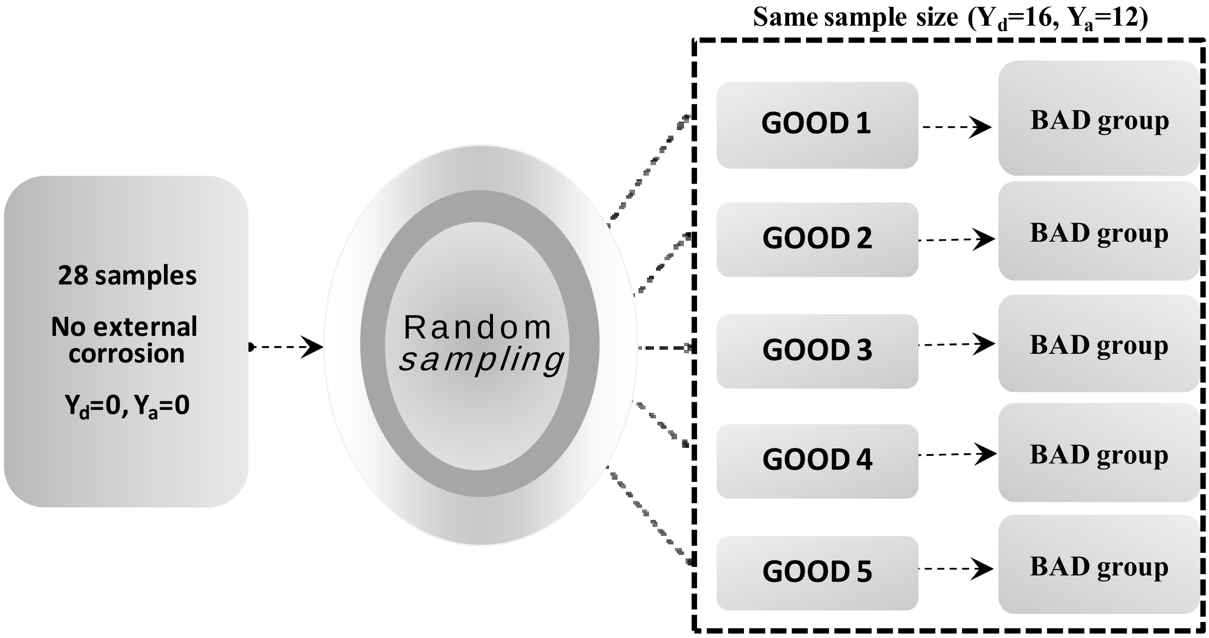

Fig. 2-3-2 Random sampling methods for balance of data size

5 random sampling methods are as follow and these methods were applied to Y_d and Y_a respectively.

1) Except the highest and lowest value in each soil properties
2) After range ascending order for pipe age, except multiple of three sample pipes
3) After range ascending order for soil resistivity, except multiple of three sample pipes
4) After range ascending order for moisture, except multiple of three sample pipes
5) After range ascending order for chloride ion, except multiple of three sample pipes

As the results of random sampling, the number of GOOD group data size is same with BAD group data size, and then total 10 cases (hereafter as 'D1~D5' and 'A1~A5') were made in each index of external corrosion like below tables. In here, 'D' means case of Y_d and 'A' means case of Y_a.

2-3-4 Examine whether each environmental factor is logically acceptable

After adjusting sample size of both groups, the average value of each environmental factor for each group is compared. When the average value of an environmental factor in BAD group is higher than that of GOOD group (Bold character), such factor is judged to have logicality, excluding soil resistivity (X_4) which has an opposite tendency. Results of this part show as bellow **Table 2-3-1**.

Table 2-3-1 Results of logicality between groups

	Case	Soil- resistivity (Ω-m)	Soil pH (-)	Moisture (%)	Cl^- (mg/l)
		X_4	X_5	X_6	X_7
Y_d	Run D1	**57.30** / 50.23	**7.37** / 7.43		
	Run D2	**68.29** / 50.23		**10.94** / 11.88	
	Run D3	**58.13** / 50.23		**10.67** / 11.88	
	Run D4	**62.91** / 50.23		**10.77** / 11.88	
	Run D5	**62.36** / 50.23		**11.24** / 11.88	
Y_a	Run A1	**57.68** / 46.43	**7.15** / 7.22		
	Run A2	**61.75** / 46.43			
	Run A3	**65.42** / 46.43			
	Run A4	**59.56** / 46.43			
	Run A5	**62.61** / 46.43		**9.95** / 10.82	

After comparing the average of the GOOD group with BAD group for each cell, the corresponding cell that is out of logicality was represented with a blank. In the case of depth of external corrosion (Y_d) in **Table 2-3-1**, it can be seen that soil resistivity (X_4) of Run D1 ~ Run D5 all accord with logicality, and the case of moisture (X_6) displays logicality in Run D2 ~ Run D5. This is a sector that allows us to indirectly know that soil resistivity (X_4) and moisture (X_6) have intimate influence on the depth of external corrosion (Y_d).

Also, as in the case of spread of general corrosion (Y_a), it can be confirmed that soil resistivity (X_4) has logicality in Run A1 ~ Run A5. However, the case of moisture (X_6) displays only in Run A5. These results show that soil resistivity (X_4) has intimate influence on the spread of general corrosion (Y_a).

2-3-5 Estimate discriminant function

DFA model is developed with the aid of SAS[15)] as a function of the selected factors, logically reasonable. For depth of external corrosion (Y_d) and spread of general corrosion (Y_a), 5 cases randomly sampled are analyzed respectively. Most reliable DFA models are then selected for Y_d and Y_a taking into consideration of misclassified observation.

Before development of DFA model with SAS, an assumption is necessary for optimization of DF. The objects which used for deduction of discriminant function must be extracted from the multivariate normal distribution. So standardization is necessary. Below **Equation 2-3-1** indicates how to standardization.

$$W_n = (X_n - m_n) / s_n \qquad \textbf{(2-3-1)}$$

In here, W_n is factor (W_4 ~W_7) of standardized as expressed in **Equation 2-3-1**, X_n is explanatory factors (X_4 ~ X_7), m_n is their entire mean values (m_4 ~ m_6) and s_n is their entire standard deviations (s_4 ~ s_6).

Table 2-3-2 and **Table 2-3-3** are findings of DFA through SAS, and in 5 cases, the highest hit ratio case is selected respectively. The hit ratio is predictive accuracy for examined data.

Table 2-3-2 Result of Y_d using SAS (n_{GOOD} = 16, n_{BAD}=16)

Y_d		Constant	X_4	X_5	X_6	X_7	d^2	Hit ratio
			W_4	W_5	W_6	W_7		
1	Z_d	0.007	0.4401	-0.187			0.049	53%
2	Z_d	-0.216	1.203		-0.307		0.341	59%
3	Z_d	-0.041	0.392		-0.455		0.107	56%
4	**Z_d**	**-0.081**	**0.601**		**-0.442**		**0.164**	**63%**
5	Z_d	-0.060	0.688		-0.171		0.131	56%

As for external corrosion depth (Y_d), equations obtained from the analyses are assessed highly reliable. As the above the table, we can obtain number 4 model which has the highest hit ratio. Number 4 model was made an equation like below.

$$Z_d = 0.601W_4 - 0.442W_6 - 0.060 \quad \textbf{(2-3-2)}$$

Equation 2-3-2 represents a linear discriminant function. If a classification index (Z_d) estimated from this equation is greater than zero, it is considered the sample falls into the GOOD category. This implies the external depth within the range of less than 0.6mm. Explanatory factors (X_4 and X_6) are standardized as expressed in **Equations 2-3-1** respectively. From coefficients in the **Equation 2-3-2**, W_4 has a larger absolute value than that of W_6. This indicates that the soil resistivity (X_4) is more influential than the moisture (X_6) on the external depth.

On the other hand, as for the spread of general corrosion (Y_a), the soil resistivity (X_4) is found as an influential factor. **Equation 2-3-3** stands for a linear discriminant function obtained for Y_a. A standardized variable, W_4 in **Equation 2-3-3**, is similar of the soil resistivity (X_4) as presented in the **Equation 2-3-1** above. If Z_a is greater than 0, then the sample is classified to the GOOD group. This implies the spread of general corrosion is estimated less than 10% of pipe surface. Below flow cart is a comprehensive process of DFA model.

Table 2-3-3 Result of Y_a using SAS (n_{GOOD} = 12, n_{BAD}=12)

Y_a		Constant	X_4	X_5	X_6	X_7	d^2	Hit ratio
			W_4	W_5	W_6	W_7		
1	Z_a	-0.002	0.665	-0.241			0.111	50%
2	Z_a	-0.018	0.771				0.168	58%
3	Z_a	-0.083	1.097				0.296	58%
4	Z_a	0.006	0.798				0.149	58%
5	**Z_a**	**-0.031**	**0.859**				**0.197**	**63%**

$$Z_a = 0.859W_4 - 0.031 \quad \textbf{(2-3-3)}$$

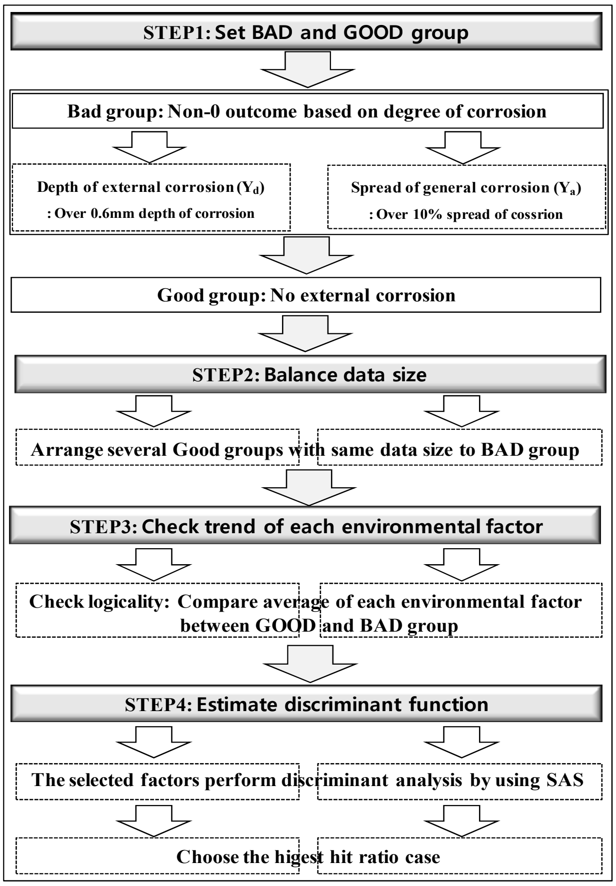

Fig. 2-3-3 Development process of DFA model

2-4 Modeling of external corrosion

Evaluation indexes of fuzzy soil properties can be obtained from the linear discriminant functions. From these indexes, we can assess corrosiveness of the soil properties. It is found that low resistivity and/or high moisture of the soil properties accelerate an external corrosion depth rate. In the case of the general horizontal corrosion, however, the low resistivity of the soil is considered dominant in affecting an extent of spread area and its corrosion rate.

As to external corrosion prediction, regression analysis is applied to find influential factors related to pipe characteristic. Among 60 sampled data, nearly a half of the sampled data didn't find corrosion on pipe surface. To minimize effects on regression model, these data are omitted in the succeeding analyses. Number of data utilized is twenty (20) and nineteen (19) samples for external corrosion depth and general horizontal corrosion respectively. It is believed that pipe characteristics and soil properties have a linear and/or and non-linear effects on pipe corrosion[16)]. To incorporate these effects into the analyses on a same basis, this non-linear effect is first expressed in the form of power regression equations with a variable of pipe characteristics. Then, multiple regression equations for the two types of external corrosion (Y_d and Y_a) are formulated as a function of the selected factors expressed in linear and/or non-linear forms.

2-4-1 Logarithmic correlation analysis

Prior to regression analysis, correlation coefficient of logarithmic data of pipe characteristic factors with corrosion indexes are estimated as shown in **Table 2-4-1**. Significant levels of reliability is also confirmed as a result of **Equation 2-2-1** which is t-distribution test corresponding to sample size 'n' and statistically significant level 'α'. When an absolute value of the correlation coefficient is greater than its significance level, the factors are assessed statistically significant.

Table 2-4-1 Logarithmic correlation between items of external corrosion and pipe characteristics

External corrosion index [significance levels of correlation coefficient]	Diameter (mm) $\log(X_1)$	Water pressure (kg/cm^2) $\log(X_2)$	Pipe age (years) $\log(X_3)$
$\log(Y_d)$ [r (n=20, α=0.05) = 0.437]	0.121	-0.312	0.463**
$\log(Y_a)$ [r (n=19, α=0.05) = 0.456]	-0.824**	0.109	-0.453

** The correlation coefficient is significant at 0.05 (bilateral)

As seen in '**' in **Table 2-4-1**, depth of external corrosion (Y_d) has a non-linear relation with pipe age (X_3), and spread of general corrosion (Y_a) with diameter (X_1). These results suggest effectiveness of adopting each factor as one of explanatory variables in the corrosion prediction equations.

2-4-2 Power regression model for external corrosion depth

Firstly, regression model of depth of external corrosion (Y_d) with a variable, pipe age (X_3), in the form of power function. Before modeling, these samples were leveling off according to average of every 5-year period due to lack of samples.

As the results of power regression model using data, we could obtain **Equation 2-4-1** as power regression model for between depth of external corrosion and pipe age. According to **Equation 2-4-1**, the estimated power coefficient (1.642) is greater than 1.0. This implies that the pipe age would affect pipe deterioration with acceleration as seen in **Fig. 2-4-1**.

$$Y_d = 0.00504 X_3^{1.642} \qquad \textbf{(2-4-1)}$$

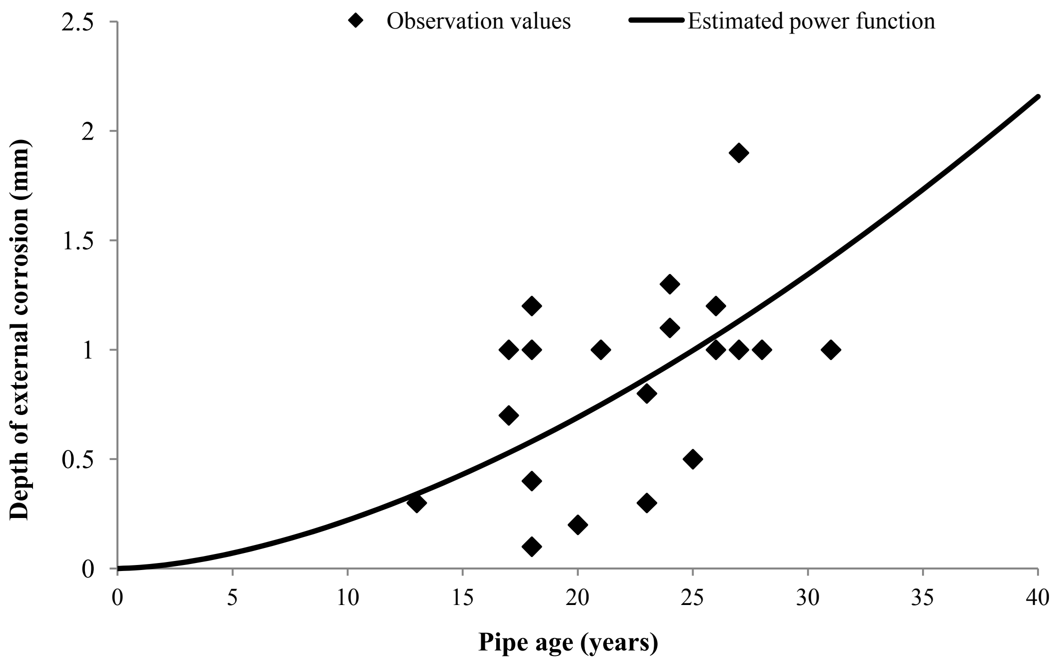

Fig. 2-4-1 Estimated trend of depth of external corrosion according to pipe age

2-4-3 Multiple regression model (MRA) for external corrosion depth

Following DFA and regression analysis in the form of power function, MRA is applied for further analysis. As the explanatory variables, the MRA utilizes pipe age expressed as 1.67th power, soil resistivity (X_4) and moisture (X_6) as previously verified effective by the discriminant function. This regression model expressed in **Equation 2-4-2** is assessed statistically significant from its multiple correlation coefficient (R) obtained through t-distribution test.

$$Y_d = -0.00325X_4 + 0.01184X_6 + 0.00491X_3^{1.642} \qquad (R = 0.516) \qquad \mathbf{(2\text{-}4\text{-}2)}$$

This implies that soil resistivity (X_4), moisture (X_6) and pipe age (X_3) would affect depth of external corrosion with acceleration as seen in **Fig. 2-4-2**.

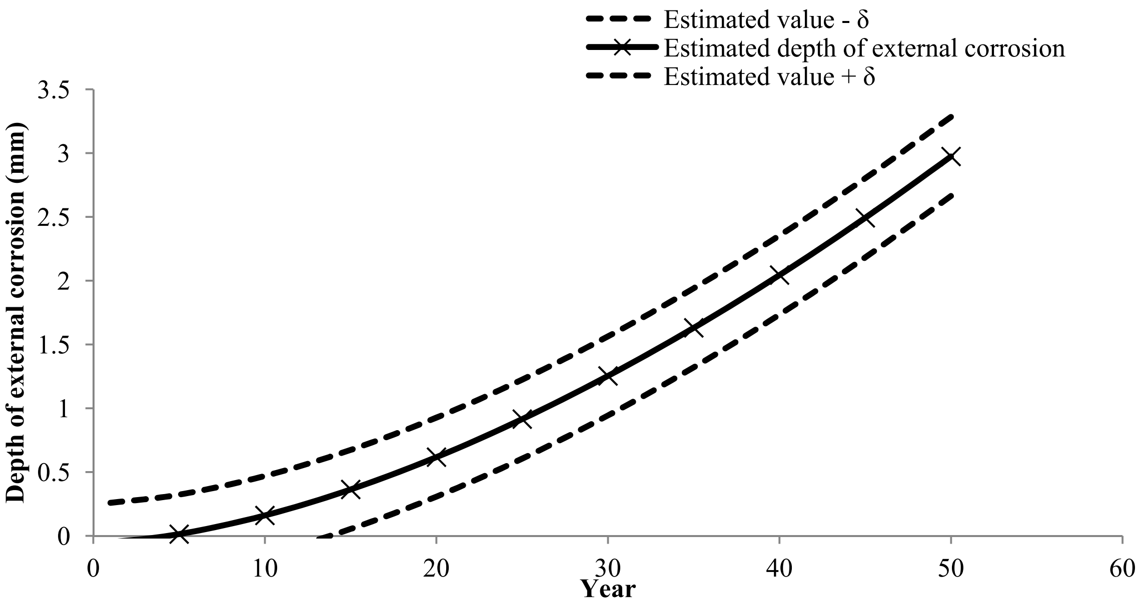

Fig. 2-4-2 Estimated depth of external corrosion according to combined influence factors

Relation between the observed and the estimated values of external corrosion depth is shown in **Fig. 2-4-3**, which indicates sufficient accuracy of our model with a mean absolute error (δ), 0.31mm.

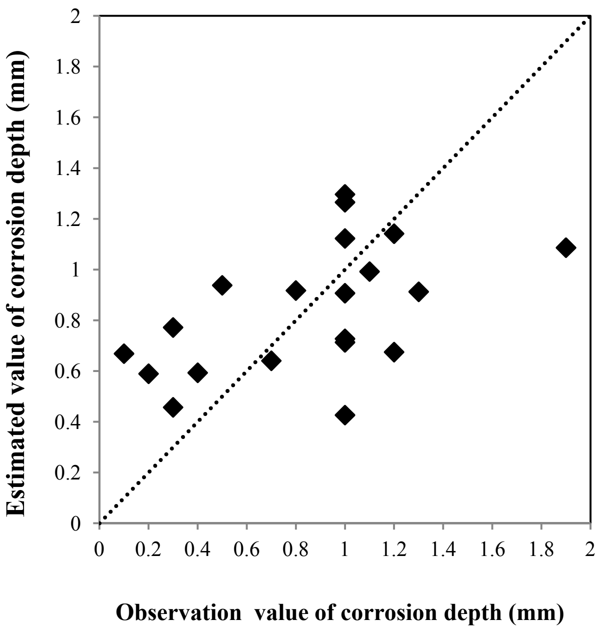

Fig. 2-4-3 Estimated values of external corrosion depth

2-4-4 Power regression model for spread of general corrosion

In the same way as stated above, a prediction model for the spread of general corrosion (Y_a) is expressed as a factor of the pipe diameter (X_1). As the results of power regression model, we could obtain **Equation 2-4-3** as power regression model for between spread of general corrosion and diameter.

$$Y_a = 8962.784X_1^{-1.392} \qquad \textbf{(2-4-3)}$$

The negative power (i.e., -1.392) of X_1 implies that value of Y_a (the corrosion spread on pipe surface in percentage) tends to progressively decrease against an increase in value X_1 (the pipe diameter). This tendency is clearly seen in **Fig. 2-4-4**.

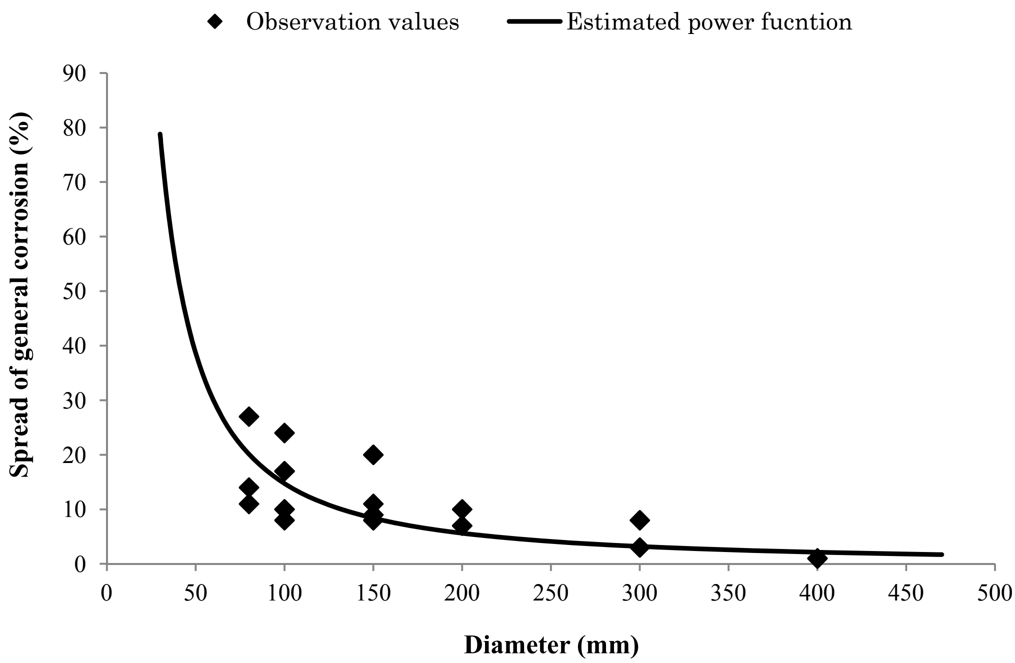

Fig. 2-4-4 Estimated trend of spread of general corrosion according to diameter

2-4-5 Multiple regression model for spread of general corrosion

Main culprit behind the general corrosion is soil resistivity (X_4) among soil properties. According to the findings of regression analysis, pipe diameter (X_1) is considered to have a negative relation with the general corrosion (Y_a). In a multiple regression equation developed here, there are two independent variables as shown in **Equation 2-4-4**. A correlation coefficient of the equation is estimated at 0.657. As examined by t-distribution test, this figure ensures reliability of the equation.

$$Y_a = 0.0325X_4 + 8522.499X_1^{-1.392} \qquad (R = 0.657) \qquad \textbf{(2-4-4)}$$

Relation between the observed and the estimated values of spread of general corrosion is shown in **Fig. 2-4-5.**

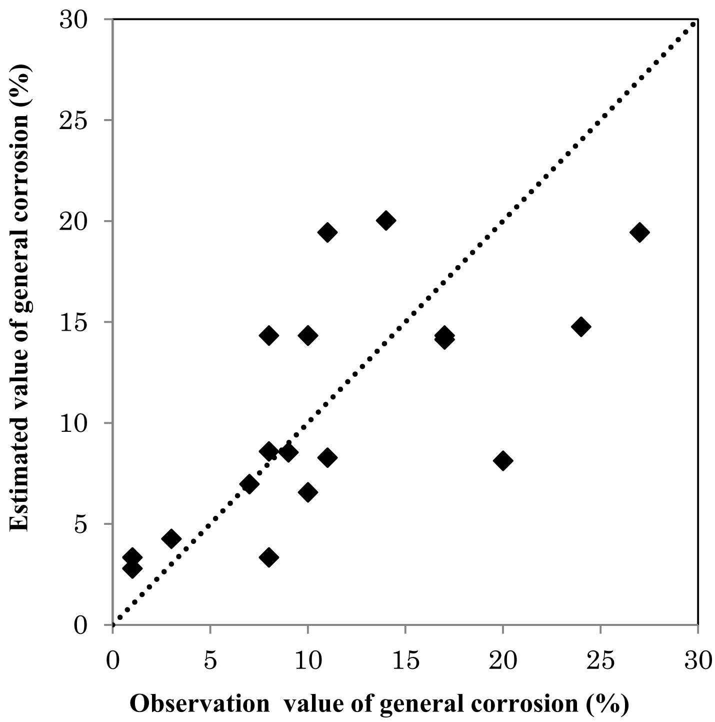

Fig. 2-4-5 Estimated values of spread of general corrosion

Severity of the general corrosion of any pipes in the target area can be simply estimated from the equation. Data required for prediction is merely pipe diameter and soil resistivity in the targeted area. The equation is not expressed as the function of pipe age. This is due to the fact that the general corrosion rate per year is rather slower than that of the external corrosion depth. Continuous efforts are required to collect data on pipe corrosion. It may be possible to develop more reliable prediction model based on process as mentioned above.

2-5 The corrosion model evaluation

In the previous paragraph, a prediction model for the external corrosion depth (Y_d) represented by pipe age (X_3), soil resistivity (X_4) and moisture (X_6) was proposed. Another method is a prediction which considers soil environment around the pipes. Corrosion depth of 60 samples in future is tentatively forecast in the **Equation 2-4-2**, assuming that the pipes are left without any maintenance for 20 years.

In this study a depth of external corrosion over 2mm is considered serious and may result in pipe damage or leakage. Analyzing the result of forecast, total 38 out of 60 samples are expected to have serious external corrosion with a depth exceeding 2 mm on their pipe surface. Locations of those samples are given in **Fig. 2-5-1**.

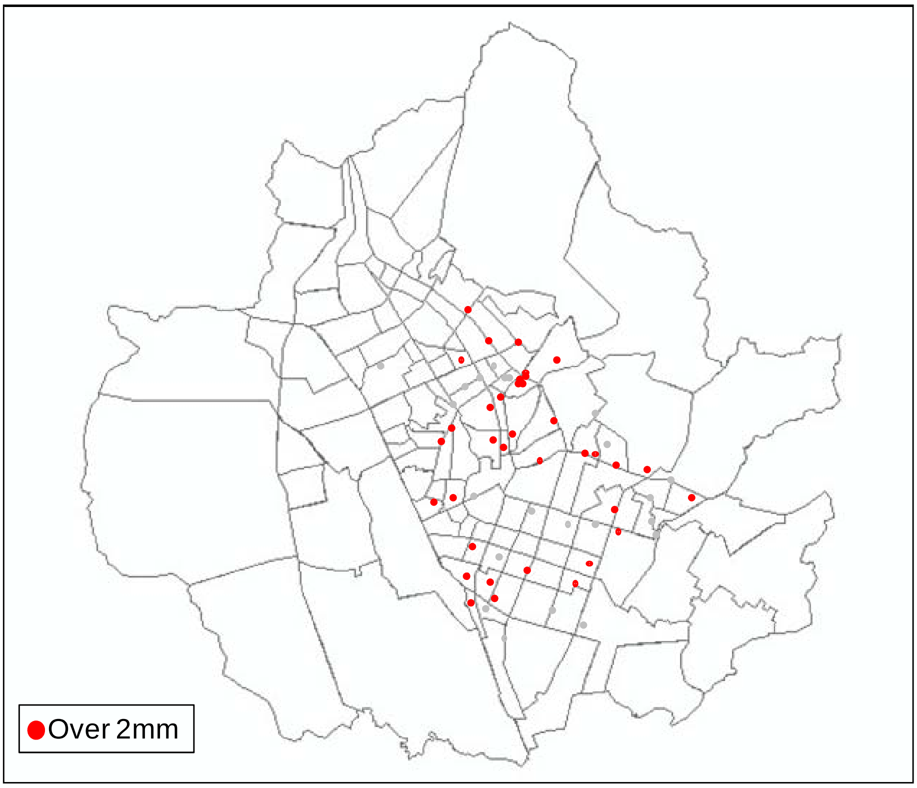

Fig. 2-5-1 Location where corrosion depth will exceed 2 mm by 2030

Out of total 60 soil samples, 39 are consisting of soft clay, and 17 of red clay, while 4 samples are of sands. Soft and red clay, accounting for over half of the total are causing a rapid growth of corrosion, but the remnants are rather slow in corrosion, predicted not to reach 2mm. These results indicate that future risk of corrosion closely relates not only to the soil factors but also to the pipe characteristics.

2-6 Conclusions

Water distribution pipes installed underground have potential risks of pipe failure and burst. After years of use, pipe walls tend to be corroded due to aggressive soil environments where they are located. That's why present study aims to discuss an influence of soil properties on corrosion. As mentioned in introduction, this study was regarded pipe corrosion as present pipe condition. Especially, in this study, we focused on external corrosion. In order to discuss it, this study intended to predict scale and severity of pipe corrosion in the target area. And then it difficult to survey all pipes in study area, data of 60 sample pipes were obtain through test excavation and soil test. In particularly statistical approach is useful to predict severity of pipe corrosion, so we applied to this study. First, discriminant function analysis (DFA) was applied in order to distinguish corrosive soil form non corrosive soil environment. Secondly, regression model was applied in order to develop external corrosion model. Finally in order to evaluation of future corrosion, evaluation model developed by multiple regression analysis. So we could obtain two conclusions as bellow.

1) In terms of depth of external corrosion in study area, soil resistivity (X_4), moisture (X_6) and pipe age (X_3). It is also confirmed that the soil resistivity (X_4) and the pipe diameter (X_1), among others, affect spread of general corrosion (Y_a).

2) It can be concluded that the multiple regression equation obtained herein provides valuable information on degree and rate of external pipe corrosion in the target area.

Continuing efforts for collecting and storing up field data are, however, considered important to improve the reliability of the proposed prediction model obtained.

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Chapter 3 Replacement plan for main distribution pipelines using economic evaluation

3-1 Introduction

3-1-1 Background and purposes

The main purpose of water distribution pipelines is to deliver water while satisfying demands for quality, quantity, and water pressure. However distribution pipelines age with the passage of time. Thus, many countries are now faced with the major task of water pipeline replacement. Aged pipelines cause leakage and other problems for water supplies. Replacement plan is needed to maintain these pipelines effectively. However, budgets for pipeline replacement are limited. Therefore, replacement plan with greatly reduced economic cost is needed for effective budget allocation.

Several studies have presented and proposed different techniques in an effort to plan the rehabilitation of water pipelines. Shehab et al. (2010) developed a cost-estimating model for water and sewer pipelines that utilizes a neural network and regression model[1)]. Malm et al. (2012) proposed a future replacement model by using historical data. The replacement model utilizes survival functions to determine the percentage of a group of pipelines that reaches a particular age[2)].

Although Ugarelli and Federico (2010) don't address water pipeline, they discuss optimal scheduling of replacement and rehabilitation for wastewater pipeline. The presented model could predict optimal replacement time based on balance between investment and expenditures[3)]. Also, Nafi and Kleiner (2010) focus on relationship between pipeline failure and cost. Using the relationship, they develop method for optimal scheduling of individual pipelines for replacement[4)].

The aim of the present study was to propose long-term plan for main distribution pipeline replacement that utilizes a damage occurrence model. In particular, this study attempted long-term replacement plan by efficiently allocating a budget for pipeline replacement. Moreover pipeline accidents that occur at unspecified times and places can be quantified by Monte Carlo simulation (MCS). The simulation model consists of post-damage maintenance (without replacement = repairing) and preventive maintenance (replacement). Unlike previous studies, our focus was on not only the economy aspect but also an assessment of the affected population. After conducting an evaluation from a benefit/cost perspective, we propose a highly effective replacement plan.

In this study is composed of simulation model and case study like **Fig. 3-1-1**.

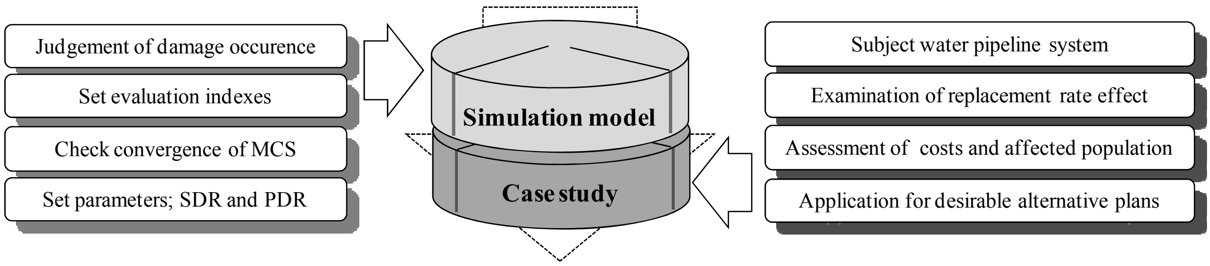

Fig. 3-1-1 Analytical process flow in this study

First, in simulation model, we need to judge damage occurrence. And then check convergence of MCS after setting evaluation indexes. And we need to set parameters like SDR and PDR. Next is case study. Firstly we compose water pipeline system, and then examine replacement rate effect. As the results of before 2 steps, we assess cost and total affected population (TC and TAP). And then our model is applied to select desirable alternative plans. Finally we select a highly cost effective rehabilitation planning based on this analytical process. For further details is known from following chapters.

3-1-2 Study area

The study focused on a simulated main distribution pipeline system, as shown in **Fig. 3-1-2**. The system consisted of 1 reservoir, 21 nodes, and 21 pipelines. Pipelines 1~17 were made of cast-iron pipe (CIP), and the other pipelines were made of ductile cast-iron pipe (DCIP). And then the population was assumed to be about 48,000 people[5)].

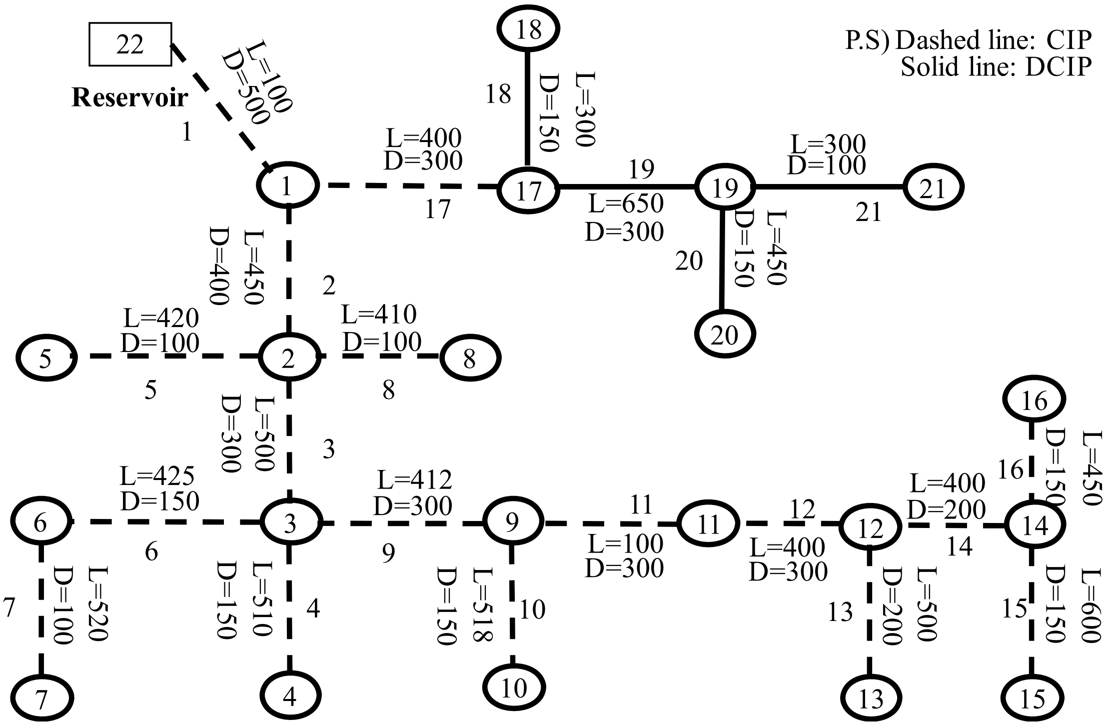

Fig. 3-1-2 Simulated main distribution pipeline system

3-2 Simulation model

3-2-1 Failure rate curve and function

Several failure models for buried pipeline are proposed in literatures. Moglia et. al (2007) develop probabilistic failure model for cast iron pipe (CIP). Specially, the model is applied to Monte Carlo simulation and calculated historical failure rate based on recorded failures of pipeline[6]. Yamijala et al. (2009) suggest predicting failure pipeline utilizing regression model. This paper compared 3 types of regression models which are time linear model, time exponential model and generalized linear models for estimating the reliability of pipelines[7].

In this study, simulation model was used to obtain the failure rate curve based on **Equation 3-2-1**, which uses reliability theory and data analysis for pipeline leakage accidents[8]:

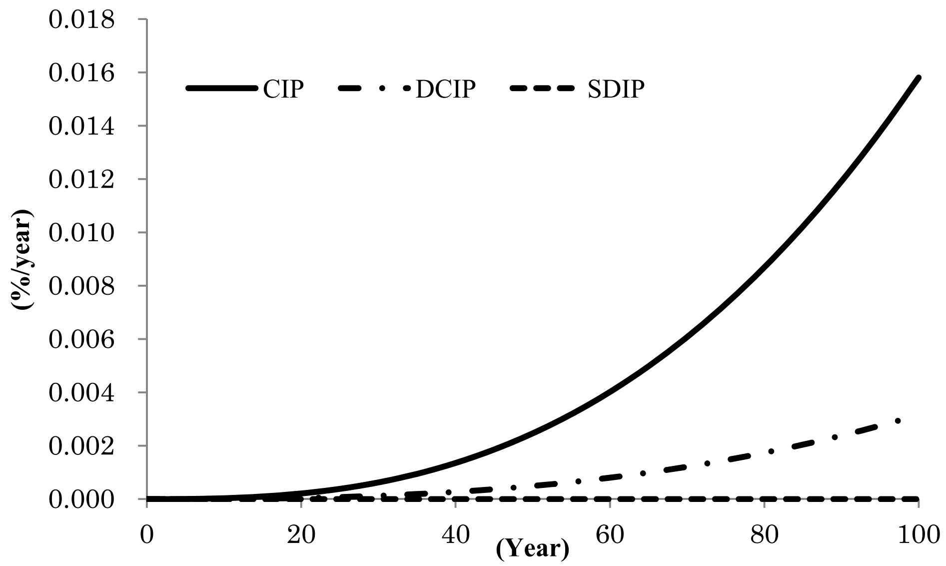

Fig. 3-2-1 Failure rate curve according by pipe materials

$$h(t) = kt^{c} \qquad (k, c, t\text{: real number}) \quad \textbf{(3-2-1)}$$

where, t: pipe age, k and c: constants for each material type of pipe. In addition, SDIP indicates DCIP with quake-proof joint.

Mori et al. (2010) was developed failure rate function through expansion of failure rate curve. This is because in order to predict failure term of sub items using failure rate curve. In here, sub item is that pipeline divided into virtual sub-items with a fixed length. At the time of failure rate curve was made, pipelines divided into 4m sub items. So failure rate function also assumed 4m sub items. Below process shows that failure rate curve change into failure rate function. This failure rate function is utilized in this paper for predicting failure term of pipelines[9)].

When **Equation 3-2-1** which is utilized "Weibull distribution" is calculated by age of sub item t, failure rate function could expand into reliability function *R(t)* as express in **Equation 3-2-2**.

$$R(t) = \exp\left[-\int_0^t h(t)dt\right] = \exp\left[-\frac{k}{c+1}\times t^{c+1}\right] \qquad \textbf{(3-2-2)}$$

Meanwhile, failure rate of sub item which was the passing of a year τ was expressed as **Equation 3-2-3.**

$$h(t) = \begin{cases} 0 & t < \tau \\ kt^c & t \geq \tau \end{cases} \qquad \textbf{(3-2-3)}$$

And then, probability of failure (P) from τ to τ+Δ was expressed as **Equation 3-2-4.**

$$\begin{aligned} P &= \Pr(\tau, \tau+\Delta) = 1 - R(\tau, \tau+\Delta) \\ &= 1 - \exp\left[-\int_\tau^{\tau+\Delta} h(t)dt\right] \\ &= 1 - \exp\left[-\frac{k}{c+1}\times\left\{(\tau+\Delta)^{c+1} - \tau^{c+1}\right\}\right] \end{aligned} \qquad \textbf{(3-2-4)}$$

The failure term (△) is calculated under various influences such as the underground soil condition and traffic load above. Moreover P is distributed within range between 0 and 1. Therefore, using the inverse function of **Equation 3-2-4**, the failure time (Δ) is obtained from **Equation 3-2-5** by substituted uniform random number [0~1].

$$\Delta = \left\{ \tau^{c+1} - \frac{(c+1)\cdot \ln(1-P)}{k} \right\}^{\frac{1}{c+1}} - \tau \qquad \textbf{(3-2-5)}$$

In this study, for calculating failure term utilizing Monte Carlo simulation (MCS), **Equation 3-2-5** changed like below **Equation 3-2-6**. In here, *c* and *k* are the constants for each type of pipe. And then R was uniform random number which was generated by 'Mersenne twister'. While *τ* represented the years of the pipeline being buried.

$$E = \left\{ \tau^{c+1} - \frac{(c+1)\cdot \ln(1-R)}{k} \right\}^{\frac{1}{c+1}} - \tau \qquad \text{(E is failure term)} \qquad \textbf{(3-2-6)}$$

After calculating failure term E, the failure term *E* and replacement term T were found and compared to determine the damage of each sub item and calculate the total cost (repair cost + replacement cost) and the affected population.

3-2-2 Monte Carlo simulation (MCS)

The failure term of pipeline was calculated by MCS. The MCS can be used to describe any technique that approximates solutions to quantitative problems through statistical sampling. This method gives approximate solution to a variety of mathematical problems by performing statistical sampling experiments on a computer. It applies to problems with no probabilistic content as well as to those with inherent probabilistic content.

The MCS is a powerful engineering tool which enables one to perform a statistical analysis of the uncertainty in structural engineering problems[10]. This tool is particularly useful for complex nonlinear problems. The fundamental step in MCS is a development of a set of uniformly generated random numbers. The cumulative distribution function (CDF) of uniform distribution is used to explain MCS. In MCS, uniformly generated random numbers are increased to obtain accurate solution[11]. When uniformly generated random numbers are increased to obtain accurate results, the computing time is increased. So, the computing time is a major concern in MCS.

To generate appropriate random number according to distribution, the uniform random number which distributed between 0 and 1 is used commonly. In present study, the random numbers were generated by 'Mersenne twister (2^{19937}-1)'. The 'Mersenne twister' provides for fast generation of very high-quality pseudorandom numbers, having been designed specifically to rectify many of the flaws found in older algorithms[12), 13)]. Also, since there is seed, it is possible to reduce the same random number multiple times. So each case study could be performed by same seed number. In this study, MCS was applied to this simulation model following the number of future years from the start to the end of replacement plan. To calculate the failure term utilizing MCS, generated random number was substituted for R in **Equation 3-2-6**. And τ denotes the pipeline age in the start year of MCS.

3-2-3 Calculation of total cost (TC)

Before calculate total cost (TC), the simulation model considers pipelines to be divided into virtual sub-items with 4m. The failure of each sub-item can be predicted by the failure rate function. We can then assume that breakage or leakage occur when sub-items reach the failure term, and the sub-items will undergo repairs. Some older sub-items will be replaced by SDIP under a budget restriction of replacement plan.

The total cost is obtained from the accumulated repair and replacement costs over the whole period of simulation. The unit cost of replacement (per pipeline length) and unit cost of repair (per failure) can be obtained from a function using the pipe diameter.

Firstly total replacement cost is calculated by multiplying total unit cost of replacement by pipeline length like **Equation 3-2-7**.

Total replacement cost (yen) = the total unit cost of replacement (¥/m)

× length of pipeline (m) **(3-2-7)**

In here, the total unit cost of replacement consists of the unit cost of replacement and the cost of the branching method like **Equation 3-2-8**.

Total unit cost of replacement (yen/m) = the unit cost of replacement

+ the cost of the branching method (¥/m) **(3-2-8)**

The unit cost of replacement is calculated by survey of construction cost for water distribution pipeline on Sep. 1998[14)]. It is composed of cost of material, labor and earthwork according to pipe diameter.

On the other hand, in case of repair cost, we assumed that when sub item occur damage or accident such as leakage, the repair cost is multiple replacement cost for sub item by 10 times. It is expressible in **Equation 3-2-9**.

The repair cost (yen) = the unit cost of replacement (yen/m) × 10 times × 4(m/sub item)

× number of damaged sub items (number) **(3-2-9)**

In conclusion, the total cost can be calculated by replacement cost plus total repair cost. It is expressible in simple **Equation 3-2-10.**

$$TC\ (yen) = \text{the replacement cost (yen)} + \Sigma\ (\text{the total repair cost (yen)}) \quad (3\text{-}2\text{-}10)$$

3-2-4 Calculation of total affected population (TAP)

In general, the evaluation of the model depends on the availability of efficiency. In this study, we considered two parts to prove efficiency. One part is cost and another is benefit. The cost usually used to the index of benefit. However, in this study, we regarded the affected population as the index of benefit. So the study calculated "benefit/cost" to estimate efficiency.

When accidents occur on the pipelines, the total affected population is calculated by summing up the population living in the downstream area rather than in the damaged part like **Fig. 3-2-2**.

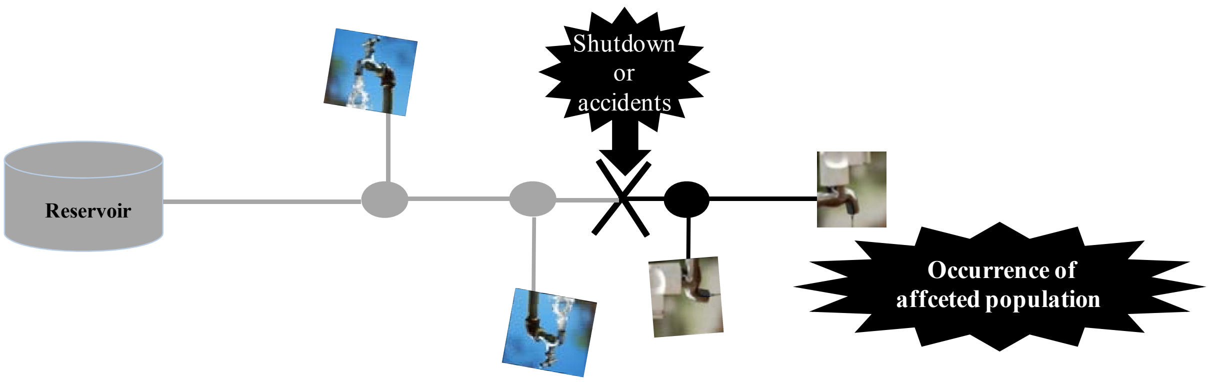

Fig. 3-2-2 Image of the affected population

Table 3-2-1 shows the accumulation of the affected population at each pipeline. For example, if P-1 pipeline occur damage or accident, total affected population are 48,000 people.

Table 3-2-1 The affected population at each pipeline

Pipeline ID	Accumulation of the affected population (people)	Pipeline ID	Accumulation of the affected population (people)
P-1	48,000	P-12	17,047
P-2	36,695	P-13	4,334
P-3	32,578	P-14	7,476
P-4	2,312	P-15	3,503
P-5	1,336	P-16	2,781
P-6	3,070	P-17	9,860
P-7	1,517	P-18	1,770
P-8	722	P-19	7,296
P-9	24,415	P-20	2,167
P-10	2,167	P-21	1,228
P-11	19,756		

In conclusion, the total affected population can be calculated by multiplying number of accidents by population using water. It is expressible in simple **Equation 3-2-11**.

$$\text{TAP (people)} = \Sigma\,(\text{the number of accidents} \times \text{the population using water}) \qquad \textbf{(3-2-11)}$$

3-2-5 Set parameters of SDR and PDR

This simulation model was assumed two parameters. First is social discount rate (SDR). SDR is a measure used to help guide choices about the value of diverting funds to social projects[15)]. In order to predict expected value of money in the future, SDR is necessary. Expected value of money can be express as **Equation 3-2-12**.

$$\text{Expected value of money (yen)} = C / (1+SDR)^M \quad \textbf{(3-2-12)}$$

where, C: present value of money, M: equals year (time). And then SDR is expressible in percent per year (%/year).

However, in this study, 0%/year SDR applied to simulation model. That is we regard expected value of money as present value of money. But, developed simulation model for this study can calculate expected value of money using SDR.

Second is population decrease rate (PDR). This simulation can also estimate the affected population in the future. In order to estimate the future population, the simulation model reflects PDR. Korea's population is expected to decrease in the future. In particular, population statics for Seoul show that the population will decrease by 1% every 5 years (**Figure 3-2-3**)[16]. Thus, PDR was assumed to be 1% per term in this study.

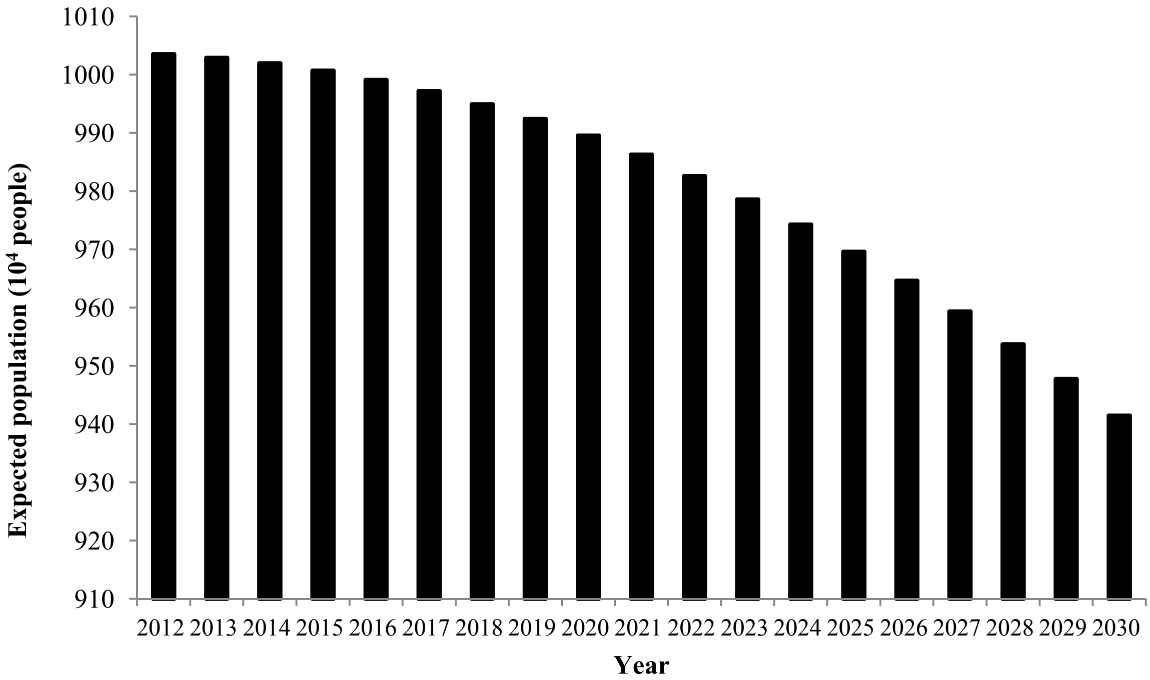

Fig. 3-2-3 Trend of changed population in Seoul

3-3 Examination of replacement rate effect

3-3-1 Determination of iteration times

MCS can yield more accurate results by increasing the number of iterations. However, this also increases the computation time. Therefore, an appropriate number of iteration is needed to effectively calculate the results against time. The number of iterations was determined in the following steps.

1) The study period was set to 10 terms over 50 years (1 term = 5 years).
2) The scenario focused only on pipeline repair (without replacement).
3) MCS initially calculated 1000 iterations.
4) The number of iterations was determined against the result of 1000 iterations.
   (Margin error ±0.5%)

In step 3), 1000 iterations were empirically found to be sufficient in this study. The study focused on a simulated pipeline system, as shown in **Fig. 3-1-1**. And then as mentioned above, the population was assumed to be about 48,000 people. Finally, **Equation 3-2-6** was applied to the simulation for obtain failure term at each pipeline.

The simulation results according to the above steps are described next. Firstly, **Fig. 3-3-1** and **Fig. 3-3-2** show the average total cost over 50 years (ATC) and average total affected population over 50 years (ATAP), respectively, based on 1000 iterations. In here, the reason why average value was used is that MCS can be obtained from average value which is calculated at each iteration time. In here, dotted lines on the graph means margin error, bar indicates appropriate iteration times.

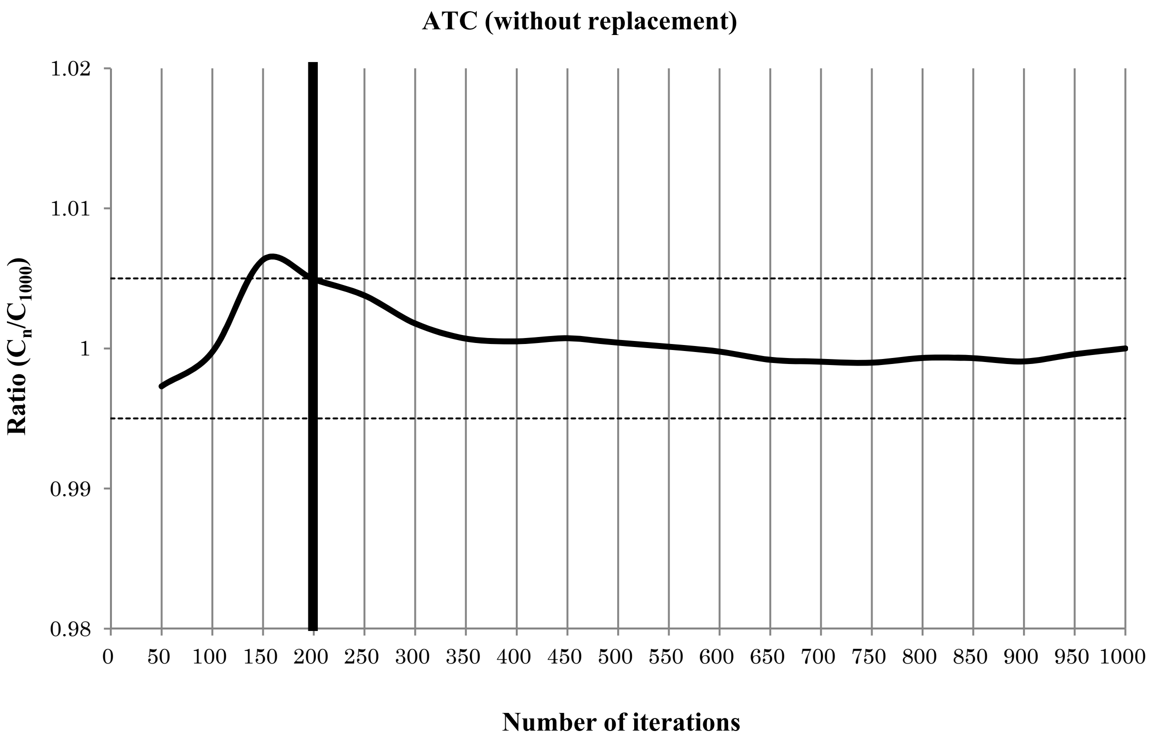

Fig. 3-3-1 ATC ratio until 1000 iterations

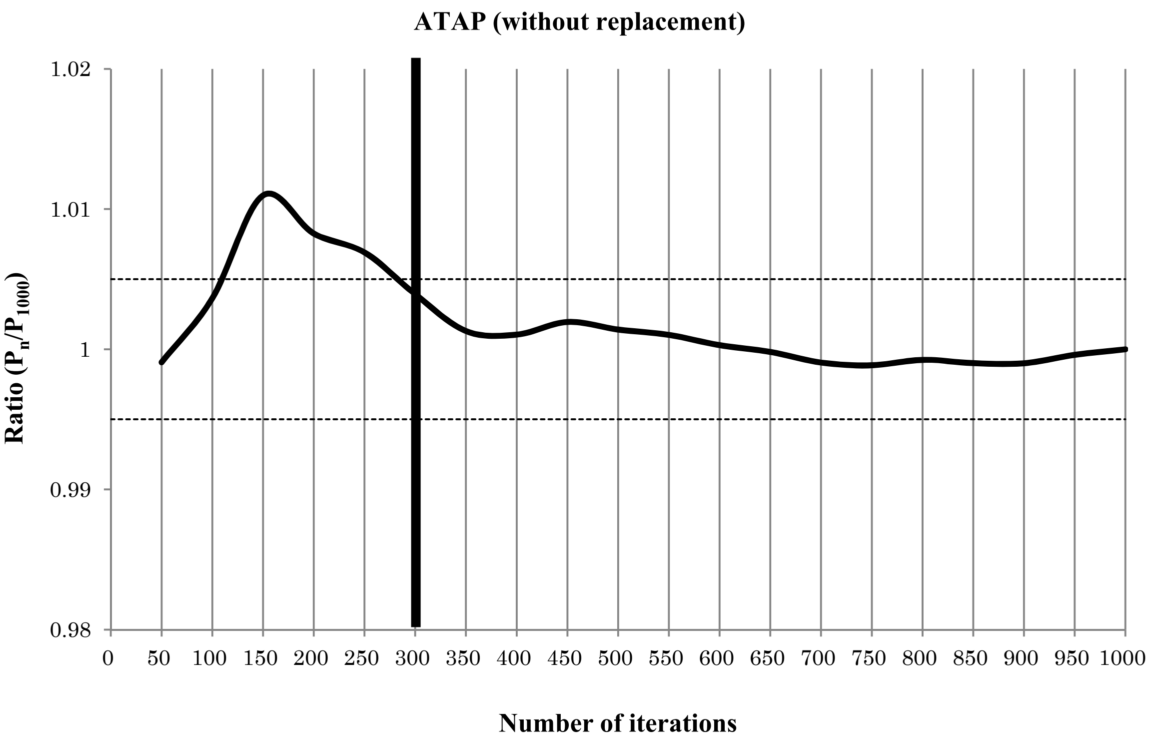

Fig. 3-3-2 ATAP ratio until 1000 iterations

The above graphs show that the ratio curve was in the margin of error (±0.5%) after 300 iterations. In other words, by 300 iterations we can get the result with a quite acceptable margin of error.

In MCS, selected data should make up a normal distribution. In order to confirm the data distribution, a histogram was applied to the obtained results. In order to confirm the determined number of iterations, the histograms were drawn according to the number of iteration times without replacement, as shown in **Fig. 3-3-3**. If the distribution for a determined number of iterations is similar to that for 1000 iterations, the number of iterations can be judged as being appropriate. Histograms were drawn according to the average number of total pipeline failures.

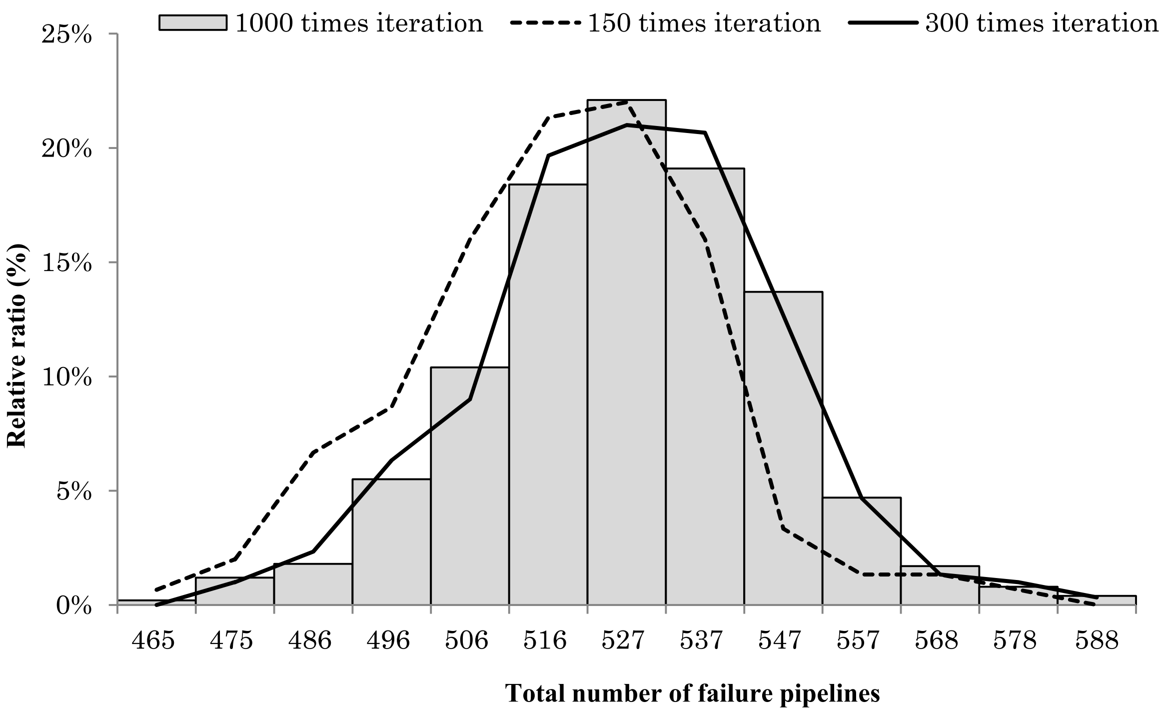

Fig. 3-3-3 Comparison with each histogram

The histogram results were also evaluated by referring to a statistics table, as shown in **Table 3-3-1**. A comparison of the mean values showed that the mean value for 300 iterations was almost the same as that for 1000 iterations. In conclusion, 300 times iteration was found to be appropriate in this study.

Table 3-3-1 Statistics table for histograms

	150 iterations	300 iterations	1000 iterations
Mean	523.42	521.83	521.89
Standard deviation	19.12	18.67	19.06
Max	588.00	588.00	588.00
Min	471.00	468.00	465.00

3-3-2 Results of calculated ATC and ATAP

To compare the effect of replacement rate, seven cases for the annual replacement rate were set (without replacement, 0.5%, 1%, 1.5%, 2%, 2.5% and 3%). The ATC and ATAP were calculated and compared over the entire simulation term for each case. By the way, replacement of the pipelines occurred in order of age of the pipeline. Of course, these calculations were performed at 300 times iteration which was determined appropriate iteration time as shown before. MCS was performed by using a random number with the same number of seeds for each case.

As the results, firstly, **Fig. 3-3-4** shows average of total number of failure pipelines. We can know that that total number of failure pipelines was decreased according to increased annual replacement rate. It shows effect of replacement pipelines. And then, **Fig. 3-3-5** shows the average total repair cost and total replacement cost at each annual replacement rate.

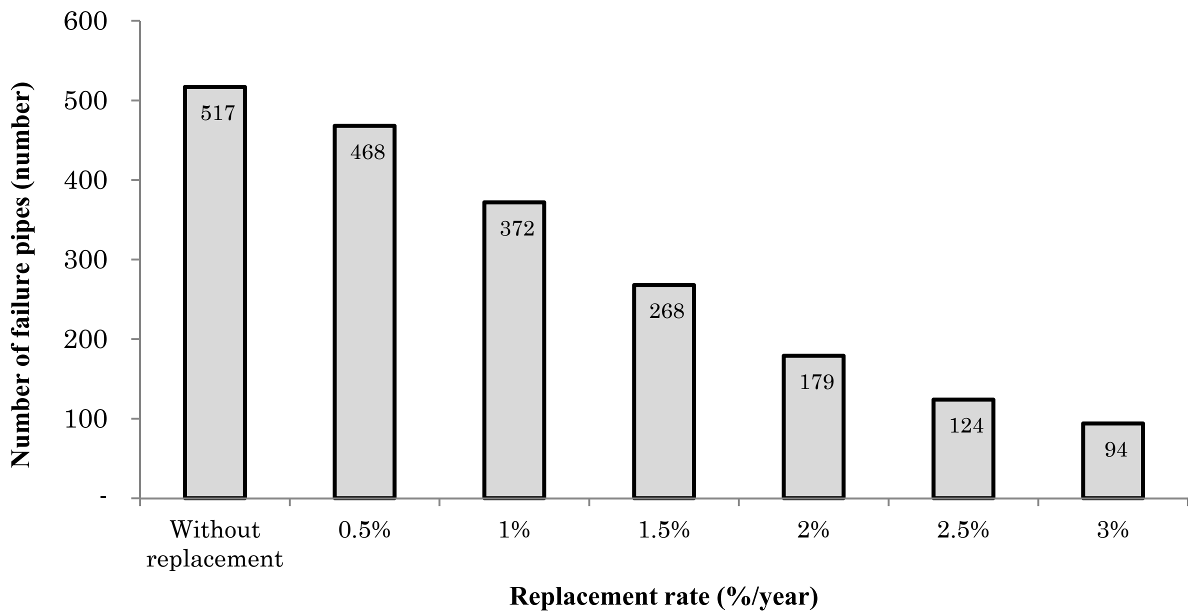

Fig. 3-3-4 Average of total number of failure pipeline at each annual replacement rate

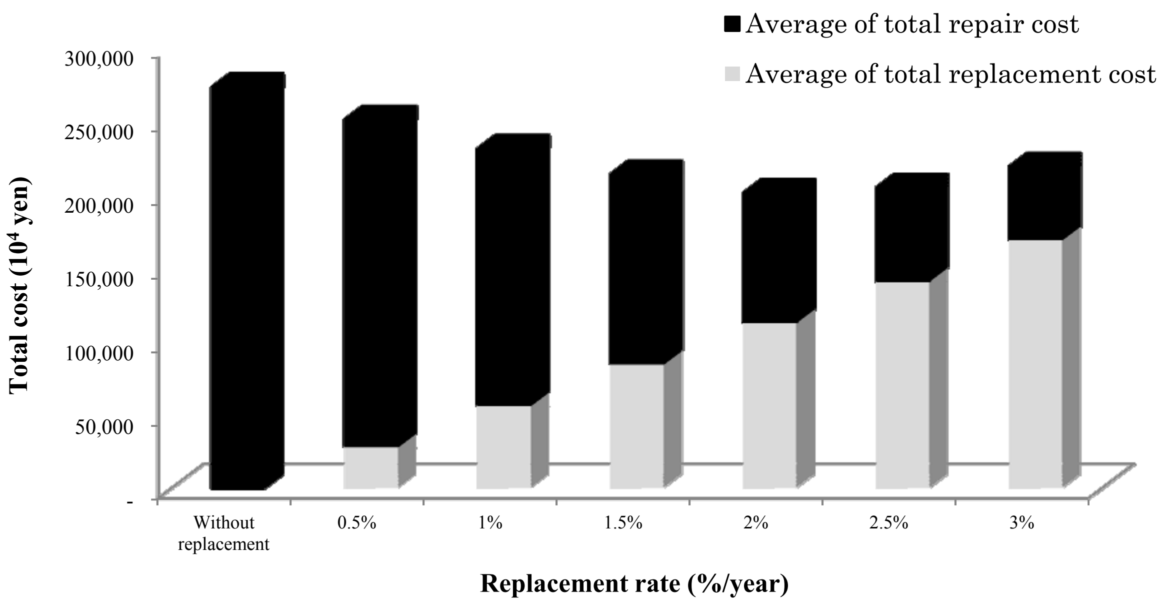

Fig. 3-3-5 Results for average total cost at each replacement rate

As the results, we can confirm that total replacement cost is increased according to increased annual replacement rate, but total repair cost is opposed to total replacement cost. On the other hand, in case of ATC is decreased from without replacement to annual 2%

replacement rate, but the ATC is increased again from annual 2.5% replacement rate**.** The second cycle of replacement restarted because the first cycle finished by 40 years. Thus, the ATC increased again from 2.5%. In conclusion, 2% is the most economical replacement rate. These results are expressible in below **Table 3-3-2**. And then, the ATC can be explained concretely through below accumulated graph (**Fig. 3-3-6**).

Table 3-3-2 Result of calculated ATC at each annual replacement rate

	Average of failure pipeline (number)	Average of total repair cost (10^4 yen)	Average of total replacement cost (10^4 yen)	ATC (10^4 yen)
Without replacement	517	273,227	-	273,227
0.5%	468	222,995	28,182	251,177
1%	372	174,934	56,396	231,331
1.5%	268	129,227	84,636	213,863
2%	179	88,293	112,866	**201,159**
2.5%	124	63,752	141,048	204,800
3%	94	49,825	169,262	219,087

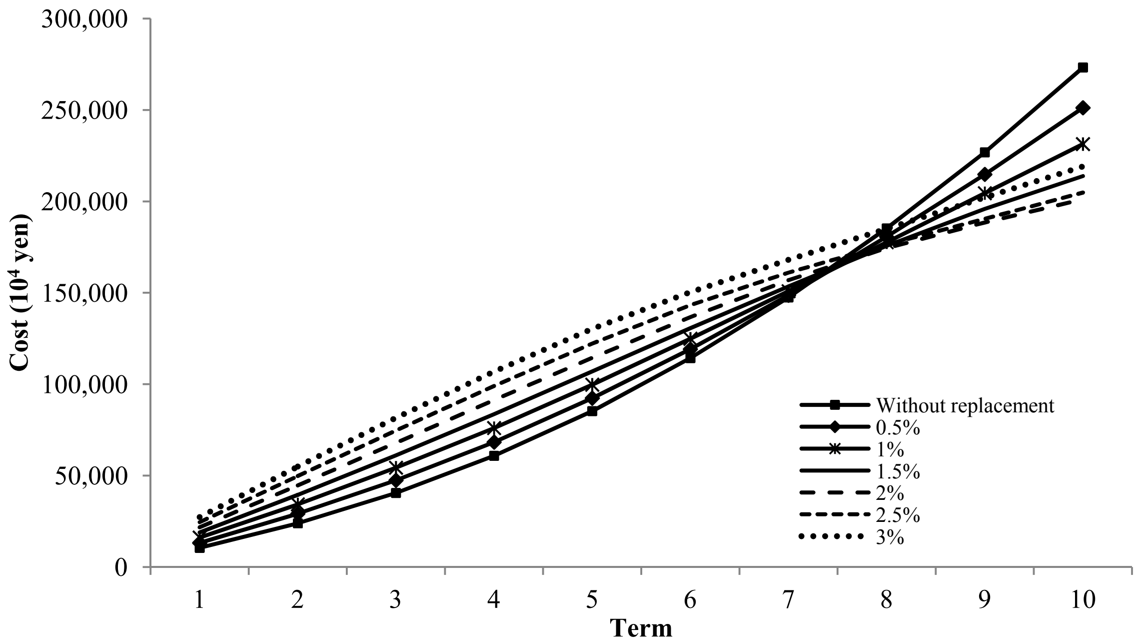

Fig. 3-3-6 Results for accumulated ATC at each term

As above the graph, curves of annual 2%, 2.5% and 3% replacement rate are decelerated according to term. It means that although total cost is higher than other annual replacement in the early, total cost is reduced from middle term. This is because a lot of pipelines were replaced in the early, so additional repair cost is reduced as by goes by. Curves of annual 1%, 1.5 % replacement rate are accelerated until end of 7 terms and decelerated from 8 terms. It means that although pipelines were replaced, effect of replacement pipeline is not big. So additional repair cost was input until end of 7 terms. However, start of 8 terms, effect of replacement began to appear. On the other hand, in case of without replacement and 0.5%, repair cost is increased continuously because of increased failure pipelines, so total cost is also accelerated according to increased term.

Next are results of the ATAP. **Fig 3-3-7** shows results of calculated the ATAP at annual replacement rate.

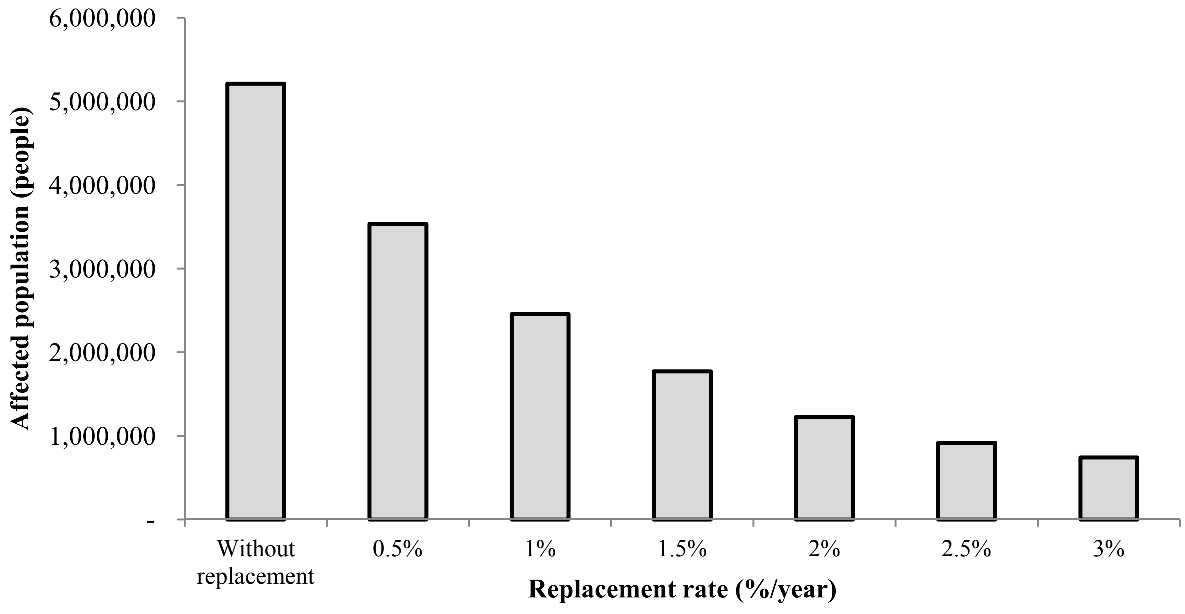

Fig. 3-3-7 Results of the ATAP at each annual replacement rate

The ATAP is decelerated according to increased annual replacement rate. It is shown that the ATAP is very sensitivity to pipeline replacement and effect of replacement is very big. The

ATAP can be explained concretely through below accumulated graph (**Fig. 3-3-8**).

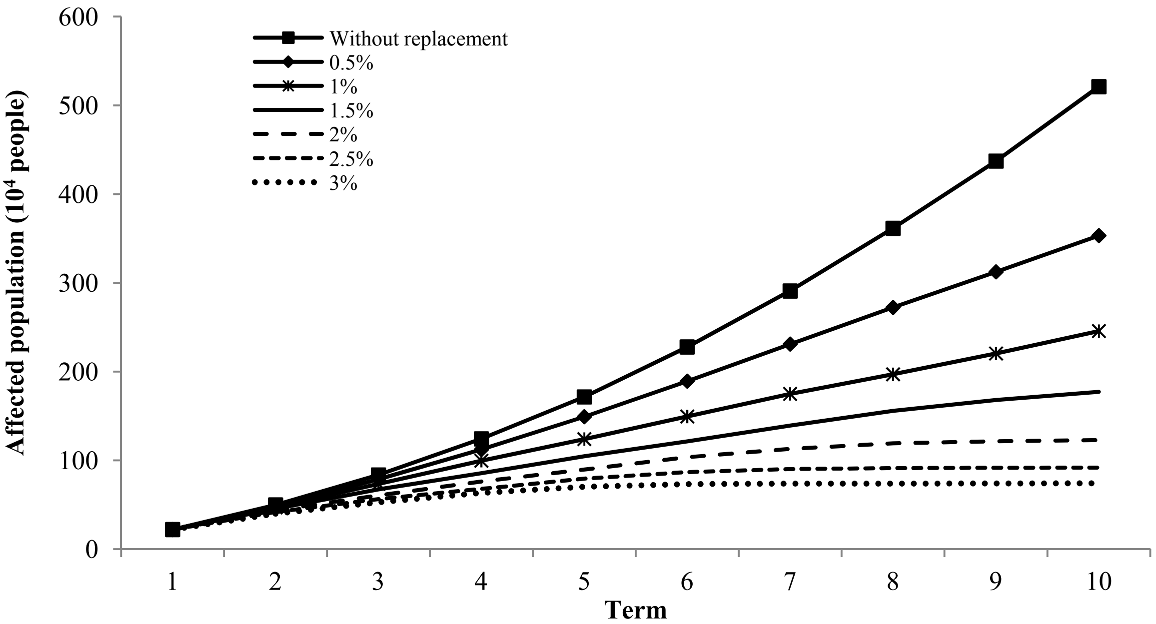

Fig. 3-3-8 Results for accumulated ATAP at each term

The results show that annual 3%, 2.5%, 2%, 1.5% and 1% are decelerated according to term. This is because failure pipelines were also decreased due to replacement. However because annual 0.5% replacement rate has marginal effect, that curve is accelerated according to term.

In conclusion, when we compared the affected population, we found that the 3% annual replacement rate also resulted in greater prevention.

3-3-3 Calculation of benefit – cost ratio (ΔP/Cost)

A benefit-cost ratio (BCR) is an indicator, used in the formal discipline of cost-benefit analysis. It attempts to summarize the overall value for money of a project or proposal. The BCR is the ratio of the benefits of a project or proposal, expressed in monetary terms, relative to its costs, also expressed in monetary terms. All benefits and costs should be expressed in discounted present values. The BCR takes into account the amount of monetary gain realized by performing a project versus the amount it costs to execute the project. The higher the BCR means the better the investment. General rule of thumb is that if the benefit is higher than the cost the project is a good investment[17)]. The analysis of the BCR applied to this study.

Below the **Fig. 3-3-9** shows the ATC and the ATAP results.

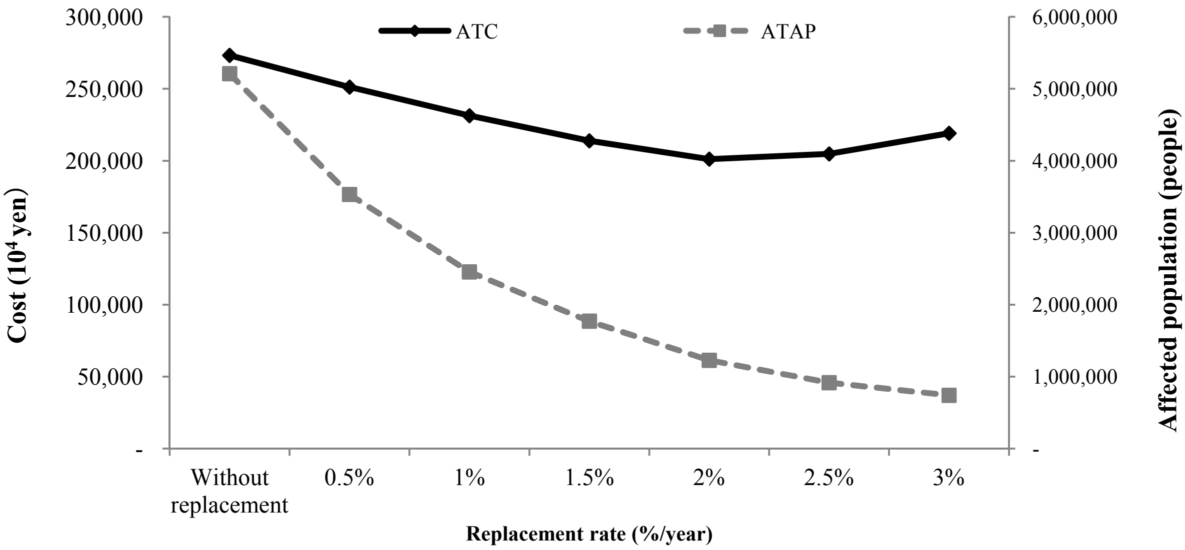

Fig. 3-3-9 ATC and ATAP results for each annual replacement rate

For example, the ATAP at 1% is almost half of the ATAP without replacement, and it means that the risk of water supply interruption at 1% is supposed to be almost half of the risk without replacement. So the gap of ATAP (ΔP) between some replacement case and without replacement case is used as an index of the benefit by replacement of water pipelines. In general, the evaluation of planning depends on the level of efficiency by a ratio of benefit to cost. In the current study, we calculated ΔP/C in order to evaluate the effect of a promotion of replacement plan. The results show the cases in order from greatest to smallest ΔP/C: 2.5%, 2%, 1.5%, 3%, 1%, and 0.5%. In conclusion, the 2.5% case was the most effective one to offer the benefit in proportion to the investment. These results are expressible in below graph which help understanding easily (**Fig. 3-3-10**).

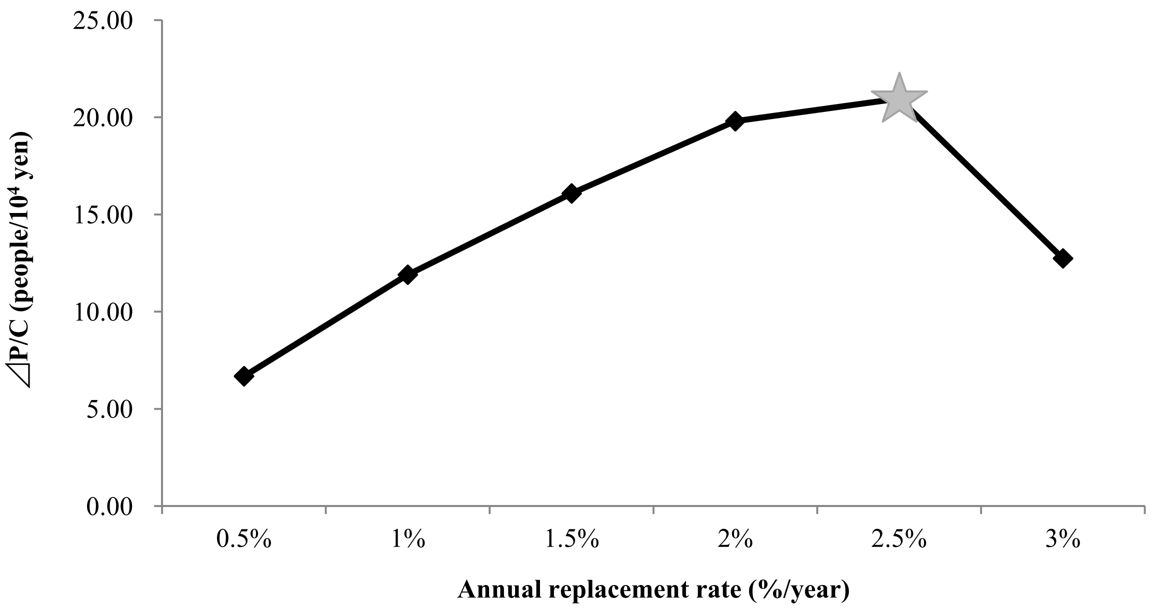

Fig. 3-3-10 Curve for results of benefit-cost ratio

3-3-4 Sensitivity analysis

Sensitivity analysis is used to determine how "sensitive" a model is to changes in the value of the parameters of the model and to changes in the structure of the model[18]. Sensitivity analysis can help the reviewer to determine which parameters are the key drivers of a model's results. In this study, we focus on PDR sensitivity.

To investigate the effect of the PDR in the simulation, sensitivity analysis was carried out for seven cases, as presented in **Table 3-3-3**. We assumed that the entire study area consists of a central district and other districts (**Fig. 3-3-11**).

Future population growth or decrease may be dependent on the economical condition change and the organization of city planning project in study area. Cases 2~5 and the standard case were applied with the same value of the PDR over the entire area. For case 6, different PDR values were applied basing a supposition of the increasing centralization of population. And case 1 was opposite hypothetic case.

Table 3-3-3 Change in future population under each case

Case	Standard	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Central district	1%/term decrease	5%/term decrease	2%/term decrease	Constant	1%/term increase	2%/term increase	5%/term increase
Other districts	1%/term decrease	3%/term decrease	2%/term decrease	Constant	1%/term increase	2%/term increase	3%/term increase

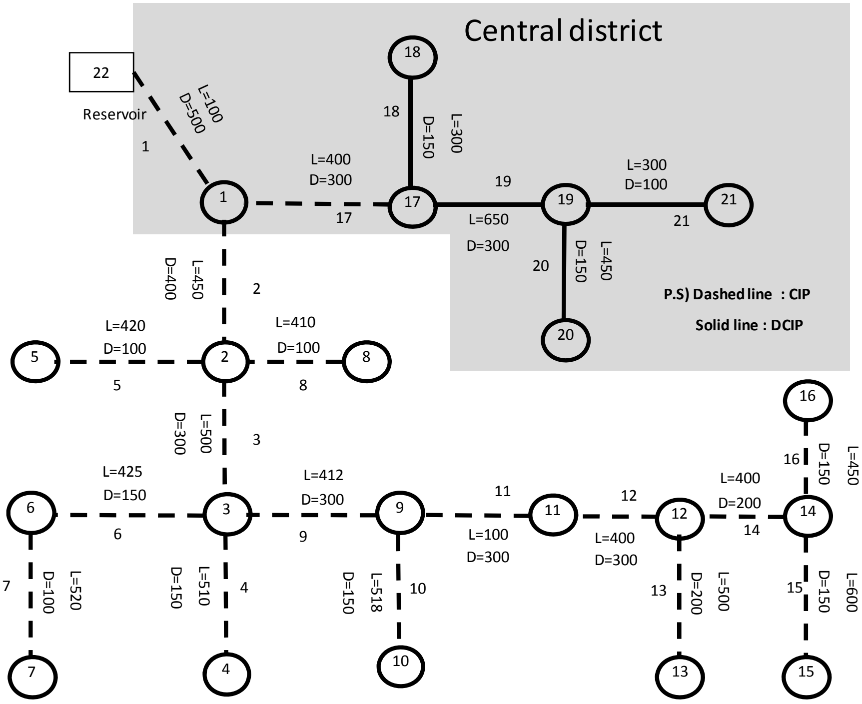

Fig. 3-3-11 Consist of study area

The results are shown in **Fig. 3-3-12**. In all PDR cases, the ATAP is gradually decreased according to the increase of replacement rate. ΔP/C was then calculated again according to the changed PDR. The results are shown in **Fig. 3-3-13**. Judging by ΔP/C in **Fig. 3-3-13**, all of the PDR cases indicate that the 2.5% annual replacement rate is the best scenario with high efficiency. In other word, the sensitivity analysis results showed that the future population growth or decrease (the settings of PDR) do not have an important effect upon the selection of most efficient case of replacement rate.

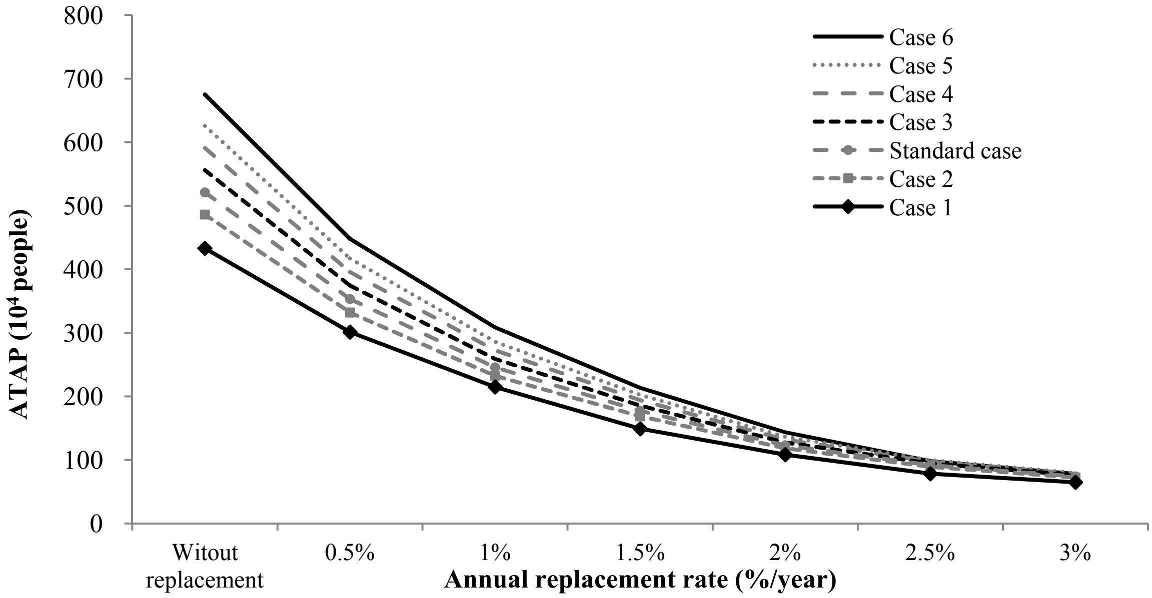

Fig. 3-3-12 Tendency of sensitivity analysis according to each PDR

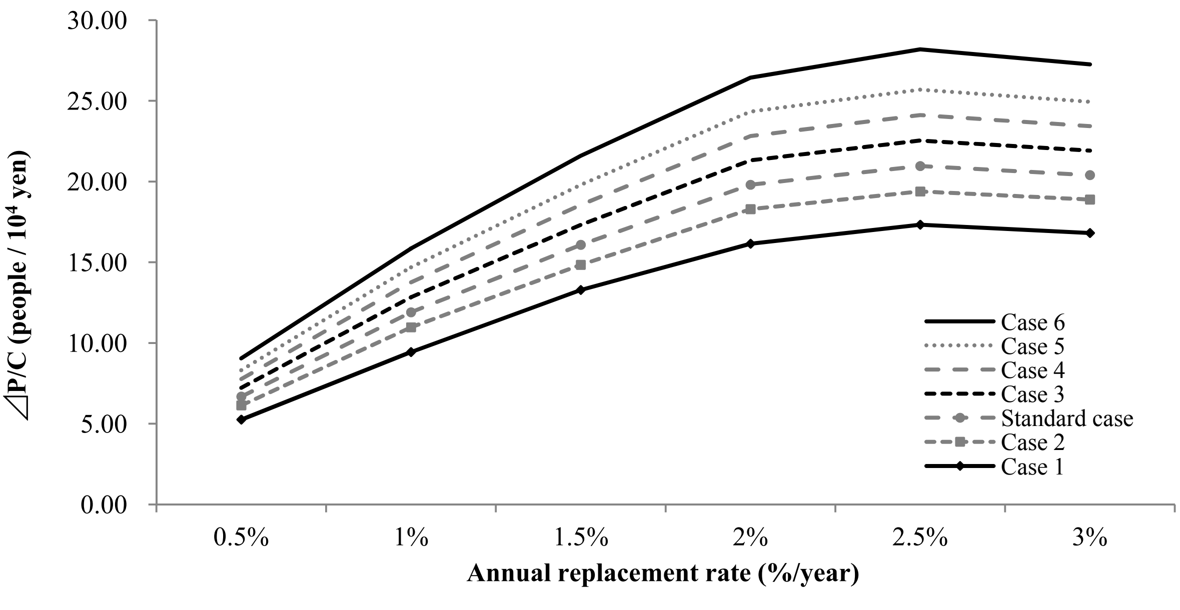

Fig. 3-3-13 Changed ΔP/C values according to each PDR

For most of waterworks, the replacement cost of pipelines reaches a large percentage of total budgets and the economy aspect is the most important factor under the severe restrictions. From this economy preferential viewpoint, this study found 2% to be the most reasonable replacement rate.

3-4 Application for key pipelines replacement plan

Key pipelines are vital pipelines located in central districts with public establishments distributed densely around them, such as hospitals, schools, and government organizations. If accidents occur on key pipelines, and the damage is serious. Thus, the replacement of key pipelines is considered to have the priority.

A simulation model was applied to key pipelines. Specifically, pipelines 1, 17, 18, 19, 20, and 21 in **Fig. 3-4-1** were considered to be key pipelines and given the utmost priority for replacement. Regardless of the fact that non-key pipelines are also renewed at the same time.

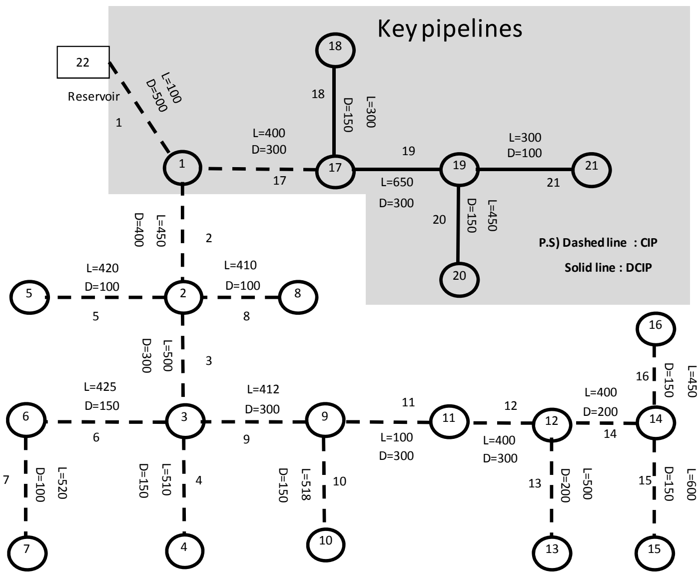

Fig. 3-4-1 Location of key pipelines on study area

3-4-1 Allocation of replacement budget

This study established five scenarios for the prioritized key pipelines to be completely replaced up to 3, 4, 6, 8, and 10 terms of budget allocation (hereafter TBA). The budget allocation method is described in **Table 3-4-1**. For example in case of 4-TBA, in 1~4 term 62% of annual budget is allocated for key pipelines replacement with 38% allocation for non-key pipelines, and after fully completing key pipeline replacement (in 5~10 term) full annual budget is used for non-key pipelines replacement. The overall annual replacement rate was set at 2% in order to replace each pipeline once in 50 years (planning period in this study). Replacement of the non-key pipelines occurred in order of age of the pipeline.

Table 3-4-1 Allocation of budget for the key pipelines and non-key pipelines

Key pipeline / Non key pipeline		Term	1, 2	3	4	5	6	7	8	9	10
	Ratio of budget allocation (%)	3 TBA	100 % / 0 %	47 % / 53 %	0 % / 100 %	0 % / 100 %	0 % / 100 %	0 % / 100 %	0 % / 100 %	0 % / 100 %	0 % / 100 %
		4 TBA	62 % / 38 %	62 % / 38 %	62 % / 38 %	0 % / 100 %	0 % / 100 %	0 % / 100 %	0 % / 100 %	0 % / 100 %	0 % / 100 %
		6 TBA	41 % / 59 %	41 % / 59 %	41 % / 59 %	41 % / 59 %	41 % / 59 %	0 % / 100 %	0 % / 100 %	0 % / 100 %	0 % / 100 %
		8 TBA	31 % / 69 %	31 % / 69 %	31 % / 69 %	31 % / 69 %	31 % / 69 %	31 % / 69 %	31 % / 69 %	0 % / 100 %	0 % / 100 %
		10 TBA	25 % / 75 %	25 % / 75 %	25 % / 75 %	25 % / 75 %	25 % / 75 %	25 % / 75 %	25 % / 75 %	25 % / 75 %	25 % / 75 %

3-4-2 Calculation of the ATC and ATAP for key pipelines

These five scenarios were implemented using MCS with 300 iterations under the condition that PDR was 1%/term and 2% annual replacement rate. As the results, firstly, **Fig. 3-4-2** shows average of total number of failure pipelines. We can know that that total number of failure pipelines was decreased little by little according to increased TBA.

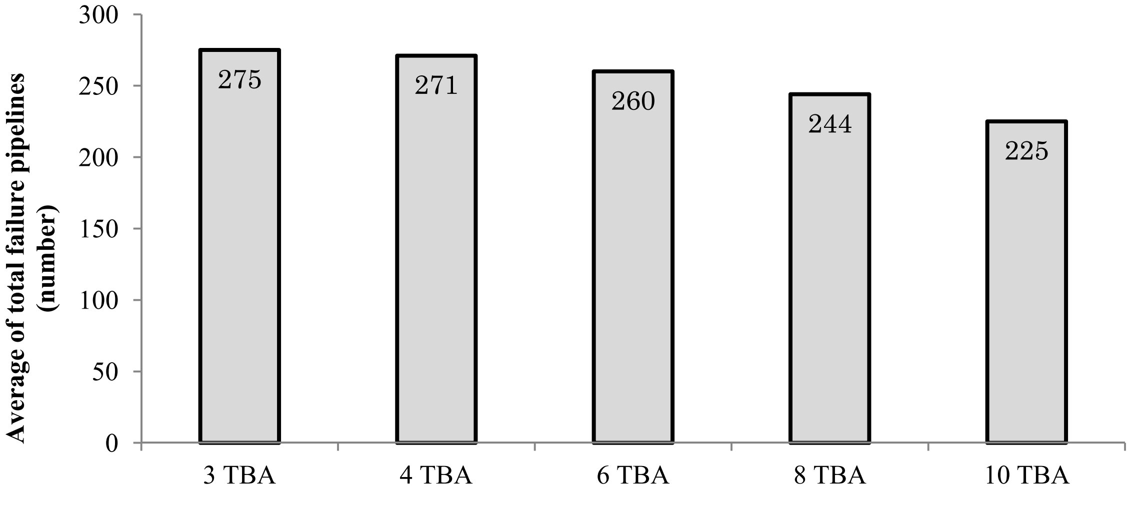

Fig. 3-4-2 Average of total number of failure pipelines at each **TBA**

As the results, there is no big gap but 10 TBA has the smallest failure pipelines. It means that allocation of replacement budget for key pipelines is a long time rather than short time. And then, **Fig. 3-4-3** shows the average total repair cost and total replacement cost at each TBA.

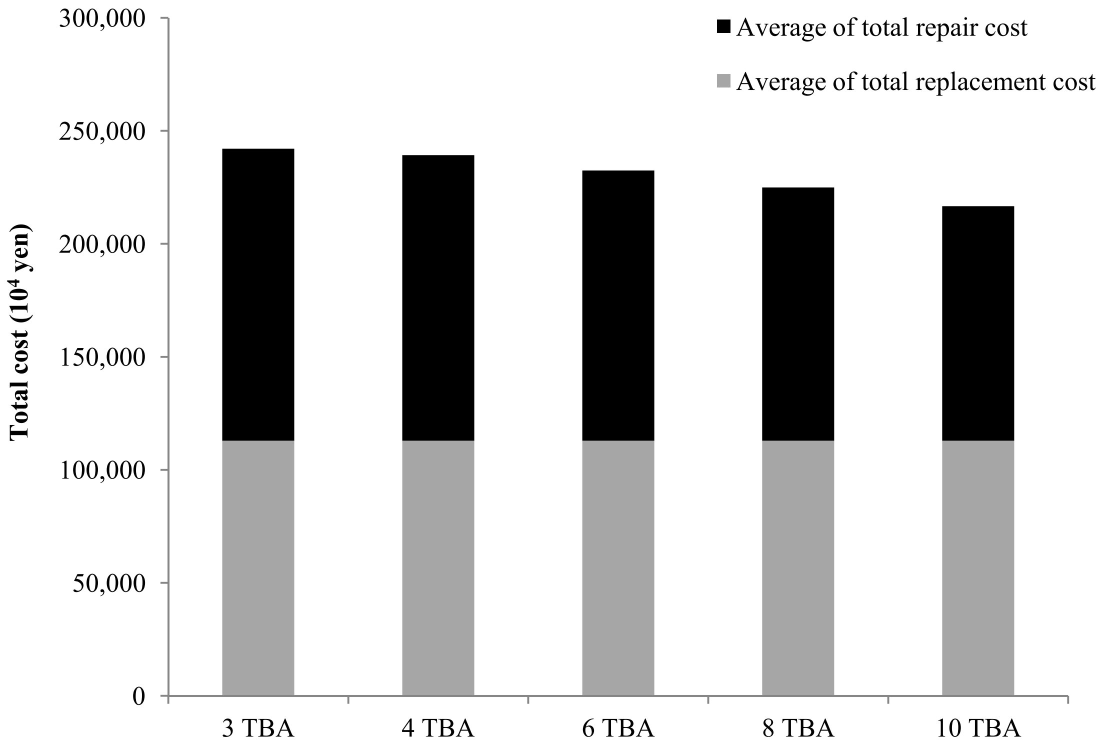

Fig. 3-4-3 Results for average total cost at each **TBA**

As the results, average of total replacement cost is same with each other, but average of total repair cost is a little different each other. This is because number of failure pipelines is different at each TBA as shown **Fig. 3-4-2**. 10 TBA has the smallest number of failure pipelines so total cost is also the lowest among the cases.

In conclusion, 10 TBA is the most economical budget allocation. All above results are expressible in below **Table 3-4-2**. Moreover, the ATC can be explained concretely through accumulated graph at each term (**Fig. 3-4-4**).

Table 3-4-2 Result of calculated ATC at each TBA

	Number of failure pipelines (number)	Average of total repair cost (10^4 yen)	Average of total replacement cost (10^4 yen)	ATC (10^4 yen)
3 TBA	275	129,175	112,866	242,041
4 TBA	271	126,364	112,866	239,230
6 TBA	260	119,562	112,866	232,428
8 TBA	244	112,095	112,866	224,961
10 TBA	225	103,768	112,866	**216,634**

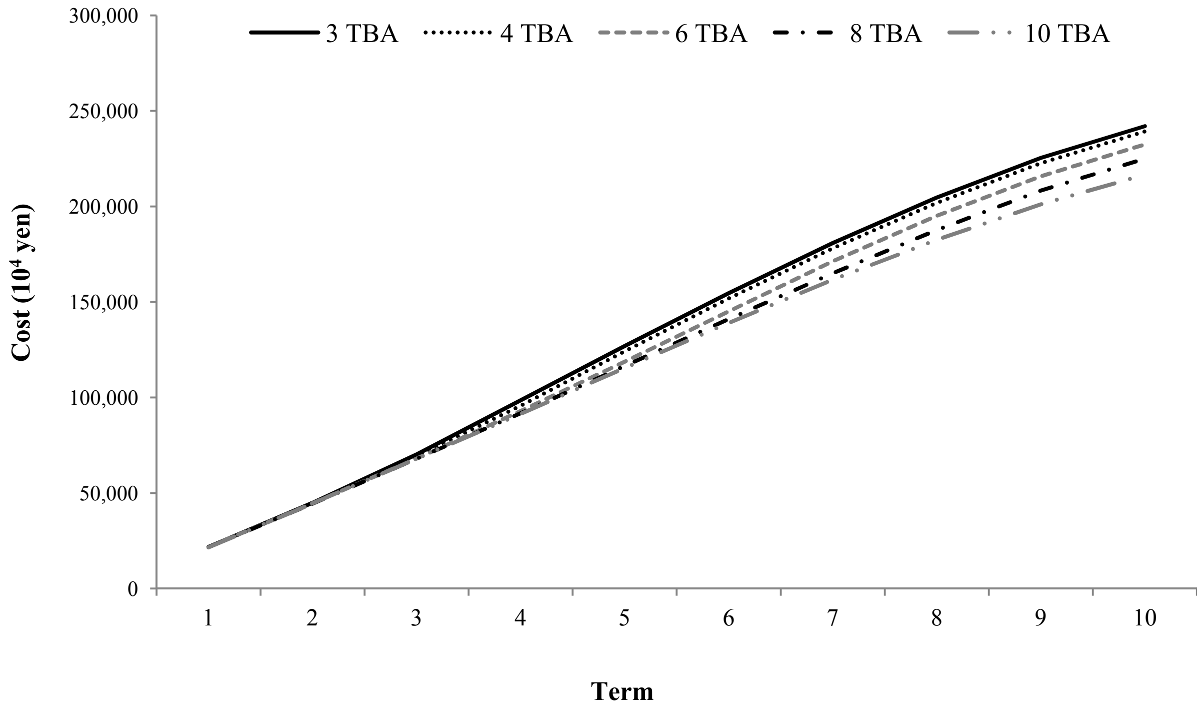

Fig. 3-4-4 Accumulated cost at each term

As the accumulated graph, the trend of curves is considered to be similar. It means that although there is difference of the ATC, it isn't meaningful to allocate budget to key pipelines in economical aspect. So in the study of key pipeline, it is important to be considered the affected population firstly. Especially, because purpose of key pipeline is to reduce the affected population in area of key pipeline, the number of affected population in key pipeline will be the main consideration.

So next are results of the ATAP and the ATAP in key pipelines. Firstly, **Fig. 3-4-5** shows the ATAP in entire study area.

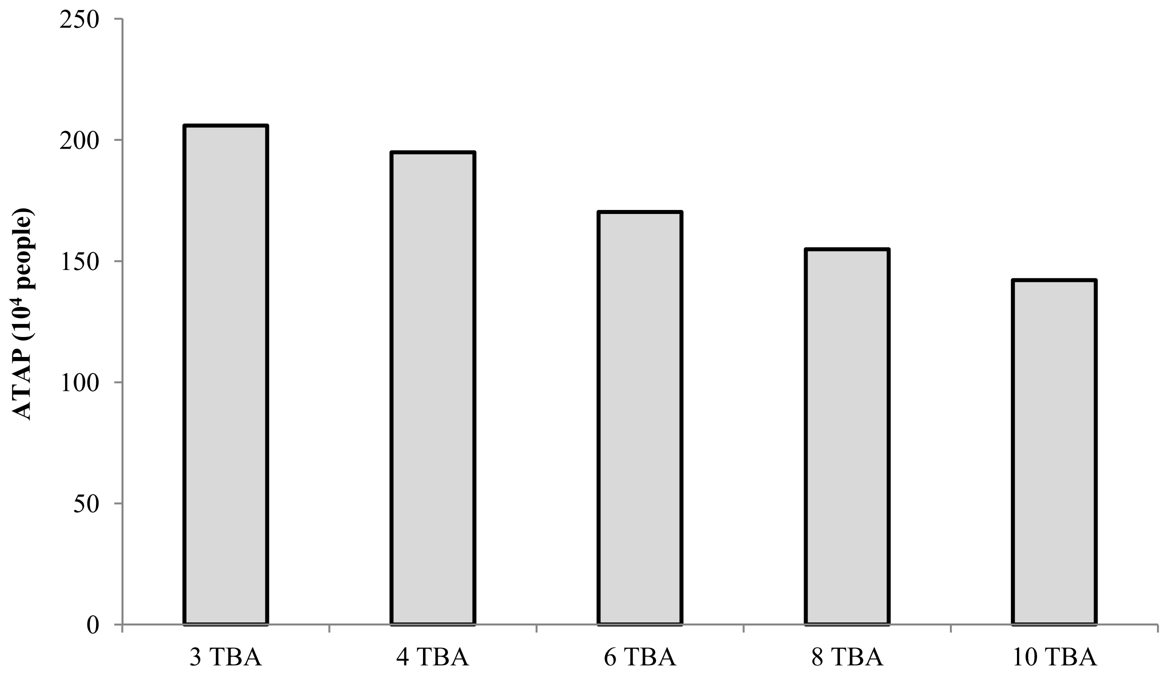

Fig. 3-4-5 Result of the ATAP in entire area at each TBA

Just as results of the ATC, results of the ATAP in entire area are same. The results show the cases in order from greatest to smallest ATAP: 3 TBA, 4 TBA, 6 TBA, 8 TBA and 10 TBA. In conclusion, the 10 TBA case was the most preventive one.

However, as mentioned before, in the study of key pipeline, the ATAP in key pipelines is main consideration. Next **Fig. 3-4-6** indicates the ATAP in key pipelines. As the results, 3 TBA is the smallest among the cases. This is because investment in as short time helped to prevent failure of key pipelines. In conclusion, 3 TBA is the most preventive case in this study.

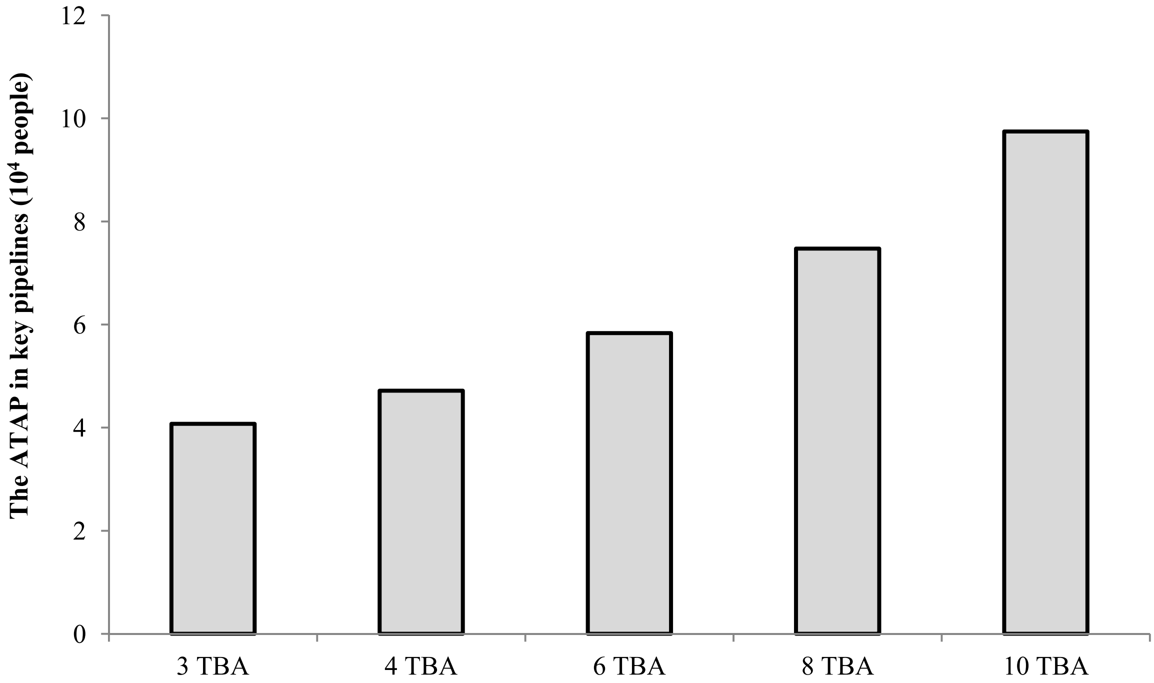

Fig. 3-4-6 Result of the ATAP in key pipelines at each TBA

The ATAP in key pipelines can be explained concretely through below accumulated graph at each term (**Fig. 3-4-7**).

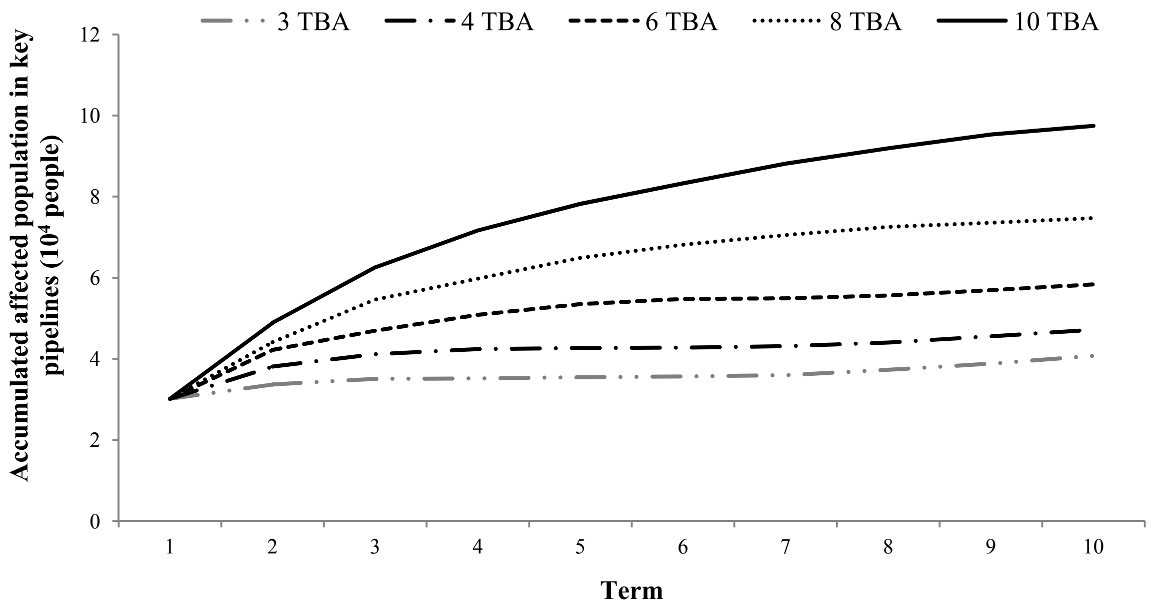

Fig. 3-4-7 Accumulated affected population in key pipelines at each term

As the graphs, we can know that in case of 3 TBA, after replacement of key pipelines, key pipelines aren't failure. Also this is effect of fast replacement for key pipelines. Next graph is compound result of the ATC with result of the ATAP in key pipelines (**Fig. 3-4-8**).

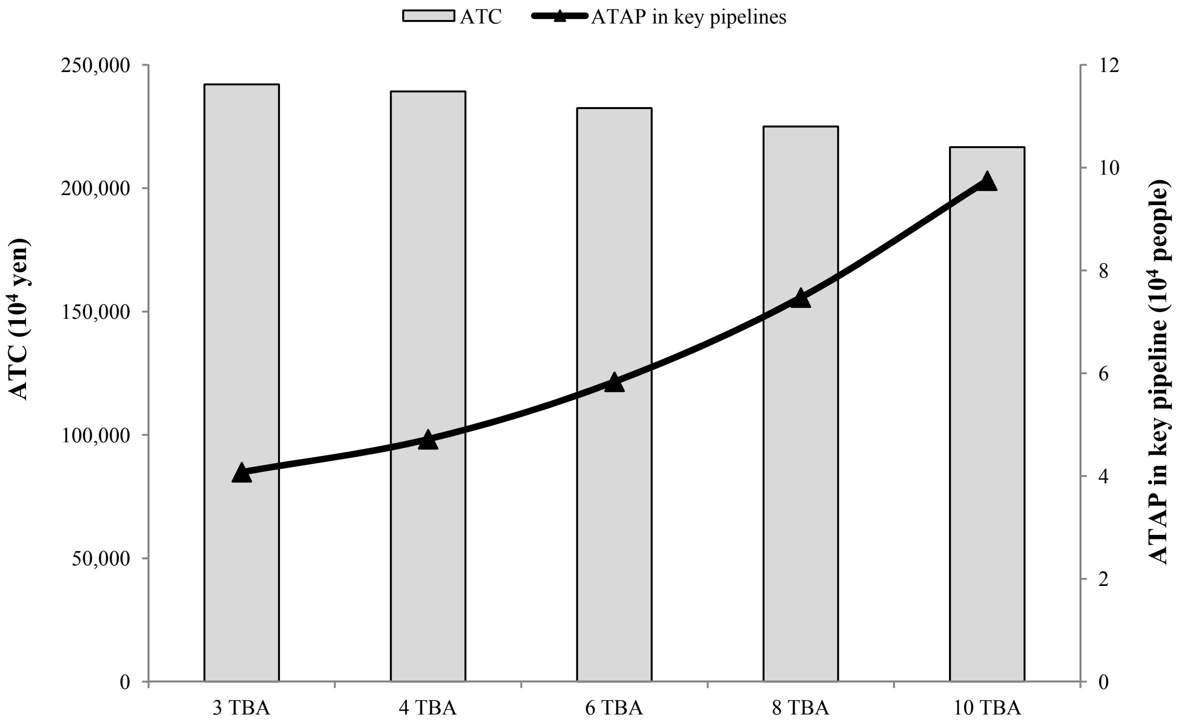

Fig. 3-4-8 Comparison of the ATC and the ATAP for key pipelines

In conclusion, the most economical scenario was 10 TBA for the entire area. On the other hand, the ATAP for key pipelines was smallest at 3 TBA. In other words, the scenario of 3 TBA provided the minimum risk for key pipelines. Because the difference in the ATC values is rather small and the most important object is to minimize the affected population, the most reasonable scenario is 3 TBA in conclusion. This result indicates that in terms of the impact on society the prioritizing replacement of key pipelines requires a higher total cost than that in the normal case.

3-5 Conclusions

Present study aims to propose long-term plan for water pipeline replacement under limited replacement budgets that utilizes a damage occurrence model. In order to set replacement plan, developed simulation model. The simulation model is used to obtain the failure rate curve which uses reliability theory and data analysis for pipeline leakage accidents. This simulation model also involves the calculation for the post-damage maintenance (breakage or leakage repairing) scenario and the preventive maintenance (replacement) scenario.

The MCS can be used to describe any technique that approximates solutions to quantitative problems through statistical sampling. Because pipeline accidents that occur at unspecified times and places, Monte Carlo simulation (MCS) is applied to simulation model. Because this study is long term simulation, we considered social discount rate (SDR) and population decrease rate (PDR).

Unlike other studies, our study considered not only the economy aspect but also the aspect of society impact. So benefit – cost ratio is applied to this study.

And then the present study was carried out several case studies which are changed annual replacement rate in order to confirm of replacement effect. Finally, the simulation model applies to key pipelines which are vital pipelines located in central districts with public establishments distributed densely around them. From the process we can obtain two conclusions as bellow:

1) An examination of the replacement rate revealed that 2.5% is the most effective rate for damage prevention and maintenance of pipelines, on the other hand 2% was found to be the most economical replacement rate.

2) In case of prioritized replacement of key pipelines, although the 10 TBA was the best in terms of economics, the 3 TBA was the best in terms of the impact on society considering the purpose of key pipeline.

The present study is expected to provide desirable alternative plans for water pipelines when the budget for replacement is limited with consideration of future conditions in study area. For the next study, this study will apply to not only simulated water distribution system but also on site of real water distribution system. So simulation model will upgrade to be appropriate reality and apply to a filed study.

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Chapter 4 Replacement plan of distribution pipelines considering risk prevention

4-1 Introduction

4-1-1 Background and purposes

The water pipeline is the most basic facility of social infrastructure. With the increasing quality of life, the level of consumer demand is also increasing. Consequently, water supply businesses are trying to supply sufficient high quality water. While water supply services work to supply sufficient high-quality water to meet demands, they are facing difficulty due to the deterioration of the water distribution network, particularly in the case of water pipelines laid in the late 1970s during rapid industrialization in Korea. These aged water pipelines are approaching 40 years in use, which is the standard facility age of water pipelines as proposed by the enforcement regulations for local public enterprises[1)].

The biggest problem of aged pipelines is the occurrence of accidents such as water leakage or pipeline burst, leading to economic loss and inconvenience for the consumers who are supplied by the water pipeline. The current reported average revenue water ratio in Korea is 83.5% and most of the non- revenue water ratio is caused by leakage from aged waterworks facilities in the water distribution system. In here revenue water means billed authorized consumption for supplied water. Waterworks are trying to increase the revenue water ratio and reduce water leakage.

To prevent these problems, water pipelines must be efficiently replaced. In the past, the replacement commenced from the oldest buried water pipelines. However, given the complex natural and artificial factors that influence water pipeline accident, water pipelines must be analyzed in conjunction with priority plans.

Nazif and Karamouz (2009) quantified the readiness of systems for disasters. This readiness was developed into an algorithm based on three system performance indexes of reliability, resiliency, and vulnerability[2)]. Choi et al. (2011) expanded this research by proposing new factors to formulate a reliability index that can be applied to small water pipeline networks[3)].

Unlike previous studies, the present study introduced pipeline risk with quantitative approach. In addition, future replacement plan with an order of replacement was also set by quantitative rank of risk. Since pipeline accidents occur at random times and spaces, the Monte Carlo simulation (MCS) was applied. The aim of this study is to help in the stable establishment of efficient water pipeline replacement plans.

4-1-2 Study area

This study was conducted by analyzing data collected from the water pipeline defects diagnosis of City S in Korea that was conducted in 2009~2010[4)]. City S is composed of 10 water distribution areas (big blocks) and 127 small blocks (**Fig. 4-1-1**). City S is composed of 127 small blocks. The present study chooses one small block as the study area among 127 small blocks (**Fig. 4-1-2)**.

The small blocks in this study area is supplied about 2400m3 of water every day. The water pressure ranges from 280kPa ~ 440kPa. And then this Study area includes 142 pipelines[5)].

This research focused only on the water distribution pipelines without service line branch and service pipelines of under 75mm. The water distribution system was also simplified by excluding transmission pipelines and service pipelines.

Table 4-1-1 shows the data of a studied network with only distribution pipelines.

Fig. 4-1-1 City S with 127 small blocks

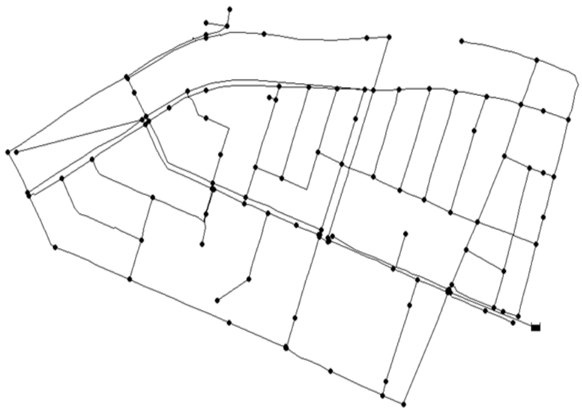

Fig. 4-1-2 Study area

Table 4-1-1 Data of study area

	Distributed amount (m^3/day)	Total length (m)	DCIP ratio* (%)	Range of diameter (mm)
City S	345,968	1,111,4322	88	80 to 1200
Small block	2,400	7,832	100	80 to 300

* Ductile cast iron pipe (**DCIP**) length / Total length

4-2 Risk analysis

First, the present study defined pipeline accidents as pipeline damages cause of natural leakage or burst. In order to maintain or prevent the pipeline accidents, it is necessary to repair quickly at leakage point or set plan of pipeline replacement. As in the previous step of this analysis, pipelines with high accidents rate were analyzed for entire distribution area considering soil environments and replacement rate by economic evaluation. In order to determine priority of replacement pipelines in a small block, this study aims to quantify the impact on water consumers in pipeline accident. Because the study area is mostly residential area, suspension or reduction of working pipeline accidents was not concerned in this study.

Three representative indexes for risk analysis of pipeline network were selected from existing researches to examine firstly, how many times pipeline damages occur; secondly, how long does it take to repair damaged pipelines; and lastly, how much water shortage is caused by damaged pipelines. This study carried out quantitative risk analyses using these three indexes according to **Fig. 4-2-1**.

The small block is composed of 142 water pipelines. Pipeline No. 142, particularly, is directly connected to the transmission pipeline, so that all water supplies will be blocked if this pipeline is destroyed. Consequently, No. 142 pipeline is the most significant pipeline and the establishment of a special emergency plan was deemed necessary. Given this, No. 142 pipeline was thus excluded from the risk analysis.

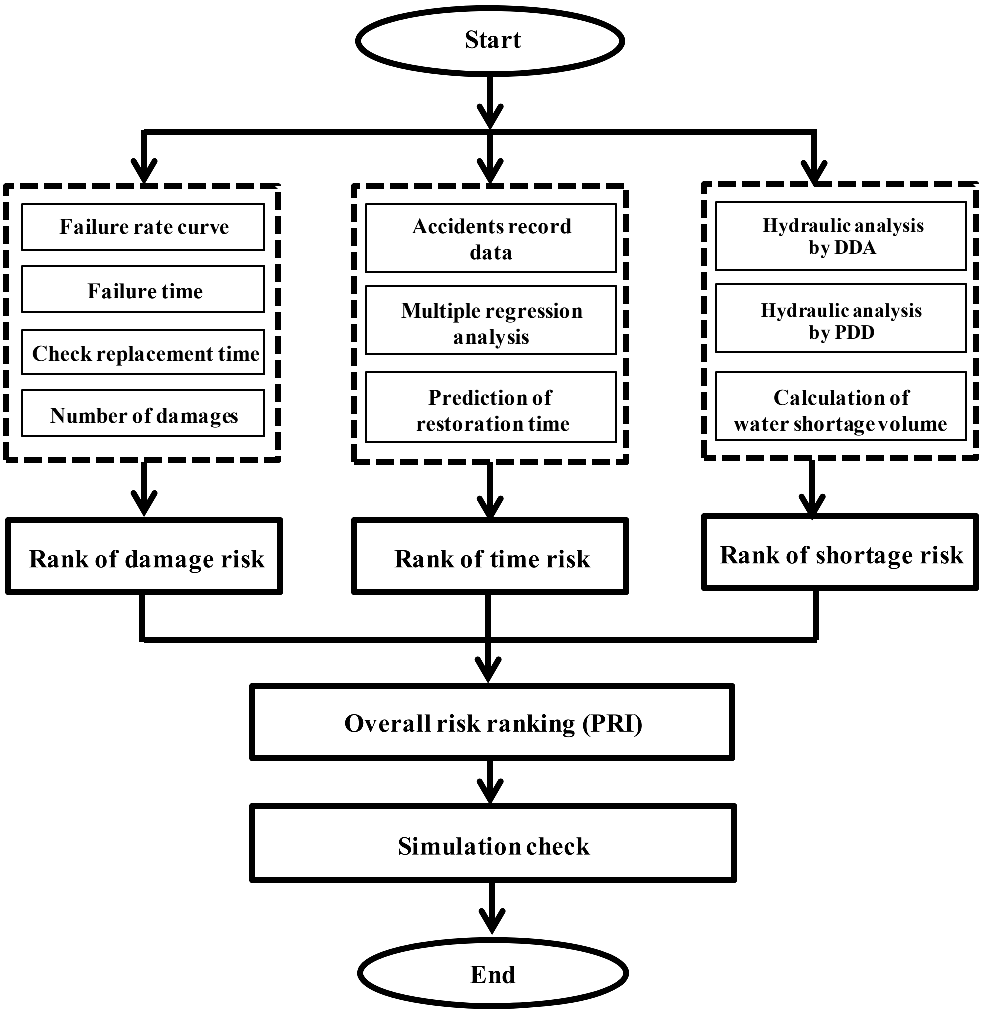

Fig. 4-2-1 Flowchart of this study by risk analysis

4-2-1 Prediction of number of pipeline damages

In previous studies, records of pipeline accidents were used to make probability models and find future damage probability. However, in this study, in order to predict the failure time of pipelines, a failure curve was obtained through a survey on waterworks businesses and record analysis of past accidents as dealt with **chapter 3**.

At last the failure time of pipelines was predicted by using **Equation 3-2-1** based on a failure curve as shown **Fig. 3-2-1**. For this study, the pipeline is divided into a constant length (4m here) of virtual sub-items, and it is assumed that accidents occur in each sub-item. In paper of Arai et al.[6)] the failure rate (%/year) is expressed as **Equation 3-2-1** conducted from reliability engineering. Assuming that each accident occurs at each sub-item, the failure rate is converted into the number of accidents per year (number/km/year). The constants *k* and *c* were estimated for each type of pipeline material from the data of regression analysis of past accidents. The expected number of damage occurrences is then calculated as **Equation 4-2-1**.

$$N = \int_{t_1}^{t_2} k(\tau + t)^c dt \qquad \textbf{(4-2-1)}$$

where, *t*: degree of time, *τ*: age of pipeline, *N*: the total number of damaged sub-items from t_1 to t_2.

And then in order to expect to damage on pipelines in the study area, the entire pipeline age increased 20 years. So the average age of pipelines is nearly 40 years. So, the number of pipeline damage was calculated using **Equation 4-2-1**. The number of pipeline damages occurring in 60 years without replacement could be predicted by synthesizing each failure rate of pipelines.

The results are expressible in **Fig. 4-2-2**. As the results, total predicted number of pipeline damages is around 174. Especially, for pipeline No. 118, nearly six damage incidents were predicted with the highest risk. On the other hand, No. 3 pipeline was predicted with almost zero occurrence of pipeline damage in 60 years, which is the last rank in the risk ranking. This indicates that No. 3 pipeline has minimum risk in this study area. Besides risk ranking is obtained by descending order of pipeline damages number.

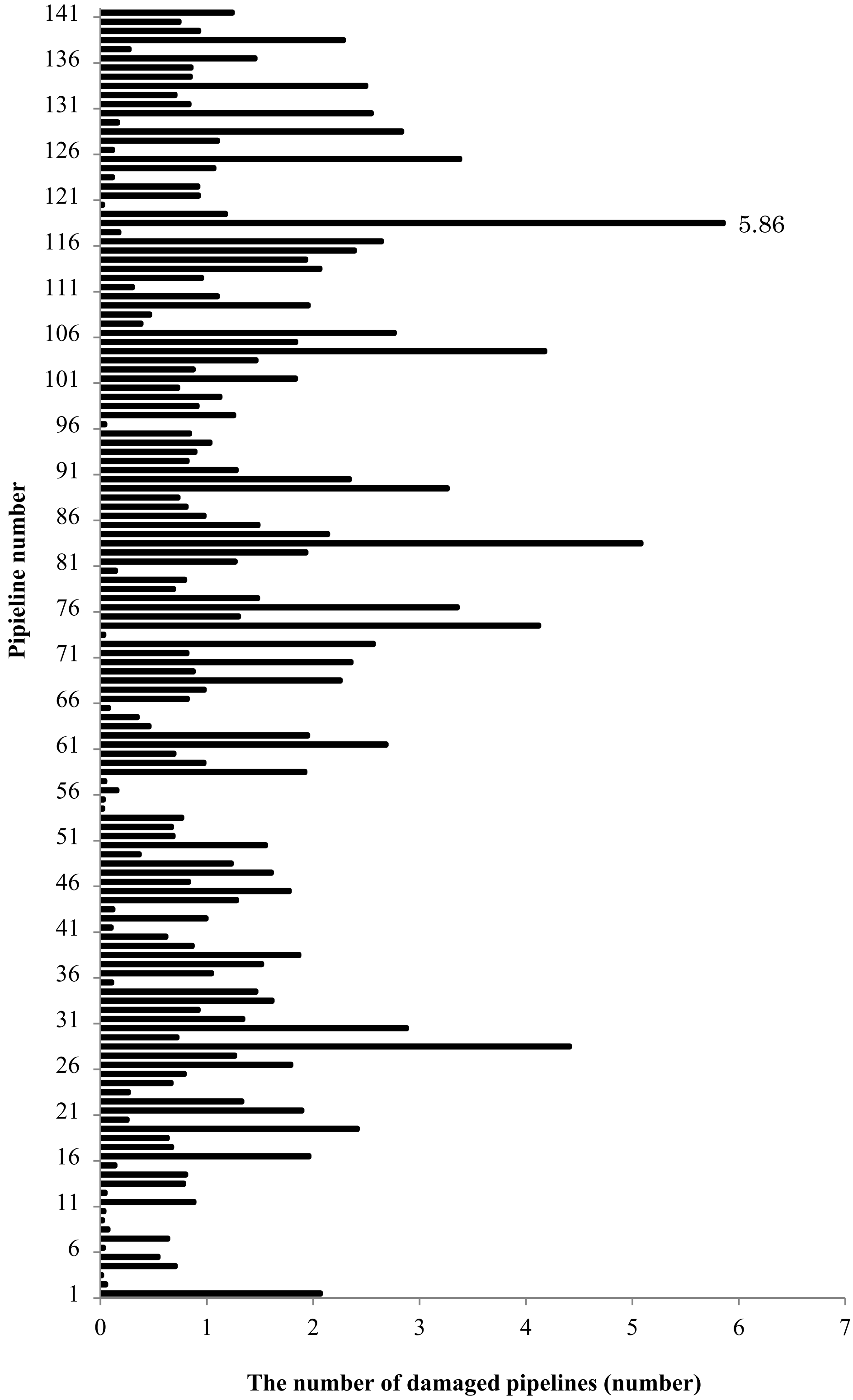

Fig. 4-2-2 Results of predicted number of pipeline damages

4-2-2 Prediction of restoration time

When pipeline accidents on pipeline occur, the service must quickly be restored to normal consumer service. If the restoration time is delayed, the incurred consumer damage will increases and add a risk factor to maintenance management. The accident restoration time is influenced by complaint registration, transport time to accident area, human factors such as working manpower, depth of pipeline burial, pipeline diameter, road width, packaging type of buried land, and numerous other burial environmental factors.

This study excludes human factors and focuses on the construction work time at damaged points. The time is influenced by the pipeline burial environment. We analyzed past records of accidents to generate a multiple regression equation that is applied to the study area. To predict the restoration time of each pipeline in the study area, a record of the accidents occurring in City S from 2006 to 2009 was analyzed. The record shows that a total of 1216 accidents were reported in the four-year period and the restoration time was widely distributed. In accordance with the characteristics of the study area, we extracted cases where DCIP material with a diameter between 80mm and 300mm are in use and that have a fast-response restoration time of within 24 hours from the accidents data. Multiple regression analysis of the resulting 145 cases was conducted on the restoration time (hr.) and burial environment. The DCIP ratio was 100% in the study area, so the material of pipeline was excluded from this analysis. **Table 4-2-1** presents the relevant data for this analysis with their mean, max and minimum values of items used as independent variable.

Table 4-2-1 The statistics of items for multiple regression analysis

Independent variable	Unit	Variable	Mean	Min	Max
Laying depth	(m)	X_1	1.22	0.7	1.8
Road width	(m)	X_2	13.31	4	39
Diameter	(mm)	X_3	167.52	80	300

Among the variables that were used in the multiple regression analysis, pipeline age and material of pipeline were used to predict the future damaged pipeline numbers, which were excluded from this analysis. The multiple regression analysis models that was formulated based on the analysis of the accident records was applied to rank the predicted restoration time from the slowest to the fastest.

Prior to regression analysis, a correlation analysis was carried out. Moreover in order to examine this model to determine whether it is likely linear or non-linear, the correlation coefficients of the logarithmic data of independent variables were also estimated as shown in **Table 4-2-2**.

Table 4-2-2 Results of correlation analysis

	X_1	X_2	X_3
Y	**-0.275**	0.245	**0.248**
(n = 145)	Log (X_1)	Log (X_2)	Log(X_3)
($R_{0.05}$ = 0.164)	-0.275	**0.290**	0.238

If correlation coefficients have smaller value than the standard value $R_{0.05}$, this means that there is no relation between each independent value and restoration time. However all factors are satisfied. And then in value of X_2, correlation coefficient is increased.

As the results, restoration time (Y) has a non-linear relation with road width (X_2). Based on results of correlation analysis, the multiple regression analysis was carried out (**Table 4-2-3**).

Table 4-2-3 Results of non-linear multiple regression analysis

Model number	Laying depth (m)	Road width (m)	Diameter (mm)	Constant	R-value
	X_1	$Log(X_2)$	X_3		
R1	-5.575	2.893	0.016	9.238	0.446
R2	-4.644	4.27		9.253	0.387
R3		3.618	0.011	2.456	0.330
R4	-0.866	6.033	0.016		0.354
R5	0.075	7.419			0.288
R6		5.387	0.014		0.330

As the results, R1 has the highest R-value among the models. So we can judge that R1 model is appropriate in this study. R1 is expressed as **Equation 4-2-2**.

$$Y = -5.575X_1 + 2.893Log(X_2) + 0.016X_3 + 9.238 \ (R=0.446) \qquad \textbf{(4-2-2)}$$

First, the variance analysis results were examined to verify the statistical significance of the regression equation. As a result, the significance of probability was 0.000 ($<\alpha=0.05$) to show statistical significance. The null hypothesis (H_0) that 'the coefficients of the independent variable included in the model is 0' are dismissed when the significant probability of the F value, which is the probabilistic indication, is smaller than 0.05. It was therefore judged useful to predict the dependent variables using the regression equation made by input independent variables[7)].

From the deduced equation, it was shown that the laying depth, road width and diameter rank exerted a strong influence. **Fig. 4-2-3** indicates fitness between observation values and estimated values by multiple regression analysis.

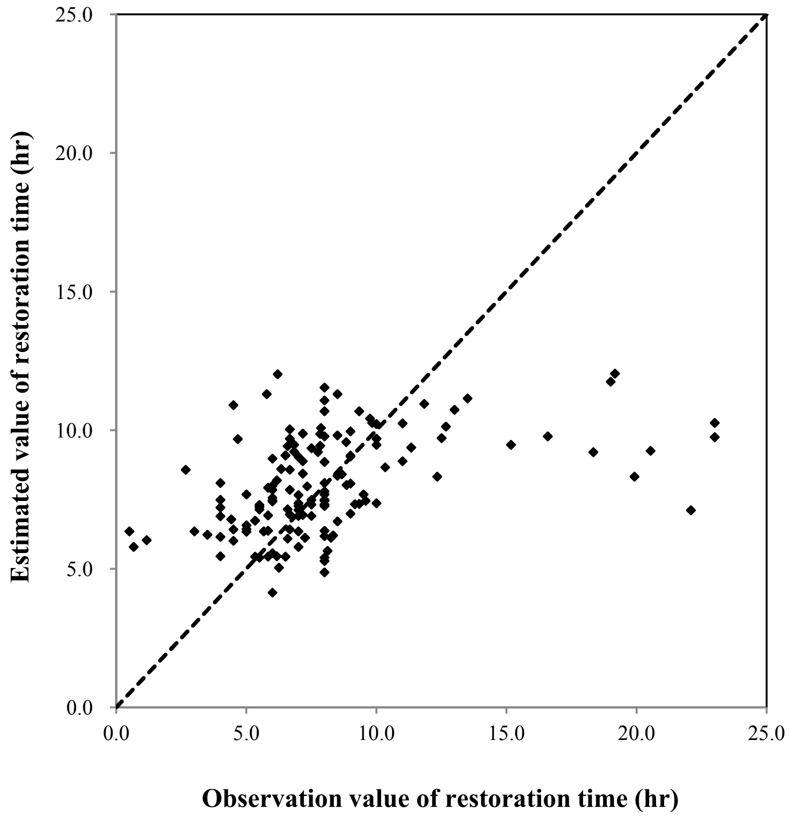

Fig. 4-2-3 Estimated values of restoration time

Equation 4-2-2 was applied to all pipelines of the study area and the predicted restoration times were obtained. The results are expressible in **Fig. 4-2-4**.

The average restoration time of the pipelines in the study area was about 7 hours. Pipeline No. 4 with a diameter of 300mm buried at a depth of 1.3m under a 45m-wide road showed a restoration time of almost 11 hours, which was the longest predicted time. In contrast to that, Pipeline No. 121 with a diameter of 80mm buried at a depth of 1.7m under a 5m-wide road showed a restoration time of almost 3 hours, which was the shortest.

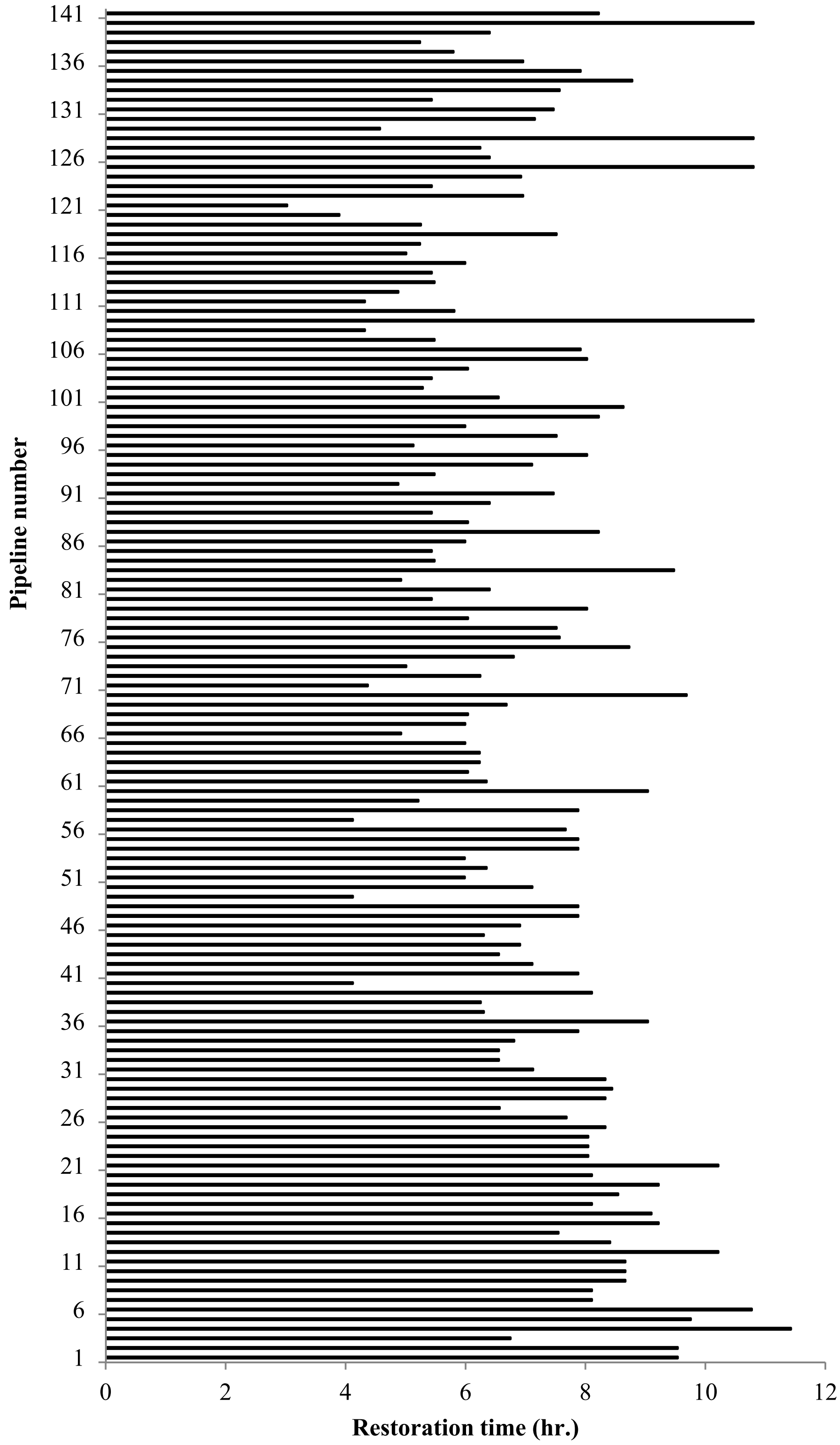

Fig. 4-2-4 Results of predicted restoration time

4-2-3 Prediction of water shortage volume

Water shortage volume was predicted to investigate the influence on consumers until the pipeline accident is restored. Water shortage in a water distribution system occurs due to the lockage of valves in the accident pipelines during restoration, causing an isolated demand point occurs in this process. This is called a direct water shortage. Meanwhile, an accident in a pipeline can result in decreasing water pressure in nearby pipelines. This is called an indirect water shortage.

For this study, the pressure dependent demands (PDD) module of WaterGEMS V8 commonly used software[8)] for hydraulic analysis of water distribution system was used to estimate direct and indirect water shortage volume.

Most water distribution analysis programs used in the field are conducted with the demand dependent analysis (DDA) model. The DDA model[9)] is a way to calculate the head under the assumption that water demand at each node is always satisfied (**Equation 4-2-3**), but has problems when the water distribution is abnormal operation.

On the other hand, the PDD model[10)] assumes that demand at each node is fully satisfied only if the minimum required water pressure at that node is satisfied (**Equation 4-2-4**). Otherwise, demand at the node is partially satisfied by relational formula between nodal demand and water pressure. This model is more reliable than the DDA model when the water distribution is abnormal, such as due to a pipeline accident.

$$Q_i^s = Q_{ri} \qquad \textbf{(4-2-3)}$$

$$\frac{Q_i^s}{Q_{ri}} = \begin{cases} 0 & H_i \le 0 \\ \left(\dfrac{H_i}{H_P}\right)^{\alpha} & 0 < H_i < H_P \\ 1 & H_P \le H_i \end{cases} \qquad \textbf{(4-2-4)}$$

where, H_i: calculated pressure at node i, Q_{ri}: requested demand at node i, Q_{is}: calculated demand at node i, H_p: pressure threshold above which the demand is independent of nodal pressure (input parameter), α: exponent of pressure demand relationship. In addition, the detailed comparison of DDA and PDD were show in **Table 4-2-4.**

Table 4-2-4 Comparison of DDA and PDD[11)]

	DDA	PDD
Application	Normal operation	Abnormal operation condition (leakage, failure, pump problem, fire demand, etc)
Reliability for abnormal condition analysis	Low	High
Basic assumption	Demands of nodes are fully satisfied	Demands of nodes are depending on available head
Weak point	Minus pressure occur under higher demand loading condition -> Unrealistic	Need of relation curve between nodal heads vs. nodal flows (Filed data are necessary)
Solving method	Continuity and loop equations	Optimization method

In this study accident occurrence on each pipeline is assumed and a simulation was conducted by blocking the water flow in the accident pipeline. The water shortage volume was calculated by **Equation 4-2-5**. The water shortage was also ranked in terms of water shortage in the pipeline accidents from the largest to the smallest.

$$\Delta Q_j = \sum_{i=1}^{m} Q_{ri} - \sum_{i=1}^{m} Q_{ji}^{s} \qquad (j = 1, 2, \ldots, n) \qquad \textbf{(4-2-5)}$$

where, ΔQ_j: water shortage volume when accident occurred on j pipeline, Q^s_{ji}: calculated water at node i when accident occurred on j pipeline, m and n: the number of nodes in the water distribution network and the number of pipelines respectively.

First, water distribution system analysis was conducted using DDA method in the normal state to determine the amount of water shortage followed by the pipeline damage in the study area. As a result, the total amount of supplied water was 2240m^3/day. Water distribution system analysis using PDD method was conducted in the same condition. First, the pressure threshold above which the demand is independent of nodal pressure should be set to satisfy the designed demand for water distribution system analysis by PDD method. The Korean Waterworks facility standard proposes a minimum dynamic water pressure of 300~350kPa for direct water supply to a 5 story building[12)]. The maximum height of direct water supply to 5 stories in this study area; thus, the pressure threshold (H_P) was set at 300kPa.

As a result of PDD water distribution system analysis in the normal state, 2240m^3/day of water was supplied. There was no difference between the DDA and PDD water distribution system analyses in the normal operation.

To estimate the water shortage that will occur due to the pipeline damage of this study area, it each pipeline from No. 1 to No. 141 was assumed to have been damaged one at a time through PDD method. The results are shown in **Fig. 4-2-5**.

As the results, Pipeline No. 1 in particular is in a very important location as it is directly connected with pipeline No. 142 and the result shows that this pipeline would have the greatest water shortage of 186.81m^3/day (8.3%). This analysis revealed that the water shortage is strongly influenced not only by the pipeline diameter or the distance of the connected pipe to the transmission pipeline, but also by the complicated configuration of the distribution network.

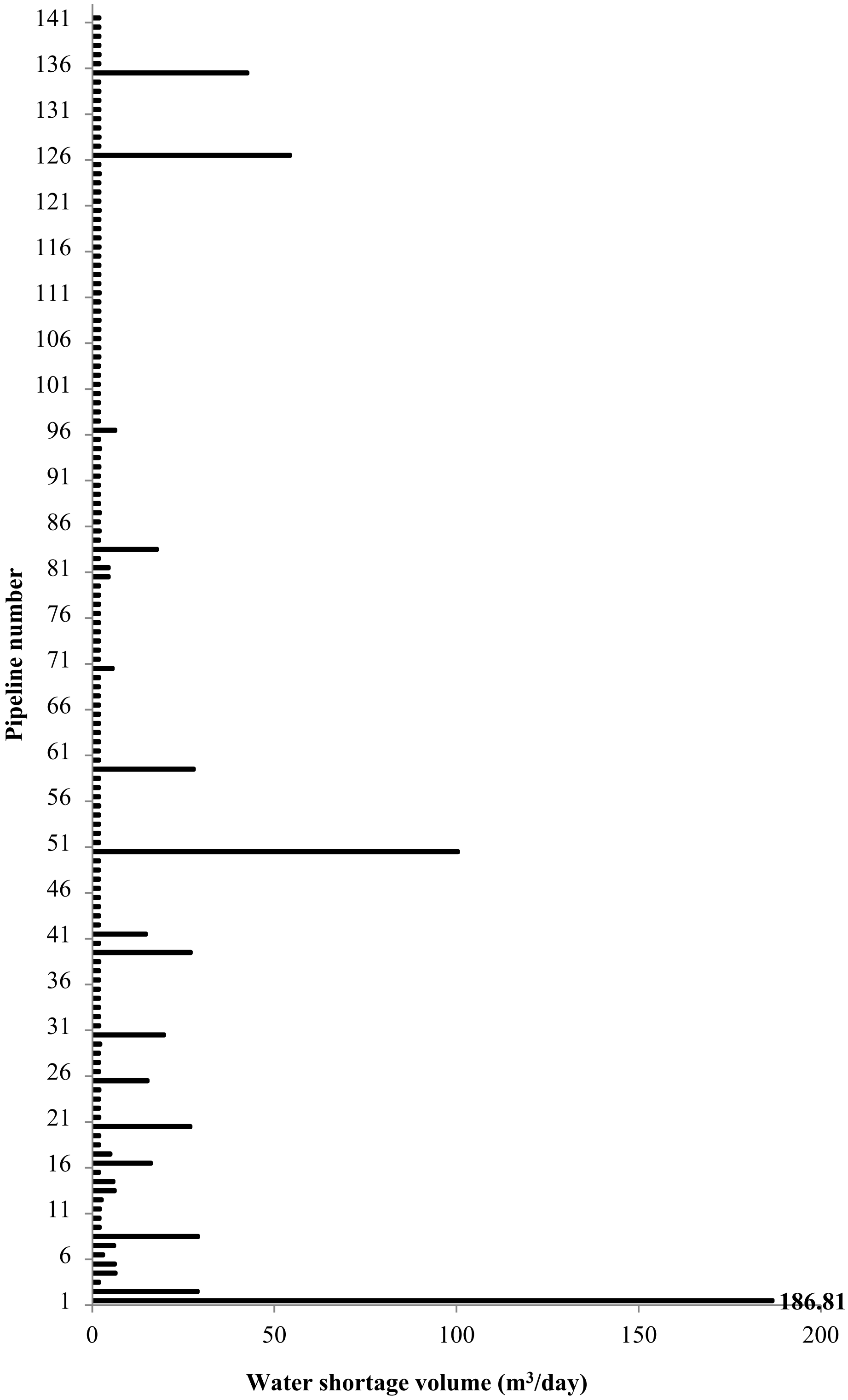

Fig. 4-2-5 Results of predicted water shortage volume

Moreover **Fig. 4-2-6** shows groups in order from the largest to the smallest amount of water shortage in the bold line, bold dotted line, line with triangle and dotted line. If the bold lines were damaged by accident, the amount of water shortage would be over 14m^3/day. And then the bold dotted line was indicated that the amount of water shortage would be over 3m^3/day, and pipelines which have over 2m^3/day water shortage were expressed lines with triangle. On the other hand, in the case of dotted lines, there are 71 pipelines and amount of water shortage would be under 2 m^3/day.

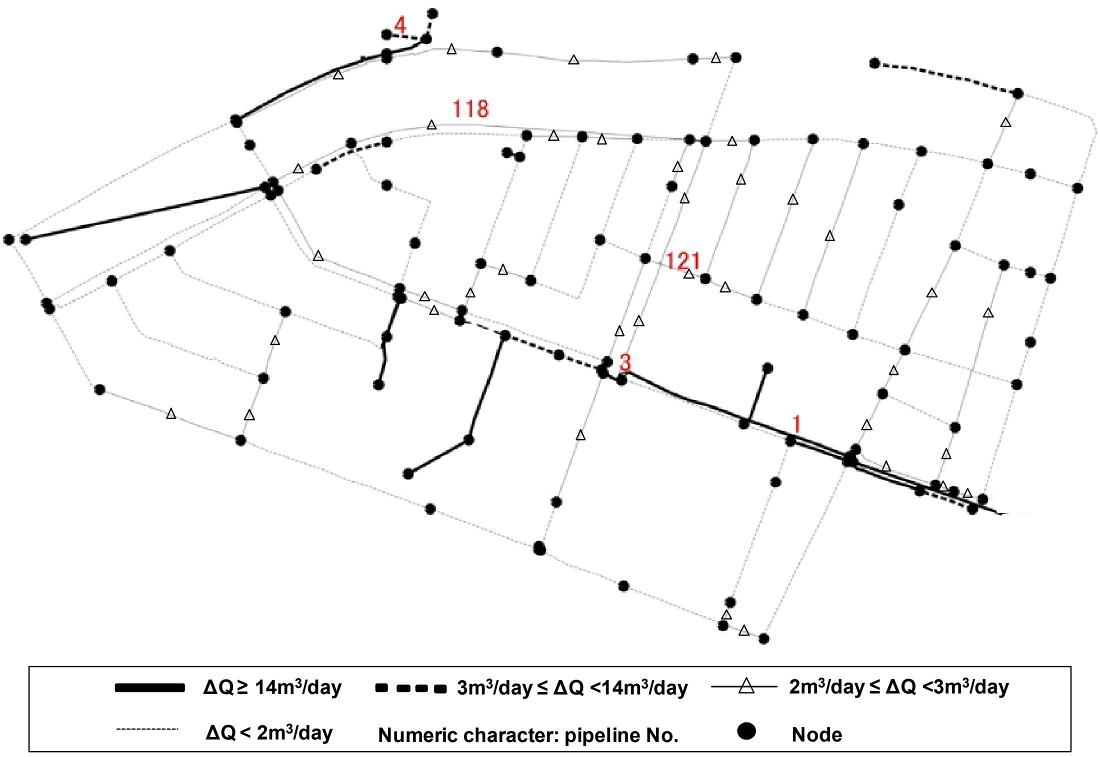

Fig. 4-2-6 Network of predicted water shortage volume

4-3 Predicted risk index (PRI)

Each risk ranking was obtained through 3 risk analyses. However, each analysis has a different risk ranking, requiring an overall risk ranking to balance each risk ranking. Consequently, the predicted risk index (PRI) was introduced in this study to estimate the overall risk ranking. PRI is a quantitative approach used to compensate for the method of deriving overall risk ranking from obtained risk analysis.

In this study, the PRI was calculated by multiplying the expected number of pipeline damages with the restoration time and the amount of water shortage. That is, the PRI in this case indicates the water shortage volume in the future period from t_1 to t_2. In this way, the PRI also becomes a quantitative impact ranking.

$$PRI_j = N_j \times RT_j \times \Delta Q_j \qquad (j = 1, 2, \ldots, n) \qquad \textbf{(4-3-1)}$$

where, **PRI**$_j$: amount of water shortage when accident occurs on *j* pipeline (m^3), N_j: expected number of damage occurrences on *j* pipeline, RT_j: restoration time (hr), ΔQ_j: water shortage volume (m^3/hr), *j*: accident pipeline number, *n*: the number of pipelines.

Using **Equation 4-3-1**, the PRI of each pipeline was calculated to decide the ranking of the largest water shortage volume. The results are shown in **Fig. 4-3-1**.

As the results of PRI, pipeline No. 1 would have the highest risk because of the highest water shortage volume. On the other hand, pipeline No. 3 was predicted with the lowest risk in 60 years. Based on the above results, the priority of pipeline replacement can be set by the PRI. The highest PRI was given the utmost priority for replacement. These results also present the estimated priority of the replacement of each pipeline from 1st to 141st rank (excluding pipeline No. 142).

Consequently, the pipeline with No. 1 risk ranking should be the first to be replaced (**Table 4-3-1**).

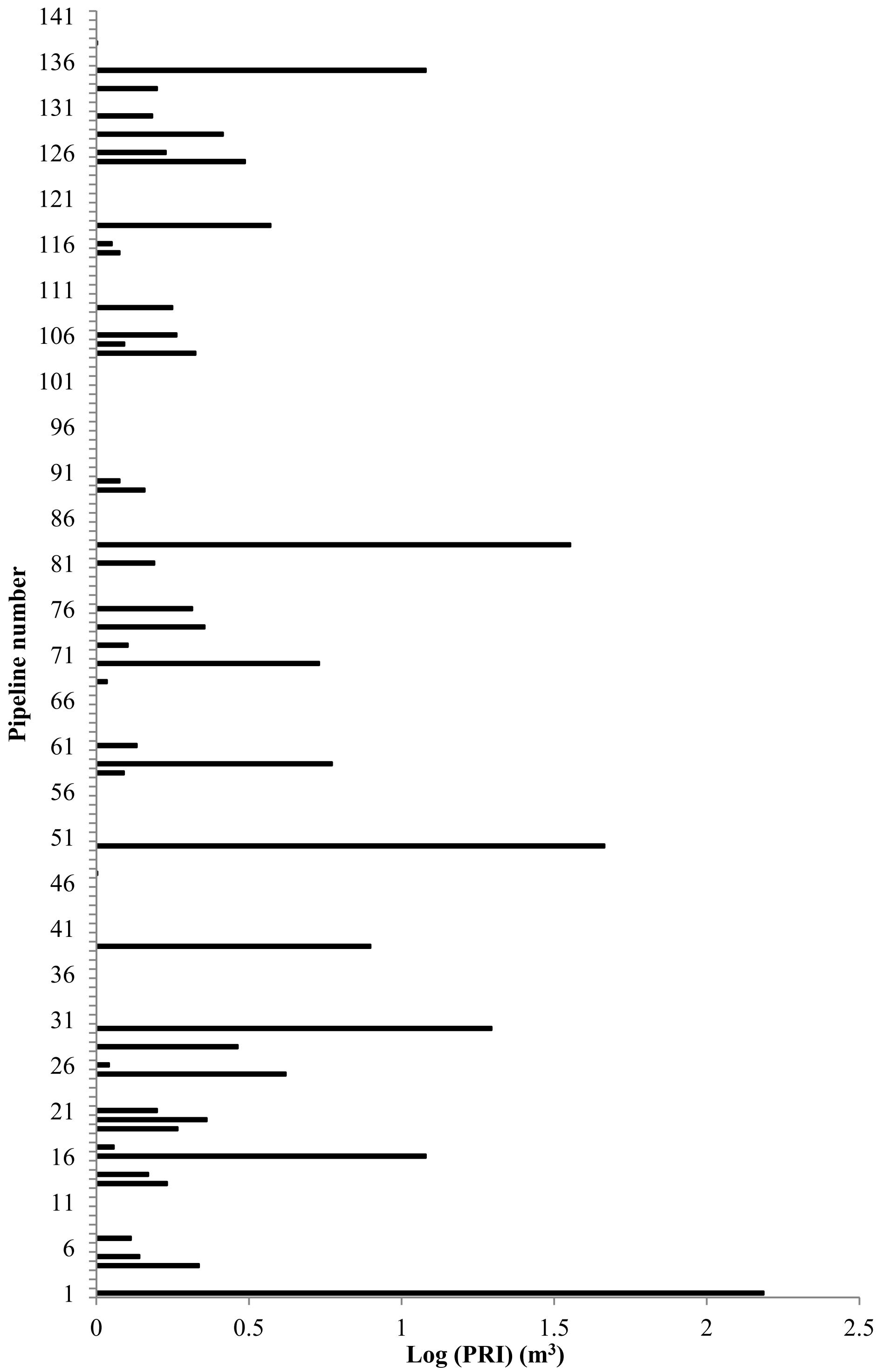

Fig. 4-3-1 Results of calculated PRI

Table 4-3-1 Priority of replacement pipeline according to PRI

Pipeline	Replacement order	Pipeline	Replacement order	Pipeline	Replacement order
1	1	51	108	101	46
2	78	52	105	102	102
3	141	53	103	103	75
4	17	54	137	104	18
5	31	55	135	105	35
6	132	56	124	106	21
7	33	57	138	107	115
8	69	58	36	108	117
9	136	59	8	109	22
10	134	60	88	110	83
11	70	61	32	111	122
12	131	62	49	112	100
13	23	63	113	113	48
14	29	64	116	114	53
15	123	65	133	115	37
16	5	66	110	116	40
17	39	67	94	117	125
18	99	68	42	118	11
19	20	69	93	119	86
20	15	70	9	120	140
21	26	71	111	121	112
22	54	72	34	122	84
23	118	73	139	123	130
24	97	74	16	124	74
25	10	75	50	125	12
26	41	76	19	126	24
27	73	77	52	127	79
28	13	78	107	128	14
29	80	79	87	129	128
30	4	80	119	130	28
31	59	81	27	131	85
32	92	82	63	132	109
33	57	83	3	133	25
34	58	84	47	134	76
35	126	85	68	135	6
36	64	86	95	136	56
37	60	87	77	137	120
38	45	88	104	138	44
39	7	89	30	139	90
40	114	90	38	140	72
41	91	91	62	141	55
42	81	92	106		
43	127	93	101		
44	67	94	71		
45	51	95	82		
46	96	96	129		
47	43	97	65		
48	61	98	98		
49	121	99	66		
50	2	100	89		

4-4 Examination of replacement order effect

Before the study, annual replacement rate was proposed considering the budget of pipeline replacement. The average pipeline age is around 20 years in this study area, so there is no need to start pipeline replacement immediately. This study assumes pipeline replacement to start after 20 years and the period of the replacement project is set for the next 60 years, because in order to match the useful life of the latest **DCIP**. In the simulation, pipelines of study area are not replaced in the first 10 years due to the budget of other small blocks. After that, pipeline replacement is simulated for the next 25 years, with no replacement for following 25 years. So after 60 years, the replacement plan will be reconsidered for the next 60 years. In short, the analysis predicted that water pipelines in the study area could be replaced at a 4%/year replacement rate.

In order to compare the effect of replacement order, three scenarios were set: (A) 4%/year replacement in order of aged pipeline, (B) 4%/year replacement in order of PRI, and (C) without replacement. Here, “without replacement” (Scenario C) means that pipelines are repaired but not replaced after damage according to their age, whereas in other scenarios the considerably few damaged pipelines are repaired after replacement. These scenarios also help confirm the effect of the replacement order.

Firstly, **Fig. 4-4-1** and **Fig. 4-4-2** show the replacement order respectively. And then **Table 4-4-1** indicates detail standard of grade for replacement order. **Table 4-4-1** indicates the details of the standard grades for the replacement order and their average values. In scenario A the older pipes would be replaced at an earlier term, and pipes of same age with a larger diameter will have priority. In scenario B, whose priority is PRI, some of the older pipes with fewer risks to consumers would be replaced after the replacement of the newer pipes with greater risks.

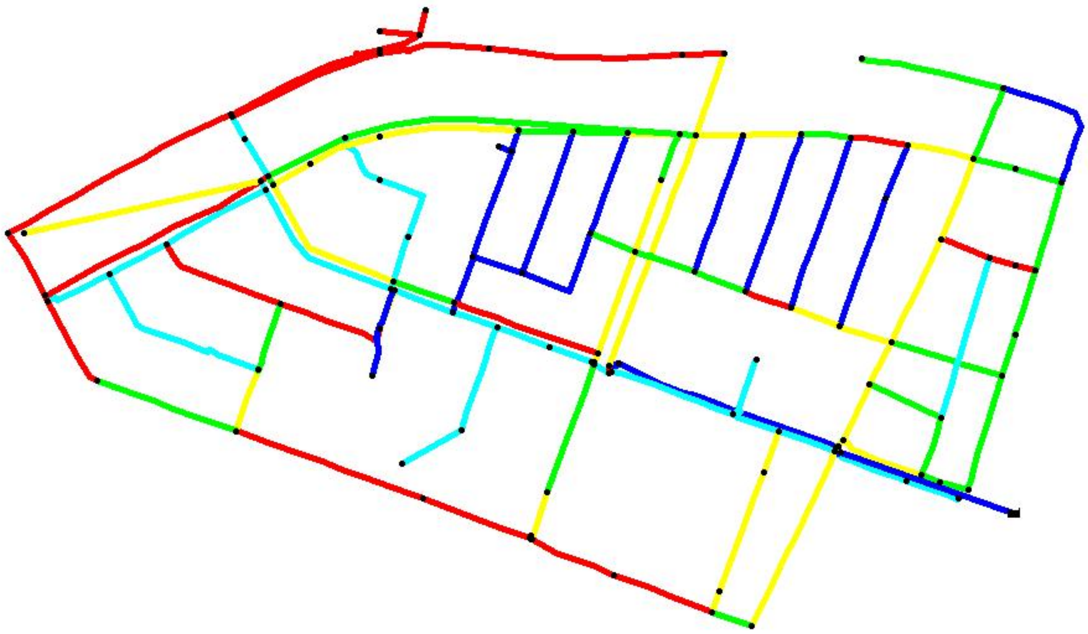

Fig. 4-4-1 Replacement in order of aged pipeline (Scenario A)

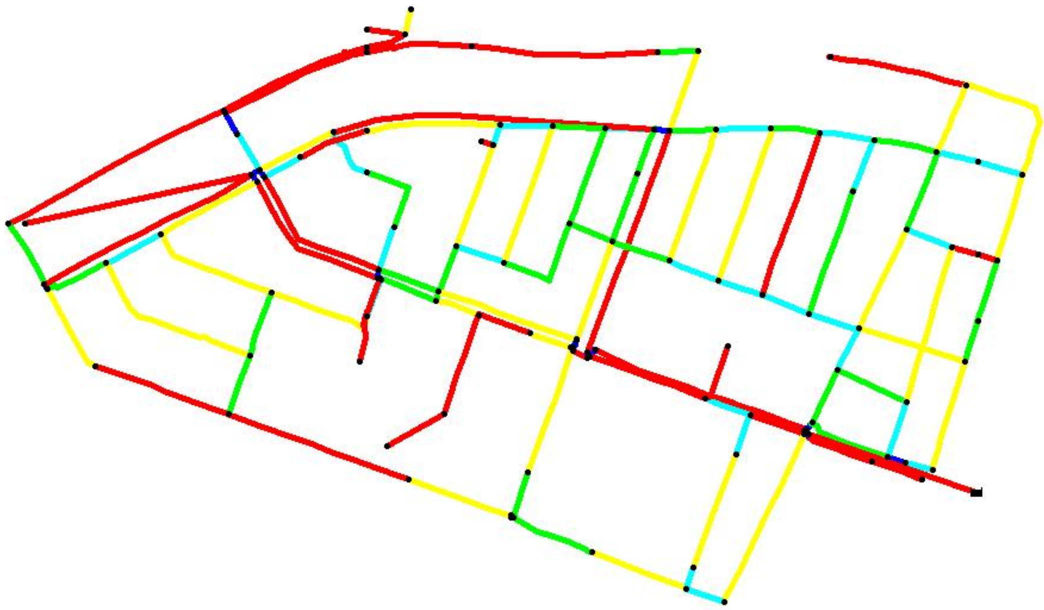

Fig. 4-4-2 Replacement in order of PRI (Scenario B)

Table 4-4-1 Grade standard of replacement order

Group	Rank of pipeline	Group color	In order of aged pipelines (Scenario A)		In order of PRI (Scenario B)	
			Average of diameter (mm)	Average of age (year)	Average of Diameter (mm)	Average of age (year)
1st replacement	1 - 30	Red	108	25	135	20
2nd replacement	31 - 60	Yellow	80	24	107	21
3rd replacement	61 - 90	Green	84	22	104	21
4th replacement	91 - 120	Sky blue	149	17	93	22
5th replacement	121 - 142	Blue	148	12	124	19

In addition, this study was used to Monte Carlo simulation (MCS). Because pipeline accidents occur at unspecified times and places randomly, MCS need to describe approximates solution such as pipeline damages. The present study assumed that pipeline damages occur when pipelines reach the failure time given by **Equation 3-2-6** before and after the replacement timing. To calculate the pipeline damages utilizing MCS, the present study assumed that pipeline damages occur when pipelines reach the failure time, and the pipelines will damage. In this study MCS ran at 1000 iteration times. 1000 iterations were empirically found to be sufficient in this study. The study period was set to 12 terms over 60 years (1 term = 5 years), and MCS was conducted for scenarios A, B, and C. As mentioned before, the study set the rate of annual replacement at 4%, the replacement period from 3 terms to 7 terms for 25 years, which was expected in the balance of all small blocks. From the MCS, the expected value of pipeline damages for each term in each case was obtained. Following this, the restoration time, the amount of water shortage, and the PRI were calculated and compared over the entire simulation term for all three cases.

As the results, **Fig. 4-4-3** shows the accumulated number of pipeline damages for each scenario. In the case of scenario C, the line sharply rises as the time lapses along the terms, showing acceleration of the number of damages. On the other hand, the two other scenarios show a deceleration after 4 or 5 terms as a result of replacement. In other words, **Fig. 4-4-3** clearly demonstrate that, in the case of the network studied, reducing pipeline damages by replacement is effective after up to 50% of pipeline replacement has been attained. The effect is expected to be consistently maintained until the end of the period planned.

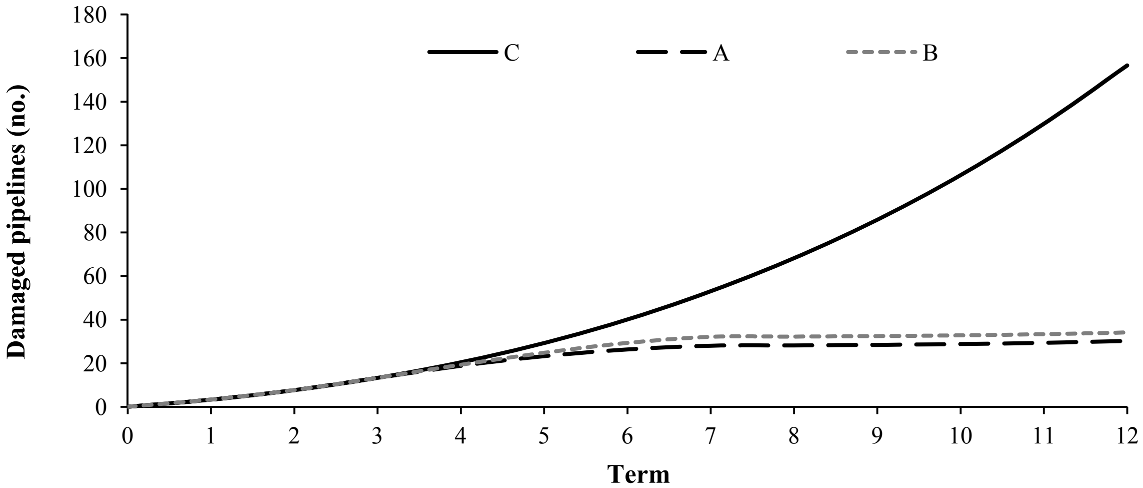

Fig. 4-4-3 The accumulated number of pipeline damages

To investigate the effect of replacement order in this study, a graph showing the accumulated PRI was drawn, as shown in **Fig. 4-4-4**. In the case of scenario C, the PRI also accelerated according as time lapsed along the terms. In scenario A, the line increases until the end of 6 terms and decelerates from the 7th term. However, in scenario B, the line decelerates after 3 terms. The effect of replacement order by PRI is clearly demonstrated by these results. When comparing the two graphs, there is a difference between scenarios A and B. From **Table 4-4-1**, we can see that in scenario A there is a tendency to replace pipelines from ones with small diameters, but in the case of scenario B it is the opposite, i.e. replacement would tend to begin from pipeline with large diameters. In this way, it is evident that PRI is more affected by diameter than pipeline age. In other words, if we consider the PRI for scenario B, replacement would not become effective until the end of 6 terms, while for scenario C we can expect to obtain stabilized effectiveness with very little water shortage volume after 3 terms.

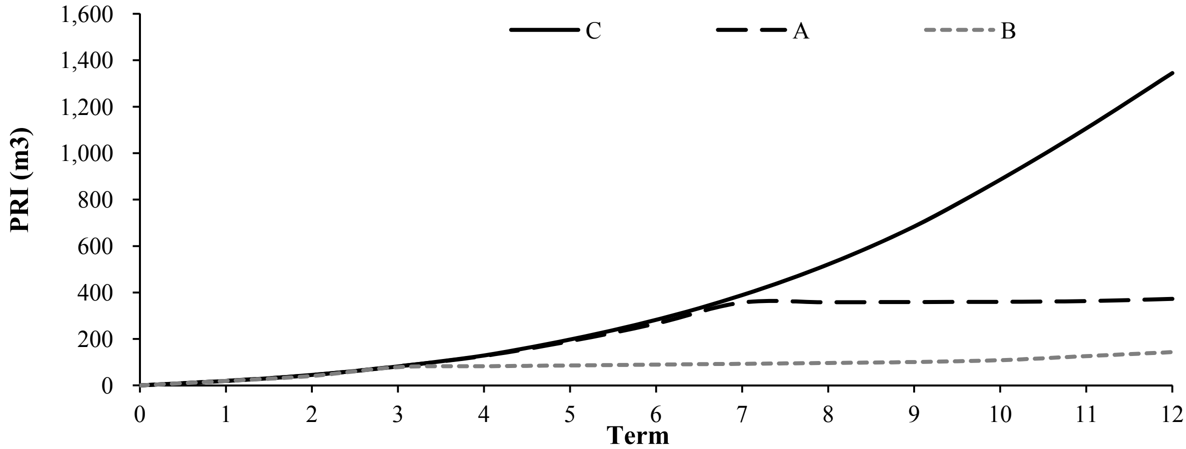

Fig. 4-4-4 Results of accumulated PRI

Finally, the numbers of pipeline damages, restoration time, water shortage volume, and PRI for each scenario are given in **Table 4-4-2** to show the effect of replacement. In the case of scenario B, the restoration time is a little longer than in scenario A, indicating that replacement in order of PRI can give us desirable alternatives for preventing the risks.

Table 4-4-2 Total of expected values

Scenario	Number of pipeline damages (number)	Restoration time (hr)	Water shortage volume (m^3/hr)	PRI (m^3)
A	30	218	41	372
B	34	238	16	143
C	157	1140	148	1345

4-5 Conclusions

This study attempts to analyze risks through three analyses. The first analysis is for predicting the number of pipeline damages to find out how many times the pipelines would be damaged in the future. The second analysis is for estimating the restoration time. It represents indirect disadvantages of pipeline damage accidents by pipeline repair time. The third analysis is for investigating the direct impact on consumers when a pipeline is intercepted at the damaged point. From these analyses, we were able to obtain the quantitative rank of risk in each analysis. As the risk ranking of each analysis is different, the overall risk ranking is necessary.

Consequently, this study introduced the predicted risk index (PRI) to estimate the overall risk ranking. The PRI becomes a quantitative impact ranking. In conclusion, the highest PRI eminently deserves the utmost priority for pipeline replacement. The PRI can propose for risk evaluation to provide sufficient guarantee of stable distribution service. As the results, we can obtain two conclusions as shown bellow.

1) 141 pipelines were assessed with a risk ranking from 1^{st} rank to 141^{st} rank. In conclusion, the pipeline with the 1^{st} risk ranking should be replaced first when establishing replacement plans.

2) In order to examine effect of replacement order based on PRI, three cases were set and compared each other. As the results, replacement in order of PRI prevents the risk compare with replacement in order of aged pipelines.

This study has proposed a risk prediction method for waterworks pipeline network management, and can be expected to be used to assist the decision-making when devising pipeline replacement plans, as well as in the maintenance and management of water distribution systems. Moreover unlike past researches, this study conducts to quantify the impact of pipeline accidents on water consumers. It helps waterworks set the specific replacement or maintenance plan. This study will be updated by a future study aimed at determining the replacement rank of 127 small blocks in the entire study area, which will consider the total cost (repair cost and replacement cost) and the benefit using PRI.

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Chapter 5 Conclusions

Nowadays, Korea is faced with pipeline deterioration and functional durability. If water leakage and accidents occur cause of deterioration and functional durability, it can cause not only cost loss but also social loss. So, in this research, a new approach was developed for pipeline replacement.

First, in the **Chapter 2** is proposed to evaluate present condition of water distribution pipeline. Especially, degree of external corrosion is regarded as representative pipeline condition. For this study, in-situ data obtained through test pit excavation and direct sampling are carefully collated and assessed. In order to evaluate indirectly, statistical approach is applied. Statistical approach is useful to predict severity of pipeline corrosion at present and in future. First, criteria functions defined by discriminant Function Analysis (DFA) are formulated to judge whether the pipelines are corroded seriously. Data utilized in the analyses are those related to soil property, i.e., soil resistivity, pH, moisture, and Chloride ion. Secondly, corrosion factors that significantly affect pipeline wall pitting (vertical) and spread (horizontal) on pipeline surface are identified with a view to quantifying a degree of the pipeline corrosion. Finally, a most reliable model represented in the form of a multiple regression equation is developed for this purpose.

As the results, influential parameters on external corrosion depth (Y_d) are soil resistivity (X_4), moisture (X_6) and pipeline age (X_3). It is also confirmed that the soil resistivity (X_4) and the pipeline diameter, among others, affect spread of general corrosion (Y_a). From all the above, it can be concluded that the multiple regression equation obtained herein provides valuable information on degree and rate of external pipeline corrosion in the target area. From these analyses, it can be concluded that our proposed model is effective to evaluate present pipeline condition.

Next in the **Chapter 3** is to propose long term plan for main distribution pipeline replacement using economic evaluation that utilizes a damage occurrence model. Especially, this study attempts long term replacement plan by efficiently allocating a budget for pipeline replacement. First, a simulation model is used to obtain the failure rate curve which uses reliability theory and data analysis for pipeline leakage accidents. And Monte Carlo simulation (MCS) is applied to the simulation model. Secondly, in order to set the best planning, several cases which are changed annual replacement rate are applied to this study. Finally, the simulation model applies to key pipelines. The key pipelines are vital pipelines located in central districts. Thus, the replacement of key pipelines is considered to be the priority.

Unlike other studies, this study considered not only the economy aspect but also the aspect of society impact. From these steps, annual 2.5% replacement rate is the most effective rate for damage prevention and maintenance of pipelines, in case of replacement of key pipelines, although the 10 -TBA scenario was the best in terms of economics, the 3-TBA scenario was the best in terms of the impact on society.

Finally, in the **Chapter 4** is to introduce efficient water distribution pipeline replacement plans considering risk prevention. Especially, this study attempts risk analysis utilizing three methods which are prediction of number of pipeline damages, restoration time and water shortage. When results of three risk analysis put together, the overall risk ranking had to be estimated by predicted risk index (PRI). In conclusion, the highest PRI was given the utmost priority for replacement.

From these analyses, pipelines were assessed with a risk ranking from first rank to last rank. In order to confirm replacement effects utilizing PRI order, three case studies which are changed replacement order are applied to MCS. As the results of MCS at each case, we can confirm effects of replacement in order of PRI. Thus, this study expected to assist decision-making in the pipeline replacement plans.

In this research is proposed effective replacement plan using 3 studies. This research will be upgrade by combining 3 studies, and apply to real water distribution system in order to prove usefulness.

Acknowledgement

I would like to express my deepest appreciation to all those who provided me the possibility to complete this dissertation. A special gratitude I give to my advisor, professor Inakazu who gave me suggestions and encouragement, helped me to coordinate my research. Without her guidance and persistent help this dissertation would not have been possible.

Furthermore I would also like to acknowledge with much appreciation the paper examiners, professor Koizumi, professor Arai and professor Kawamura who have been instrumental in the successful completion of this dissertation.

In addition, I would like to thank professor Koo, who was advisor professor when I was in the master's course. Without his support, this dissertation would not have been possible because he introduced me doctoral fellowship in Tokyo Metropolitan University. I shall never forget your kindness as long as I live. Specially, I would also like to thank to Foundation of Asian Human Network Databank for their financial support granted through doctoral fellowship.

I would like to thank members of our laboratory, professor Yamazaki, professor Kunizane and students for your kindness, friendship and support. Specially, I would like to thank Dr. Min, who as a senior, was always willing to help and give his best suggestions. It would have been a lonely lab without him.

The author wishes to thank my family. Above all things, I would like to thank my partner, Heejo, for her love, kindness and support she has shown during the past three years it has taken me to finalize this dissertation. I will be grateful forever for your love. And my darling daughters, Seohyeon and Seorin, I love you so much. Furthermore I would also like to thank my parents and brother for their endless love and support. I would also like to thank my father-in-law and mother-in-law for the word of encouragement.