THESIS

Study for Improving Water Distribution System Reliability

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In Partial Fulfillment of the Requirements
for the Degree of Master of Engineering
Graduate School, Korea University

Seoul, Korea
December 2007

碩 士 學 位 論 文

상수관망의 신뢰성 향상에 관한 연구

Study for Improving Water Distribution System Reliability

高麗大學敎 大學院

사회환경시스템공학과

金 晳 賢

2007年 12月

金 重 勳 教授指導

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金晳賢의 工學碩士 學位論文

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2007年 12月

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Abstract

New methods are presented to improve reliability of a water distribution system reasonably.

For the work, the Park's model(2006) is chosen as a tool to analyze systems and study improvements of system reliability. On the basis of the results from the analysis of the model, the methods improving the system reliability are summarized as follows. The first method is increasing durability of each pipe belonging to minimum cut sets. The second method is reforming a system by installing valves to reduce damage or unintended isolations. As results of the applications, the methods should be combined adequately to improve it effectively. To combine them, the following procedures are adopted.

The first procedure is to determine types of reinforcement(Type 1~3) for all pipes. Firstly, pipes in the "Type 1" do not need to be reinforced. Secondly, in the "Type 2", they are reinforced by increasing their durability. Finally, one or two valves are installed on pipes in the "Type 3" to isolate them.

As the second procedure, two rules are proposed which have their own purpose respectively. The "Rule 1" is focused on the reliability considering total construction cost. On the other hand, the "Rule 2" has a purpose of decreasing extent of damage by pipe failures. As a result, the "Rule 1" is more effective than the "Rule 2" to increase the system reliability while the "Rule 2" is more effective than the "Rule 1" to decrease the extent of damage. They should be applied to a system according to what the purpose is.

In conclusion, the methods can be guidelines on plans to improve the system reliability under restricted capability to maintain and manage systems.

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Chapter 1. Introduction

1.1. Background

A Water Distribution System (WDS) is one of social facilities to supply water for people living in cities or towns. It plays roles for transporting, distributing and supplying water and is a very complicated structure consisting of pipes, pumps, valves and so on. According to data from the Korea National Statistical Office in 2004, the total length of water pipes is 5,322km and 3,344km in the WDSs. It is nearly 63% of the whole system.

As clearly stated in the Korea Standards for Water Service Facilities, it should be constructed reasonably to supply water for people with proper quality and pressure as demands at nodes fluctuate with time and also reliably to minimize negative effects on water consumers when various accidents happen such as pipe failures.

In Korea, water supply through waterworks started in 1908. At the time, the diffusion rate was just 22% but had risen up to 91% in 2004 (Korea National Statistical Office). However, there have been zones having not enough water owing to concentration of population by industrialization. Moreover, suspension of water supply occurs frequently because of components failures resulting from deterioration of related infrastructures and other causes. Furthermore, the seriousness of the problems has been increasingly recognized because of other problems such as water pollutions. Hence, reasonable high degree of skills are strongly required to design and maintain WDSs.

The reliability of a WDS is a important index expressing what state it is in, it plays important roles for design, operation and setting up proper maintenance plans. Generally, WDSs are constructed widely on residential districts. Furthermore, water pipes are laid underground and used for a long time. Therefore, it is hard to maintain them and various accidents occur repeatedly.

From these facts, improving the reliability of a WDS seems to be a worthwhile subject to investigate. Moreover, premeditative renewals and improvements are essential to rise stability of water supply and Resonable design & maintenance plans are also requested to accomplish the goal of supplying sufficient water with proper pressure for people.

1.2. Objectives / Contents

The objective of this study is proposing methods to improve the system reliability reasonably.

The methods will be different according to models to assess the system reliability. So to speak, the validity of methods to improve the system reliability comes from the validity of models to estimate it so that it is important to choose a proper model.

Hence, in this study, the previous papers related with the system reliability are surveyed. Especially, the Park, J.I.'s model(2006) making up for weak points of the existing works is analysed in detail. On the basis of the results, the methods which can be used in practical affairs objectively are proposed. And then the methods are applied to actual networks and results are examined.

The contents and frameworks follow as.

In chapter 1, Introduction, background and objective of this study are presented.

In chapter 2, Literature review, the previous papers are surveyed. Furthermore, the chosen model established by Park, J.I.(2006) is analysed considerably to suggest directions to improve the system reliability.

In chapter 3, Plans to improve system reliability, theoretical plans are suggested from the results of analysis of the model. On the basis of the plans, defects of the model are considered to propose rules which can be used in practical affairs objectively. The rules are divided into two types according to purposes of reinforcement; improvement of system reliability or decrease of damage.

In chapter 4, Applications, the rules suggested in chapter3 are applied to two actual networks. Furthermore, the results are analysed and compared.

In chapter 5, Summary and conclusions, the whole contents and follow-up researches are stated briefly.

Chapter 2. Literature review

2.1. Trend of study

The previous papers related with this study are largely divided into three parts : 1) How to define the system reliability, 2) How to assess it, 3) How to improve it.

2.1.1. Definitions of system reliability

Mays(1996) classified system reliability by mechanical reliability and hydraulic reliability. Of these, the mechanical reliability is the ability of distribution system components to provide continuing and long term operation without the need for frequent repairs, modifications, or replacement of components or sub-components. The hydraulic reliability is defined as the probability of satisfying nodal demands and pressure heads. The system reliability is ensured when the two kinds of reliability are satisfied simultaneously and they should be considered to assess the system reliability practically.

If a WDS supplies water for people stably, it can be said that the system reliability is ensured, but it is a very complex structure consisting of various components which do not have 100% reliability respectively. Furthermore, it has possibility of danger resulting from causes like superannuated facilities, increased demands owing to population explosion and so on.

The main reason inducing abnormal conditions in a WDS is failures of one or more components having different reliability respectively. Mays(1996) largely divided failures causing abnormal conditions into mechanical failure and hydraulic failure. The mechanical failure considers system failures owing to pipe breakages, pump failure, power outages, control valve failures and so on. The hydraulic failure considers system failures because of demands and pressure heads being exceeded that could be a result of changes in demand and pressure head, inadequate pipe size, old pipes with varying roughness, insufficient pumping capacity, and insufficient storage capacity. Namely, the reliability is defined as the probability that the given demand nodes in the system receive sufficient supply with satisfactory pressure head.

Lansey et al.(1989) and Bouchart et at.(1991) considered variations of demand at nodes with time in addition to the mechanical and hydraulic failure, and Xu et al.(1999) defined it as demand variation failures. Cullinane(1989) estimated the system reliability by combining mechanical availability of components and hydraulic availability.

In this study, mechanical failures of pumps, water cleaning centers, sources of water supply are not considered because those failures do not occur frequently and when they fail, it causes a break down of the whole system. Instead of them, the range of this study is limited to pipe failures which occur more frequently in substance.

2.1.2. Methods to assess system reliability

Until now, there have been works related with the system reliability but there are not methods be accepted and used generally. Ostfeld (2004) divided them into three types: connectivity / topological reliability, hydraulic reliability and entropy.

In this chapter, they are categorized into three types similar to Ostfeld (2004): (1) connectivity / topological reliability, (2) hydraulic reliability, (3) others.

1) Connectivity / topological reliability

The connectivity / topological reliability refers to measures associated with the probability that a given network remains physically connected.

Asgarpoor and Singh(1992), Ramirez et al.(2006) mentioned that all components in a system have n states. Besides, conditions of nodes and the system can be determined according to conditions of components. Namely, if the components have N states and the number of components is M, the number of states of the system will be N^M, but it is impossible to consider all of them for a large network. When the states are simplified to 2, normal or abnormal, the number of states is reduced to 2^M. Thus, some cases of them will not cause abnormal conditions. Hence, the number of states causing abnormal conditions will be X less than 2^M.

State enumeration method can be used to assess the system reliability for a small network, but it requires too much labor and time for a large network. the following procedures are usually applied to assess the topological reliability. (Quimpo, R.G and Shamsi, U.M, 1991)

(1) State enumeration method - the method finds all possible combinations of the states of the components. A network of n binary components therefor as 2^n states.
(2) Network reduction method - the method divides the network into smaller units of series and parallel networks.
(3) Path enumeration technique - it computes reliability from the set of all operative paths between the node pairs of the network.

The basic principle behind each of these methods is to transform the topology of the system into a structure that consists only of series or parallel components or paths.

The path enumeration method involves generating a set of probabilistic events of which the union yields the node-pair reliability. If the events are disjoint, the sum of their probabilities gives the required reliability. If they are not disjoint, they must first be converted into disjoint events. This can be done through any of several techniques. Combinatorial methods, fault tree analysis, minimal path set or minimum cut set analysis may be used. Nearly all methods suggest that before analysis by an enumerative method, series parallel reduction should first be applied to the network. The enumerative algorithm may then be used to analyze the reduced network.

For a water distribution network, although the disconnection of the arcs appears complex, it can be shown that the network can be decomposed into elementary blocks of components for which the reliability may be determined individually and be used subsequently to calculate the reliability of whole system or components. The simplest block, of cause, consists of just a single arc or components. For reliability analysis as well as for system simplification, it is useful to consider special arrangements include components that are connected in series, in parallel, in mixed series-parallel, and in bridge or tree configurations.

A block consisting of k components in series with reliability s_1, s_2, ...,s_k will have a block reliability.

$$S_B = \prod_{i=1}^{k} s_i \qquad \text{<1-1>}$$

Thus, a block with the same n components in parallel will have a block reliability.

$$S_B = 1 - \prod_{i=1}^{k} (1 - s_i) \qquad \text{<1-2>}$$

The reliability of a component can be calculated by using hazard functions. After calculating the reliability of each block, we will find that the blocks themselves may be connected in series or parallel. A string of blocks in series may again be represented by still another block with a reliability equal to the product of reliability of all the blocks in the string.

Many researchers have endeavored to develop methods to reduce calculations reasonably and apply them to practical affairs.

Tung(1985) introduced six techniques, event tree method, cut set method, tie set method, conditional probability method and fault tree method, to calculate the system reliability and applied the techniques to a simple network. As a result, Tung concluded that the cut set method is the most effective for evaluating the system reliability.

Shamsi et al.(1990), Quimpo and Shamsi(1991) evaluated water distribution network reliability by using minimum cut sets. Jacobs(1991) suggested a method to reduce calculations. Historical data about leakages in a city was used to determine the maximum number of failures during a specific time interval. The extent of damage is only limited to the broken pipe.

Goulter et al.(1986) suggested a method to evaluate probability that a node is isolated from a source. The value is evaluated by calculating probability of simultaneous failure of pipes connected to the node. But it is hard for the method to be applied to real networks because all pipes connected to the node have similar diameter. And it has little theoretical foundation on the assumption that water is supplied to the node properly when any one of them is operational,

Wagner et al.(1988a) suggested a analytical method to calculate rechability and connectivity. the rechability of a specified demand node denotes the situation in which this node is connected to at least one source. The connectivity denotes the situation in which every demand node in the network is connected to at least one source. Since any one node will be connected whenever the entire system is connected, it is obvious that the reachability for any node will always be greater than or equal to the connectivity for the network as a whole. But measures of connectivity and reachability are fairly easy to calculate only for moderately sized, complex system. Namely, it is very hard to apply it to large networks.

Goulter et al.(1990) defined the system reliability as the probability that any failure does not occur in a system. Node failure means that the node is isolated from a source or demand is not fully supplied to the node. That is to say, probability that the node is operative is product of probability it is not isolated and probability that it receives water normally.

Shamsi et al.(1990), Quimpo and Shamsi(1991) used minimal path sets and minimal cut sets to evaluate Node Pair Reliability(NPR) : probability that two nodes are connected mutually.

Kansal et al.(1995) suggested the Appended Spanning Tree (AST) algorithm to calculate connectivity of the whole system. The algorithm is used to get Spanning Trees which are exclusive mutually If they are exclusive, availability of the system is product of availability of each Spanning Tree. But this method was not applied to large networks consisting of many components.

Yang et al.(1996a) proposed a reliability analysis method. The method focuses on source-demand connectivity, which is used as a measure of the mechanical reliability of a network. The mechanical reliability index is computed using the minimum cut set method. The identification of minimum cut sets consists of four stages: (1) For source-demand pair; (2) for individual demand nodes; (3) for a group of demand nodes; and (4) for all demand nodes in the system. By using the multiple-stage approach, the total number of simulations required in the analysis is greatly reduced. But this method also limits the extent of damage to the broken pipe.

2) Hydraulic reliability

The hydraulic reliability is defined as the probability of supplying water for people with proper nodal demands and pressure heads.

In many previous papers, hydraulic simulations were used for estimating hydraulic variability resulting from topological changes or capacity losses of a system by eliminating components be assumed to failure conditions. In other words, through hydraulic simulations, it is estimated that how enough the system can supply water for people under various conditions. The results are used as standards to decide whether it is a minimum cut set or not and also used for assessing the system reliability directly.

Cullinane et al.(1986) suggested a step function to determine hydraulic availability. When pressure at a node is more than the pressure criteria, hydraulic availability is 1, otherwise, 0. Through the function, nodal availability of each node in a system is calculated over the whole time. The hydraulic availability of the system is the arithmetical mean of them.

Su et al.(1987) defined the system reliability as the probability of satisfying nodal demands and pressure heads for various possible pipe failures in a water distribution system and suggested a method being based on the minimum cut set method to estimate the system reliability. A minimum cut set is a set of system components which, when failed, causes failure of the system(low pressure). To determine the minimum cut sets, hydraulic simulations are performed with elimination of one or more pipes which are assumed to failure conditions. If pressure at any node falls below the pressure criterion, the combination of pipes is regarded as a minimum cut set.

Bao and Mays(1990) defined hydraulic reliability as the probability that the system can provide the demanded flowrate at the required pressure head and suggested a method to estimate the nodal and system hydraulic reliability considering uncertainties of water demands, required pressure heads, and pipe roughness. The framework of the method is based on a Monte Carlo simulation consisting of random number generation, hydraulic network simulation, and computation of reliability.

Cullinane et al.(1989) suggested a continuous hydraulic availability relationship which more realistically models minimum pressure requirements for water distribution systems.

Fujiwara et al.(1993) defined the system reliability as the complement of the ratio of the expected minimum total shortfall in flow to the total demand, and the maximum total flow supplied under a link failure is computed by a network flow analysis.

Yang et al.(1996b) applied a stochastic simulation method to evaluate impacts of components failures on meeting demand at a certain quantity level. Simulation is conducted in a manner such that a sampling experiment of the system performance is repeated a sufficient number of times and the results are analysed to obtain the desired reliability index. Given the mean time to failure and repair time of links, a large number of synthetic system conditions are generated and operations of system under the different conditions are simulated.

Khomsi et al.(1996) presented a computer model to evaluate the system reliability. Both mechanical failure and hydraulic failure are incorporated into a simple stochastic model. A network solver identifies nodal pressure for individual pipe failure conditions over a range of network demands, where both pipe failure and network demands are of known probabilities. The probabilities of pressure deficiency at nodes are calculated, from which the availability of supply is determined.

Guercio et al.(1997) suggested a technique that supplies a linear programming algorithm to optimal design constrained by reliability. It made up for a weak point that the large computer time for reliability-optimization restricts its practical use for design. It only considers failures of single pipe to determine minimum cut sets of the system and nodes.

Xu et al.(1999) suggested a approach being capable of recognizing the uncertainty in nodal demands and pipe capacity as well as the effects of mechanical failure of system components and defined capacity reliability as the probability that the nodal demand is met at or over the prescribed minimum pressure for a fixed network configuration under random nodal demands and random pipe roughness.

Shin, H.G. et al.(1999) suggested a new concept, hydraulic connectivity. It is the probability that every demand node in the network is connected to at least one source with proper pressure and flowrate.

Gargano et al.(2000) presented a methodology which is based on the statistical analysis of dimensionless performance indices(hydraulic performance indices) derived from a large number of simulations of various demand scenarios and operation conditions. The hydraulic performance index is assumed to the probability that, under a given operation condition, the hydraulic performance index will be above a certain threshold. Finally, the system's overall reliability considering mechanical and hydraulic reliability is estimated using the overall reliability index which is defined as the weighted mean of the hydraulic performance indices obtained for the various operating conditions.

Shinstine et al.(2002) defined reliability as the probability of satisfying nodal demands and pressure heads for various possible pipe failures in the water distribution system at any given time and evaluated it by using the minimum cut set method. But this method also has disadvantages that the extent of damage is only limited to the broken pipe like others and failure mode approach being based on the assumption that minimum cut sets are exclusive mutually is used.

Xu et al.(2003) defined the capacity reliability as the probability that the nodal demand is met at or over the prescribed minimum pressure for a fixed network configuration and suggested two algorithms for estimating the capacity reliability of ageing water distribution systems recognizing the uncertainties in nodal demands and the pipe capacity.

Park, J.H. et al.(2003) suggested a synthetic model to evaluate hydraulic and mechanical reliability at once. The hydraulic reliability is calculated through Monte Carlo simulations by generating nodal heads, demands and roughness of each pipe randomly. The mechanical reliability is calculated by doing the steady state analysis for sequential failures of components in the system. Nodal heads from the analysis are used to evaluate the reliability. But the extent of damage is only limited to the broken component.

Al-Zahrani et al.(2004) suggested a method to calculate nodal and system reliability of a water distribution system by considering the nodal demand and pipe roughness as stochastic values. First, steady state hydraulic simulations are performed to determine nodal pressures. Second, nodal and system reliability are calculated using the minimum cut set method with pipe failure probabilities which are determined on the basis of Generic Expectation Functions such as triangular, gamma, exponential and normal distributions. The complete failure probability is product of the failure probability and the pipe replacement probability. To determine minimum cut sets, hydraulic simulations are performed with elimination of one or more pipes which are assumed to failure conditions. If pressure at any node falls below the pressure criterion, the pipes are regarded as a minimum cut set. But this method also regards the extent of damage as the broken pipe and the failure mode approach is used.

Jun, H.D.(2005) suggested a method for estimating practical extent of damage owing to pipe failures by combining the concept of "segment" suggested by Walski(1993) and the new concept of "unintended isolation". Through the method, the extent of damage can be extended to suspension of water supply including low nodal heads at any node. Thus, the reliability of a system is indirectly estimated from the number of customers out of service by a statistical failure analysis.

Park, J.I.(2006) suggested a method based on the practical extent of damage suggested by Jun(2005) to determine minimum cut sets of a system. A minimum cut set is a set of system components which, when failed, causes low nodal heads or suspension of water supply. Thus, the system reliability is calculated by using the "success mode approach".

Baek, C.W.(2007) developed the HSPDA(Harmony Search PDA) model making up for weak points of existing PDA(Pressure Driven Analysis) models to do the hydraulic simulations under abnormal conditions and suggested a new reliability assessment method, RDDM(Reliability using Distance Measure Method) which is considering both nodal heads and demands simultaneously.

3) Others

Almost previous works mainly consider the probability that the system can provide the demanded flowrate at the required pressure head. But Ostfeld (2002) suggested a stochastic simulation considering quality of water. It is used to do the reliability analysis of single and MWDS (Multi-quality Water Distribution Systems). MWDS refer to systems in which waters of different qualities are taken from sources, possibly treated, mixed in the system, and supplies as a blend.

2.1.3. Works for improving system reliability

In the previous works, methods to improve the system reliability are categorized as follows. The first method is minimizing probability of failure or headloss by increasing durability or faculty of each component. The second method is to reduce extent of damage owing to failures of components by installing isolation valves or constructing alternative paths. Finally, the third method is ensuring hydraulic reliability by increasing pump capacity or determining pump operation rules.

Su et al.(1987) only considered failure probability of each pipe in the optimization model. Using failure data obtained from the City of St. Louis, a regression equation was obtained to calculate a parameter to compute reliability of a pipe. The model is used to determine the optimal combination of pipes subject to continuity, conservation of energy, nodal head bounds, and reliability constraints.

Duan(1990) developed a reliability-based optimization model for water-distribution systems. Goals of the model are as follows. (1) Design of the pipe network including the number, locations, and size of pumps and tanks; (2) Design of the pumping system using a reliability-based procedure considering both hydraulic failures of the entire network and mechanical failure of the pumping system; and (3) Determination of the optimal operation of the pumps.

Bouchart(1991) suggested two methods to improve system reliability. The first method is increasing the design demand at nodes so that the probability of actual demand's exceeding the design value is reduced. The second method is adding isolation valves to reduce the length of pipe which has to be isolated in order to repair the broken pipe.

Gupta(1996) presented a heuristic approach for reliability based design of water distribution systems. The approach is iterative, considers pump and pipe failures only, and is based on the trade-off between reliability and cost of the water distribution systems. An initial water distribution system is selected and the ratio of marginal increase in reliability to marginal increase in cost (MIRMIC ratio) for each pipe by changing its size to next higher one is evaluated. Pipes with large MIRMIC ratios are selected for change to next higher size and the iterative procedure is continued until a water distribution system of desired reliability is obtained.

Kim, S.W. and Kwon, J.S. (1997) estimated the system reliability by using a dynamic reliability model for various types of connection; series, parallel, series-parallel. A method to improve system reliability was also presented. In the method, pipes having high sensitiveness ,which is defined as the ratio of variation in the system reliability to variation in reliability of a pipe, are reinforced preferentially.

Dandy and Engelhardt(2006) demonstrated the use of genetic algorithm to generate trade-off curves between cost and reliability for pipe replacement decision.

Jun, H.D. et al.(2007) proved the importance of adequate valve locations for reducing size of damage by pipe failures. It was done by analyzing how valve locations have influence on the system reliability and damage.

2.2. Model selection and analysis

Improving system reliability means eliminating or decreasing expected reasons causing abnormal conditions in a water distribution system. The validity of methods to improve the system reliability comes from the validity of models to estimate it. So, selecting a proper model for improving system reliability should be the first.

As stated in chapter 2.1, many works have a blind point which does not consider suspension of water supply occurring frequently because the extent of damage is only limited to the broken pipe. In the papers, hydraulic simulations were used for estimating hydraulic variability according to topological changes or capacity loss. In other words, through hydraulic simulations, it is estimated that how enough the system can supply water under various conditions.

Park, J.I.(2006) developed a model making up for weak points of the previous works. The model can estimate the system reliability more precisely and effectively. Characteristics of the model are as follows: (1) The model introduces the method suggested by Jun(2005) to determine the practical extent of damage owing to pipe failures. (2) It determines minimum cut sets on the basis of the estimated extent of damage. (3) The system reliability is estimated by using the "success mode approach".

The reasons why the model is chosen to study methods for improving system reliability are as follows. (1) The method suggested by Jun(2005) to determine the practical extent of damage owing to pipe failures is used. (2) Calculation errors are minimized by using the "success mode approach". (3) The model is applicable to large networks.

In this chapter, on the basis of the analysis of the model, theoretical methods to improve system reliability are suggested.

2.2.1. Practical extent of damage owing to pipe failures

In many previous papers, the extent of damage is only limited to the broken pipe, while Jun, H.D(2005) suggested a method for estimating the practical extent of damage by combining the concept of "segment" suggested by Walski(1993) and the new concept of "unintended isolation".

1) Segment

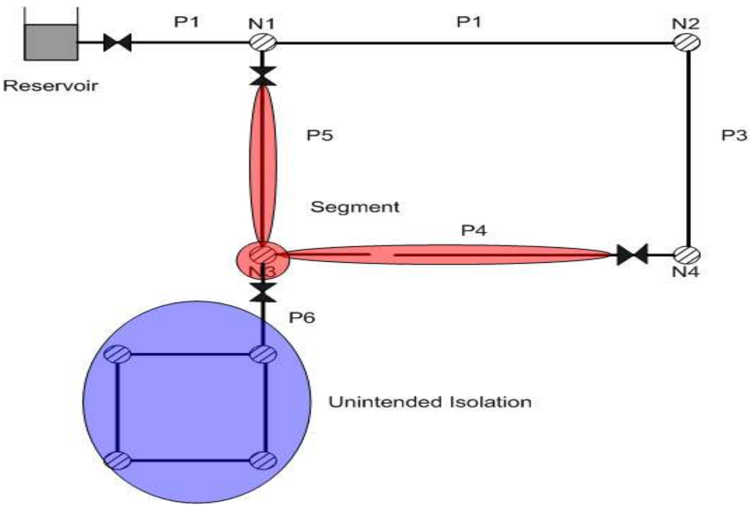
Walski(1993) defined a segment as the portion of network that should be isolated by adjacent isolation valves to conduct repairs on a pipe. Namely, when a pipe is broken, the adjacent pipes to the broken pipe may need to be closed as well to repair the broken pipe. The pipes and nodes isolated by valves are defined as a segment.

<Fig. 2-1> shows a segment associated with pipes of the network. When pipe P4 fails, the segment made up of pipe P5, P4 and node N3 must be closed to conduct repairs on P4. As a result of the failure of pipe P4, water supply is cut off on node N4.

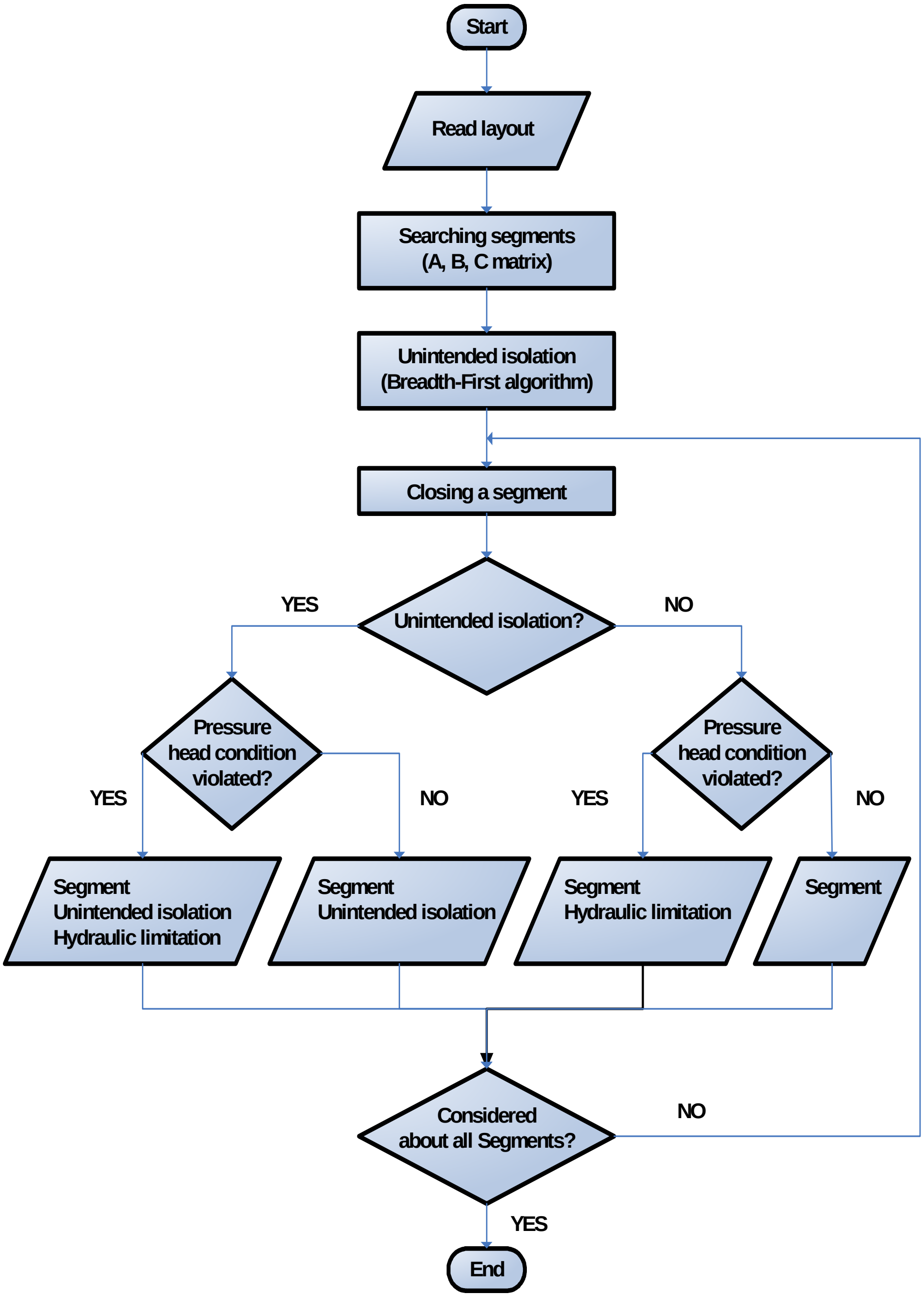
2) Unintended isolation

When a pipe is broken, in addition to the segment that is intentionally isolated to conduct repairs, there may be other parts of the network that become disconnected from the sources depending on the network topology. Jun(2005) defined that kind of isolation as the "unintended isolation". There are two kinds of unintended isolation. First, there may be a section surrounded by a segment, i.e., the end nodes of an unintended section are within a segment or are connected to pipes within a segment. Second, usually it may occur in a branched distribution system that a segment may be the only path from the water source to the unintended section so that if the segment is isolated, there is no path to provide water to the section. To find the unintended isolation, Jun developed the updated Bredth first search algorithm by working up Bredth first search algorithm suggested by Dossey et al.(1998). It is based on matrices of a network named as A, B, C matrix respectively.<Fig. 2-2>

When a unintended isolation happens, consumers in the section are not able to receive water from the source until repairs are completed. As shown in <Fig. 2-1>, the segment consisting of P4, P5 and N4 causes a unintended isolation.



<Fig. 2-1> Segment and unintended isolation



<Fig. 2-2> Flow chart to estimate extent of damage (Park, 2006)

2.2.2. Fault Tree Analysis (FTA)

Minimum cut sets come from a fault tree which display the relationship between a potential event affecting system performance and the reasons or components of the system, environmental conditions, and other factors. Minimum cut sets indicate dangerousness or safety of a system, It contributes to determine the most effective methods to improve the system reliability. So, understanding the fault tree analysis should be the first to know how to estimate the system reliability from minimum cut sets.

1) Definition of the Top Event

It is important that the TOP event be defined in a clear and unambiguous manner. The description of the TOP event should always answer the following questions:

What : Describes the critical event that is the focus of attention

Where : Describes where the critical event occurs

When : Describes when the critical event occurs

In this model, the TOP events are described as follows:

What : suspension of water supply, low pressure at any node

Where : Zones or nodes in the system

When : A pipe is broken

2) Fault Tree Construction

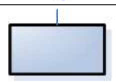
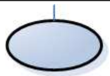
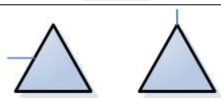
The fault tree analysis was firstly used by the Bell Telephone Laboratories in 1962 for estimating the safety of Minuteman missile launch.

The fault tree analysis is carried out by diagrams involving these two types of building blocks: gate symbols and events symbols. Theses are used in drawing the fault tree diagrams. <Table 2-1> and <Table 2-2> show the different gate symbols and event symbols used in fault tree analysis along with brief descriptions of each. Construction of a fault tree begins with the TOP event and proceeds downward to link to basic events through the use of different gates. Completion of the fault tree requires specification of the output of each gate, as determined by the input events to the gate.

<Table 2-1> Gate Symbols for fault tree analysis

	Gate Symbol	Gate Name	Casual Relation
1		AND gate	Output event occurs if all input events occur simultaneously.
2		OR gate	Output event occurs if any one of the input event occurs.
3		Inhibit gate	Input produces output when conditional event occurs.
4		Priority AND gate	Output event occurs if all input events occur in the order from left to right.
5		Exclusive OR gate	Output event occurs if one, but not both, of the input events occur.
6		m out of n gate (voting or sample gate)	Output event occurs if m out of n input events occur.

<Table 2-2> Event Symbols for fault tree analysis

	Event Symbol	Meaning of Symbols
1		Basic event with sufficient data
2		Undeveloped event
3		Event represented by gate
4		Conditional event used with inhibit gate
5		House event. Either occuring or not occuring
6		Transfer symbol

AND and OR gate are frequently used to construct a fault tree. Under the AND gate, output event occurs when all input events occur simultaneously. Output event occurs when any one of the input event occurs under OR gate. Others are detailedly stated in <Table 2-1>

In event symbols, the circle means a basic event which is not decomposable any more. Probability that a event happens, failure rate and repair rate of all basic events in a system should be known clearly to obtain a quantitative solution of fault tree. A lozenge is a undeveloped event. It means that reasons causing a event are not clear for want of information or data. Other symbols are stated in <Table 2-2>

The TOP event is the most important range criterion of a system. It is defined as the primary failure of the system. It is hard to select the TOP event adequately because it can exist as several cases in a system. Generally, it should be defined clearly so that probability that a event occurs must be quantifiable and decomposed into basic events to find reasons of the occurrence of the TOP event.

3) Qualitative analysis

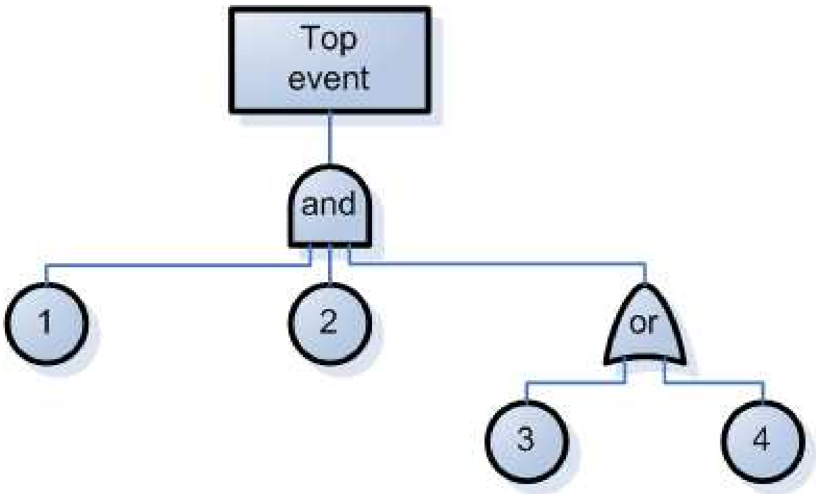
In a fault tree, sets are combinations of basic events and a cut set is a set of basic events whose simultaneous occurrence results in the occurrence of the TOP event. A cut set is said to be minimal if the set cannot be reduced without losing its status as a cut set. In other words, when a cut set contains another cut set, the TOP event can occur with only the contained cut set. So, the large cut set containing the small cut set can be excepted from the list of cut sets.

A path set is a dual set of cut set. So to speak, the TOP event does not occur if all event in the path set do not occur. Similar to the definition of minimum cut sets, a path set is said to be minimal if the set cannot be reduced without losing its status as a path set.

For example, let us consider the fault tree in <Fig.2-3>. the number of sets is 16: {ф}, {1}, {2}, {3}, {4}, {1, 2}, {1, 3}, {1, 4}, {2, 3}, {2, 4}, {3, 4}, {1, 2, 3}, {1, 2, 4}, {1, 3, 4}, {2, 3, 4}, {1, 2, 3, 4}. Of these, the number of cut sets is 3: {1, 2, 3}, {1, 2, 4}, {1, 2, 3, 4}. And {1, 2, 3, 4} can be excepted from minimum cut sets because it contains {1, 2, 3} and {1, 2, 4}. Finally, minimum cut sets are {1, 2, 3} and {1, 2, 4}.

Path sets are that the TOP event does not occur if all events in the set do not occur. The number of them is 13: {1}, {2}, {1, 2}, {1, 3}, {1, 4}, {2, 3}, {2, 4}, {3, 4}, {1, 2, 3}, {1, 2, 4}, {1, 3, 4}, {2, 3, 4}, {1, 2, 3, 4}. Of these, path sets not containing others are minimum path sets: {1}, {2}, {3, 4}. Namely, if event 1 does not occur, if event 2 does not occur and if event 3 and 4 do not occur, the TOP event does not occur.

By using the "MOCUS" algorithm, minimum cut sets(or minimum path sets) can be calculated from a fault tree. But the focus of this study is understanding the fault tree analysis generally so that detailed explanations are omitted.



<Fig. 2-3> Example of fault tree

4) Application to estimate the reliability of water distribution system

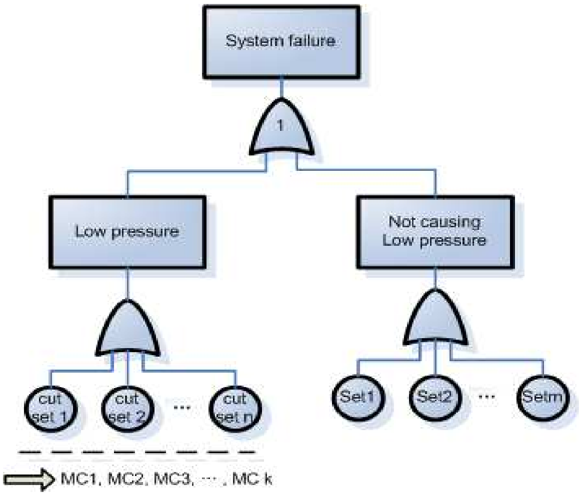
In a water distribution system, minimum cut sets are minimal sets of components whose simultaneous occurrence results in the occurrence of system failure. The important points are: (1) How to define failures of components. (2) How to perform simulations considering the failures (3) How to determine the TOP event.

<Table 2-3> shows differences among the previous models and the Park's model.

<Table 2-3> Comparison existing models with Park's model

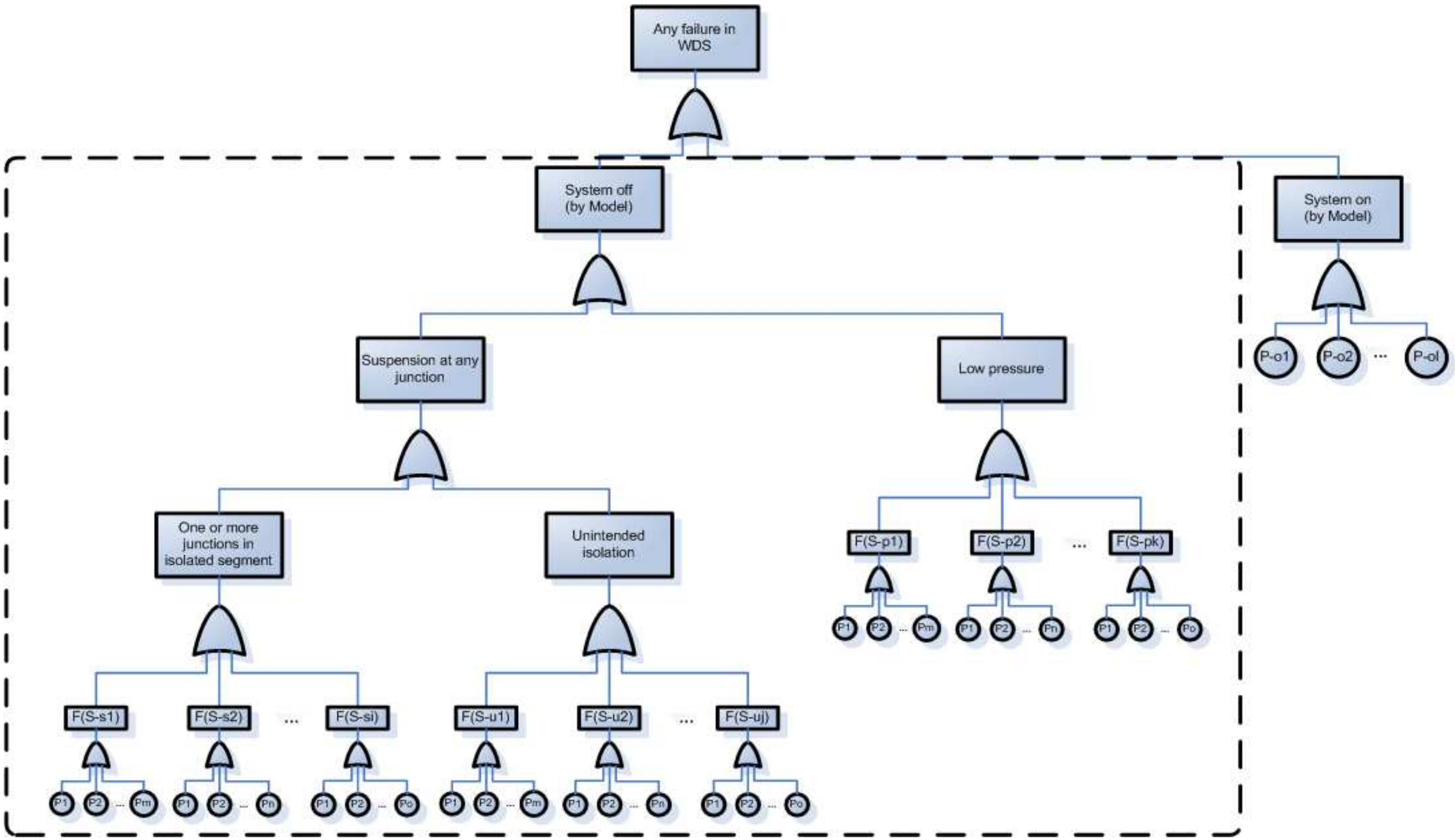
	Su et al.(1987), etc.	Park (2006)
Failure	Considering 2~3 pipe's failures limited to itself	Segment+untended isolation
Simulation model	KYPIPE, EPANET	EPANET
TOP events	Low pressure	Suspension, low pressure

The previous models only consider a simultaneous failure of 2~3 pipes in a water distribution system. Minimum cut sets are determined by the pressure criterion. So to speak, when a failure simulation is performed by eliminating components considered as failed, if pressure at any node in the system is lower than the pressure criterion, the set of components will be considered as a cut set. But it is a impractical assumption because, as already stated in chapter 2.2.1, the practical extent of damage according to a pipe failure is not the pipe itself but extended to a segment and a unintended isolation in some cases. Furthermore, it is hard to trust the results from the failure simulation to find whether nodes having low pressure are in the system or not. <Fig. 2-4> shows the fault tree of the previous models.



<Fig. 2-4> Fault tree of previous models

In the contrast with the previous models, the Park's model only limits pipes to destructible components on assumptions that the probability of simultaneous failures of two or more pipes is zero and the events are exclusive mutually. Reliability of each pipe is calculated by the equation suggested by Su et al.(1987). Thus, the method, suggested by Jun(2005) to determine the practical extent of damage owing to pipe failures, is used in the model. Through the method, the extent of damage owing to pipe failures can be extended to suspension of water supply as well as low nodal heads.



<Fig. 2-5> Fault tree of Park's model

In <Fig. 2-5>, the TOP event is defined as any failure in the system, but the part shown in dotted line is related with the model. Through hydraulic simulations using EPANET, minimum cut sets are determined by the following questions: When a pipe is broken, (1) are one or more nodes in the isolated segment? (2) Not case 1, does a unintended isolation happen? (3) Not case 1 and 2, is the pressure of any node in the system under the pressure criterion?

If any event among them happens, the model treats the situation as a abnormal condition regardless of size of damage. In this study, the abnormal condition is named as "system-off" and the contrary concept is named as "system-on".

In <Fig. 2-5>, P-si is the i_{th} pipe which, when failed, causes suspension of water supply and F(S-si) is a failure of the segment including the pipe. Be similar to this definition, P-uj is j_{th} pipe which, when failed, causes a unintended isolation and F(S-uj) means of a failure of the segment including the pipe. Next, P-pk is the k_{th} pipe which, when failed, causes suspension of water supply and F(S-pk) means of the failure of the segment including the pipe. Finally, P-ol out of the dotted line is the o_{th} pipe which does not cause any abnormal condition even if it is broken. Namely, they are not in minimum cut sets.

The important concept in the model is that the isolated segment including the broken pipe is not operational even if others are not broken. Namely, all pipes in the segment must be operational for the segment to be operational. In such meaning, all gates in the fault tree become OR gate. Thus, Park(2006) determined minimum cut sets by a segment but the basic event is a pipe failure so that minimum cut sets can be expressed as a failure of individual pipe.

Since all gates are OR gate, when applying the MOCUS algorithm, the minimum cut sets are {P-s1}, {P-s2}, ... ,{P-si}, {P-u1}, {P-u2}, ... ,{P-uj}, {P-p1}, {P-p2}, ... ,{P-pk}. On the other hand, the minimum path set is {P-s1, P-s2, ... ,P-si, P-u1, P-u2, ... ,P-uj, P-p1, P-p2, ... ,P-pk}. In a different expression, if any one of minimum cut sets is not broken - if all pipes in the minimum path set are operational, the system will be operational without any suspension of water supply, unintended isolation and node having low pressure.

It is possible to estimate the structural effects from failures of pipes by using the segment searching algorithm and the unintended isolation searching algorithm suggested by Jun(2005). EPANET interfaced with Visual Basic is used as a hydraulic simulation model. Detailed explanations about the algorithms are described in the reference.

5) Success mode approach

On the basis of the determined minimum cut sets, the system reliability can be estimated through the "success mode approach". The following equations, <2-1> and <2-2>, are used to calculate it.

$$r = \prod_{k=1}^{K} P\left(S_{C_k}\right) \qquad \text{<2-1>}$$

$$P\left(S_{C_k}\right) = \prod_{i=1}^{I} P\left(S_{P_i}\right) = P\left(S_{P_1} \cap S_{P_2} \cap S_{P_3} \cap \cdots \cap S_{P_I}\right) \qquad \text{<2-2>}$$

r = System reliability

S = Success probability

C_k = k_{th} segment defined as a minimum cut set

P_i = i_{th} pipe in C_k

Namely, the system reliability can be expressed as a product of reliability of each pipe which belongs to minimum cut sets.

Chapter 3. Plans for improving system reliability

On the basis of the results in the previous chapter, methods to improve the system reliability are summarized as follows. The first method is improving durability of each pipe belonging to minimum cut sets. Namely, in Eq. <2-1, 2>, if each S_{p_i} increases, the system reliability will be improved. The second method is reforming the system structurally by installing isolation valves to reduce damage or constructing alternative paths to control unintended isolations. Through the method, the number of S_{p_i} in the equations decreases and S_{p_i} is lower than 1 so that the system reliability is improved.

3.1. Improvement of system reliability through increase of pipe durability

In this chapter, reasonable plans for improving the system reliability are presented by analyzing whether durability of each pipe makes any influence on the system reliability or not.

3.1.1. Optimization using Genetic Algorithm

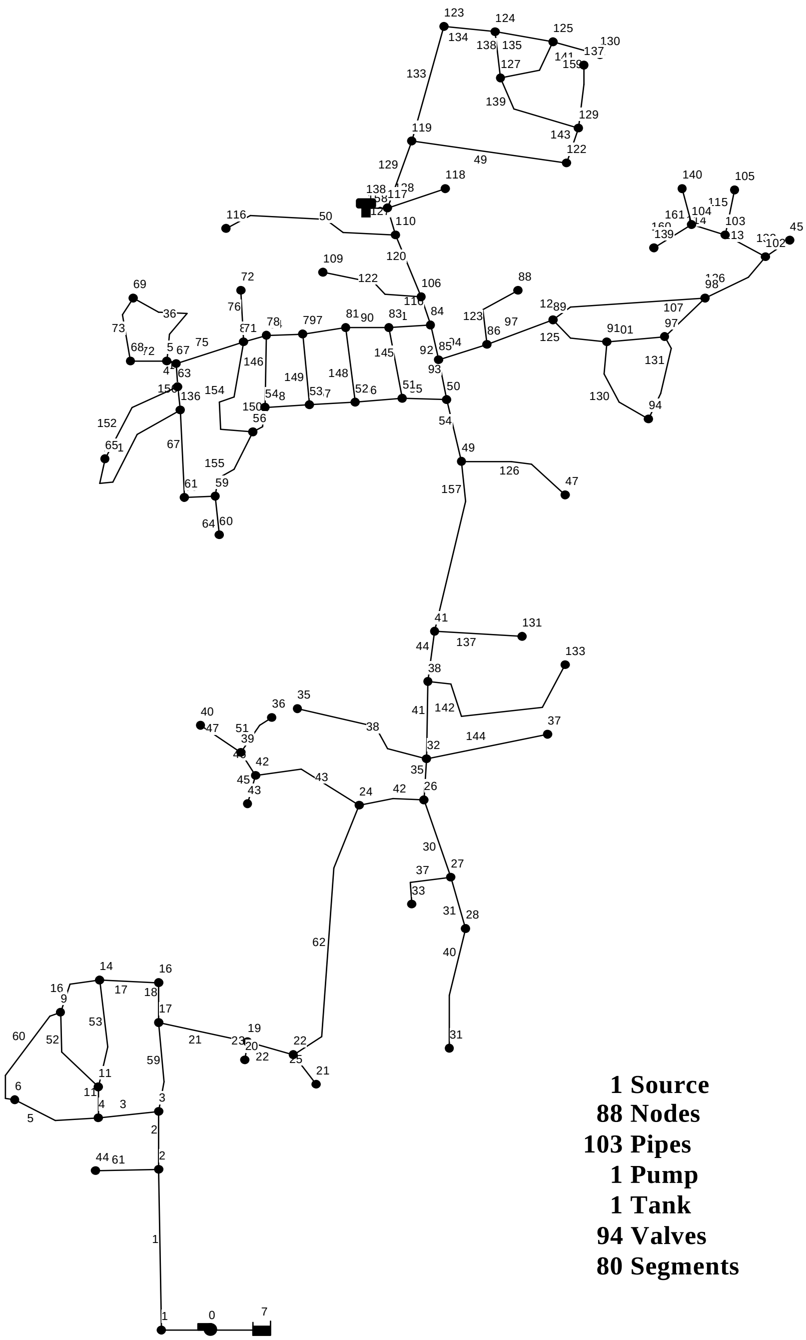
According to the previous works done by Park(2006) and Su et al.(1987), with the same conditions such as construction cost, the system reliability will be different depending on how to choose each pipe's diameter or valve locations and so on.

This study suggests methods to find the optimal combination of pipes to maximize the system reliability by the Genetic Algorithm and analyze effects of changing pipes by rising construction cost.

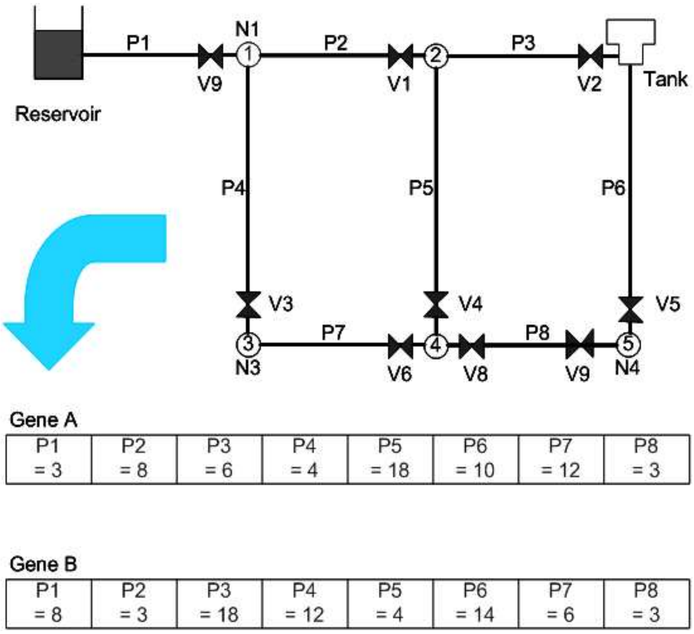
In this study, cost is a constraint and the objective function is maximizing the system reliability. The main purpose of this optimization is to know how increase of pipe durability effects on the system reliability. The study area is Cherry Hill in the state of Connecticut, USA. It consists of 90 nodes, 104 pipes (6, 8, 12 ″), 94 isolation valves and so on.

The reliability of each pipe is calculated by the regression equation suggested by Su et al.(1987) and failures of pipes are only considered in this problem because failures of other components, reservoirs, pumps, tanks, etc., will cause a break down of all or great part of the system and pipe failures are very common accidents in water distribution systems comparing with others in substance. That means reliability of each component except for pipes are assumed to 100%.

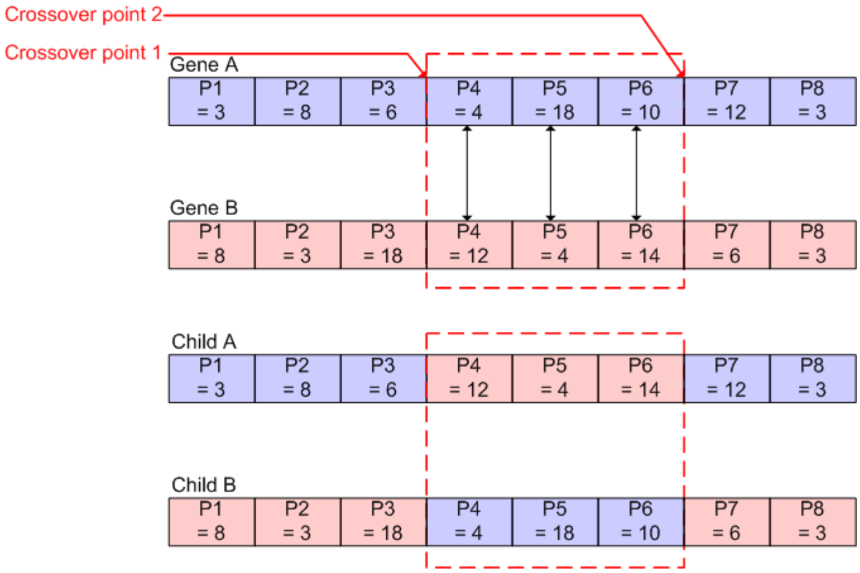
<Fig.5~8> show a procedure of the Genetic Algorithm, generating genes, two points crossover and mutation. three kinds of standardized commercial pipes are used in this study. The idea to do the crossover and mutation operation comes from the NOEXCS(Non-ordered, extended-set, combinational crossover) (Vitkovsky et al., 2003)



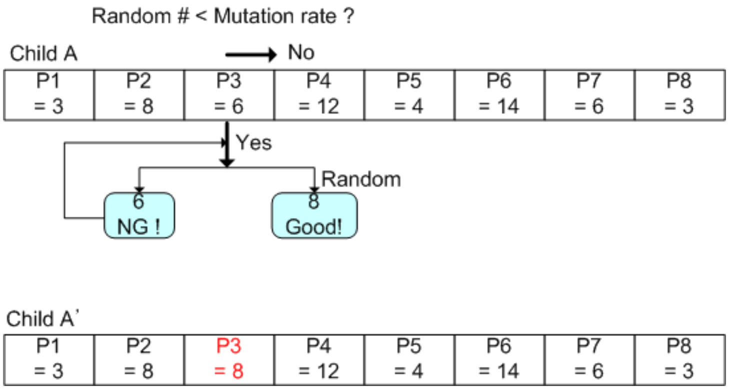
<Fig. 3-1> Cherry Hill network



<Fig. 3-2> Generating genes



<Fig. 3-3> 2 points crossover



<Fig. 3-4> Mutation

where PMS=30, crossover rate=0.75, mutation rate=0.01.

The cost to lay water-pipes underground is calculated by Eq.<3-1> and reliability of each pipe is estimated by the regression equations, <3-1~5>, using historical failure data obtained from the City of St. Louis.(Su et al., 1987). Thus, the existing pipes in the system consist of three kinds of pipes, 6, 8, 12″ and those pipes are also used in this optimization.

$$Cost(D,\ L) = \sum_{i,\ j} 1.1 \times D_{ij}^{1.24} \times L_{ij} \qquad \text{<3-1>}$$

$$\alpha_i = \frac{0.6858}{D_i^{3.26}} + \frac{2.7158}{D_i^{1.3131}} + \frac{2.7685}{D_i^{3.5792}} + 0.042 \qquad \text{<3-2>}$$

$$\beta_i = \alpha_i \times L_i \qquad \text{<3-3>}$$

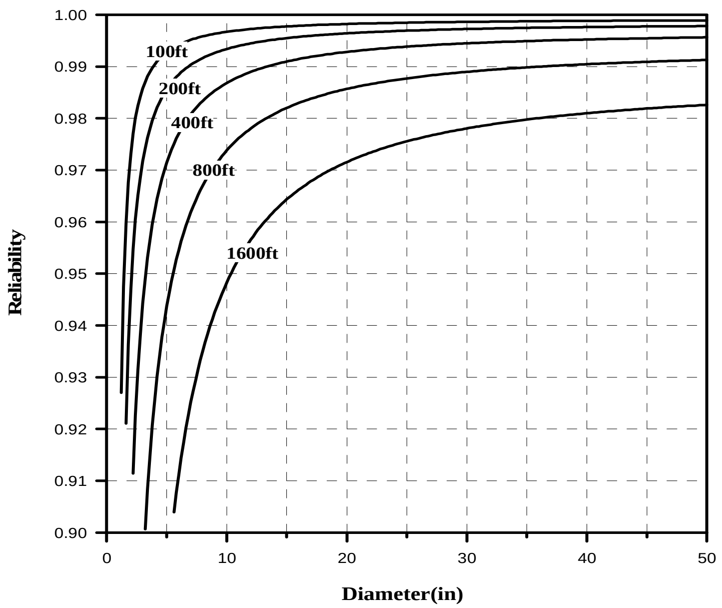
$$f_i = 1 - e^{-\beta_i} \qquad \text{<3-4>}$$

$$r_i = 1 - f_i \qquad \text{<3-5>}$$

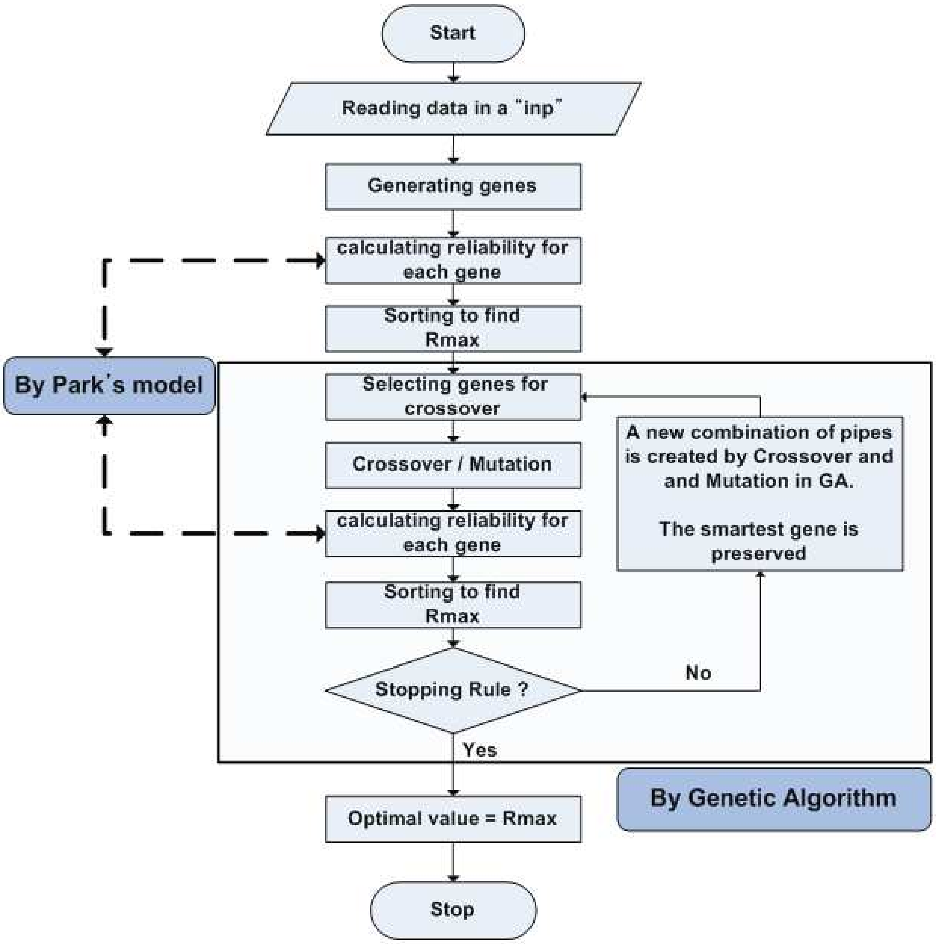
Where i =Pipe index, D =Pipe diameter(in), L =Pipe length(mile),

α =Breaks/mile/year, β =Breaks/year, f =Failure probability, r =Reliability.

This problem is closely related with interactions between cost and reliability. <Fig. 3-5> shows reliability of each pipe with diameter and length. According to the equation, pipe reliability increases in proportion to diameter and the exponent is just 1.24 so that cost increases almost linearly as diameter increases. The other side, pipe reliability increases or decreases greatly with diameter less than 10〃 but there is only small fluctuation relatively when diameter is more than 10〃. That is to say, the Genetic Algorithm finds the optimal solution to maximize the system reliability under limited cost through iterative interactions between cost and reliability. The system reliability is probability that the system is operational without any suspension of water supply, unintended isolation and node having low pressure. <Fig. 3-6> shows the flow chart of this problem.



<Fig. 3-5> Pipe reliability (Su et al., 1987)



<Fig. 3-6> Flow chart for optimization

1) Results

In this problem, the constraint of cost is assumed to the cost for laying pipes of the original system. The total cost is, estimated by Eq. <3-1>, $ 1,224,942.

After the optimization procedure, the system reliability has increased from 0.1373 to 0.1461 even if the cost has decreased a little. <Table 3-1~2> show differences between before and after.

<Table 3-1> Optimization results

	Cost ($)	Increase rate (%)	System Reliability
Original	1,224,942	0	0.1373
Optimized	1,218,033	-0.56	0.1461

<Table 3-2> Diameter changes

Pipe ID	Length (ft)	Diameter (inch) - Original	Diameter (inch) - Optimized
2	550	12	6
3	526	8	8
11	288	8	12
16	576	8	12
17	530	12	6
18	583	8	6
21	815	12	12
22	431	12	12
23	88	8	8
25	288	8	12
30	767	12	12
31	312	12	12
35	383	12	6
38	1438	8	8
41	743	12	12
44	479	12	8
54	600	12	8
55	420	8	8
56	420	8	6
57	420	8	12

<Table 3-2> Continued

Pipe ID	Length (ft)	Diameter (inch) - Original	Diameter (inch) - Optimized
58	420	8	12
64	360	8	12
65	364	8	8
67	838	8	12
71	240	12	6
72	300	12	8
73	623	12	12
75	647	12	8
76	479	12	8
83	216	12	6
84	375	8	6
87	375	8	12
90	375	8	12
91	375	8	12
92	300	12	12
93	400	12	6
94	240	12	12
97	623	12	12
101	527	8	12
107	527	8	8
113	407	8	6
114	312	8	12
115	455	8	6
116	264	12	6
120	647	12	12
127	240	12	12
128	551	8	8
129	671	12	12
133	1150	8	12
134	455	8	6
135	551	8	12
138	407	8	8
139	1007	8	12
141	431	8	6
143	335	8	12
145	700	6	6
146	700	8	6

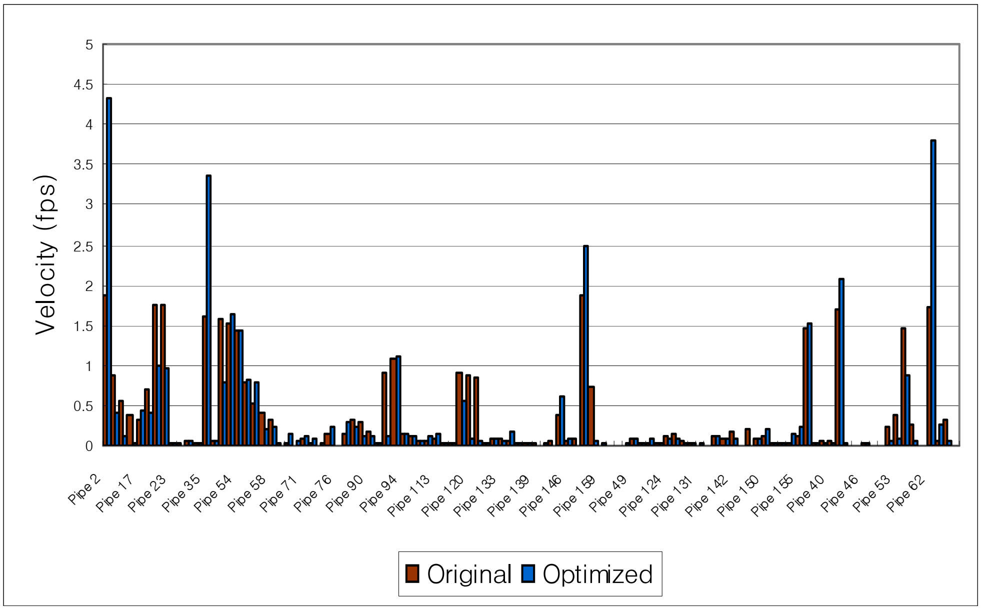
<Table 3-2> Continued

Pipe ID	Length (ft)	Diameter (inch) - Original	Diameter (inch) - Optimized
156	216	8	12
1	1850	12	8
158	200	12	12
159	743	8	6
160	300	8	12
161	400	12	12
48	790	8	6
49	1413	8	6
50	1703	12	12
122	887	12	8
123	766	8	8
124	1200	8	6
125	528	8	12
126	1079	8	12
130	887	8	12
131	768	8	6
132	250	8	8
136	647	8	8
137	700	8	8
142	1821	8	12
144	1102	12	12
148	700	6	8
149	700	6	8
150	384	12	12
151	1533	12	12
152	839	8	8
154	1104	8	8
155	958	8	8
157	1796	12	8
36	1006	12	6
37	500	8	12
40	1127	8	12
42	576	12	8
43	1100	8	12
45	300	8	12
46	300	8	6
47	400	8	12

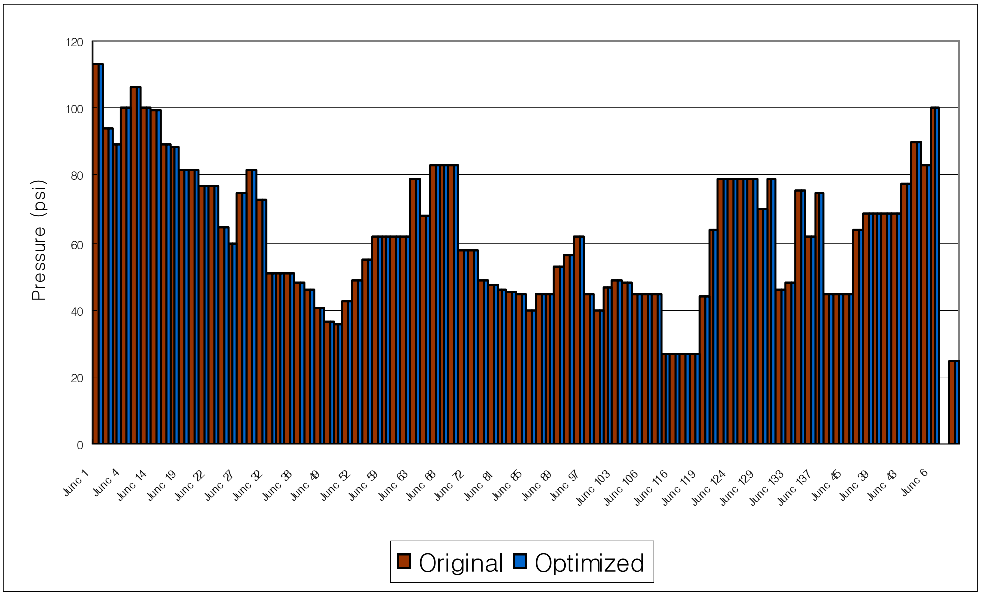
<Table 3-2> Continued

Pipe ID	Length (ft)	Diameter (inch) - Original	Diameter (inch) - Optimized
51	400	8	12
52	910	6	8
53	1072	8	12
59	838	12	12
60	1000	8	8
61	400	8	12
62	2500	12	6
4	83	12	6
5	870	8	12

<Fig. 3-7~8> show changes of velocity in each pipe and pressure at each node. The velocity variation is relatively big with diameter but pressure at each node is almost same with it in the original network.



<Fig. 3-7> Velocity at each pipe



<Fig. 3-8> Pressure at each node

<Table 3-3> Results of analysis

*MC : Minimum Cut set

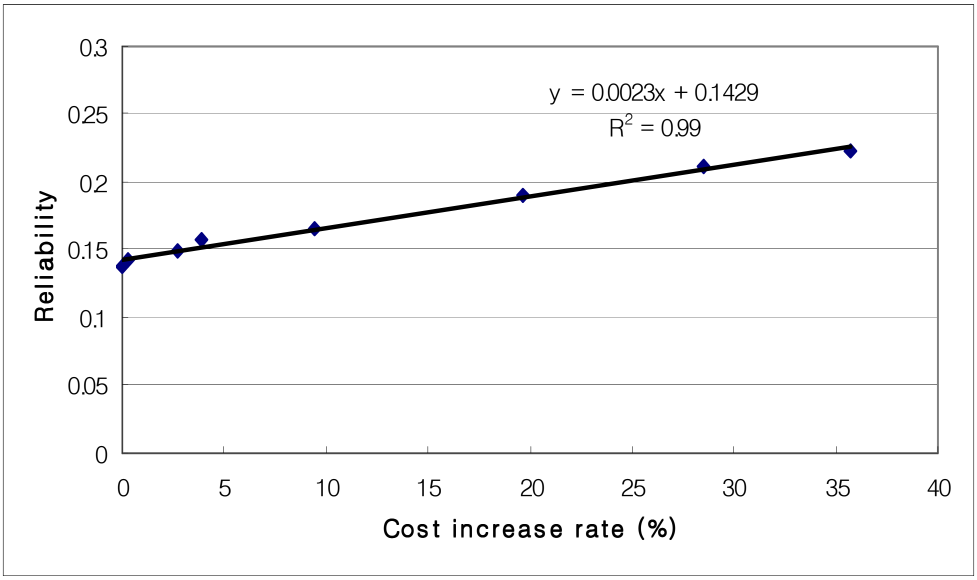
		No. of pipes	Diameter change		
			Decreased	Not changed	Increased
Not in MC*		13	7	4	2
In MC	Suspension	84	25	29	30
	Unintended isolation	6	1	3	2
	Low Pressure	0	0	0	0
	Total	90	26	32	32
Total		*103*	*33*	*36*	*34*

<Table 3-3> shows diameter changes. There are 103 pipes in the system. Of these, 33 pipes decreased, 36 pipes are not changed and 34 pipes increased.

2) Expansion of applications

In this chapter, an expanded optimization problem is considered where the decision variables are also diameter of each pipe. Unlike the previous work, six kinds of commercial pipes, 6, 8, 10, 12, 14, 16″, are used and extra costs from 10 to 40% of the original cost are added to it at each case to promise flexibility of system reliability.

The results of this work are shown in <Fig. 3-9>. A point means the maximum reliability which can be obtained at the matched cost. Comparison of cost increase and reliability reveals a linear relation between them.



<Fig. 3-9> System reliability with cost

3) Conclusions

The following conclusions can be taken from the results.

(1) According to Eq.<2-2>, the durability change of each pipe not in minimum cut sets does not have any influence on the system reliability. There are 13 pipes which are not in minimum cut sets. Of these, the number of increased pipes is just 2 as shown in <Table 3-3>

(2) Economically, the pipe which has high effectiveness by contrast with cost should be reinforced preferentially. Of cause, it must be in minimum cut sets.

(3) In views of safety, the important pipe has high failure rate or causes many customers out of service when it failed.

(4) From the results of the optimization, increasing pipe durability without structural improvements has low effectiveness. The following statements support it additionally.

- For example, when designing a system, the system reliability becomes 0.223972 from 0.137310 by substituting pipes of 12 inch diameter for all pipes. but $1,634,173 is also required to construct it. Thus, When substituting 16 inch for all of them, the system reliability becomes 0.313946 but $2,334,652 is also required. It is almost two times of the original cost.
- When reinforcing a existing system, the efficiency is predicted to be reduced more because expenses for removing existing pipes are required additionally.
- The number of pipes comes to be many as a network grows bigger. Hence, the efficiency is predicted to be reduced more.

3.2. Improvement of system reliability through structural reformation

Generally, there are three methods to reform a water distribution system structurally. The first method is adding isolation valves to reduce the length of pipe which has to be isolated in order to repair the broken pipe. The second method is constructing alternative paths to minimize probability that unintended isolations occur. Finally, the third method is ensuring water supply in emergencies by constructing water tanks.

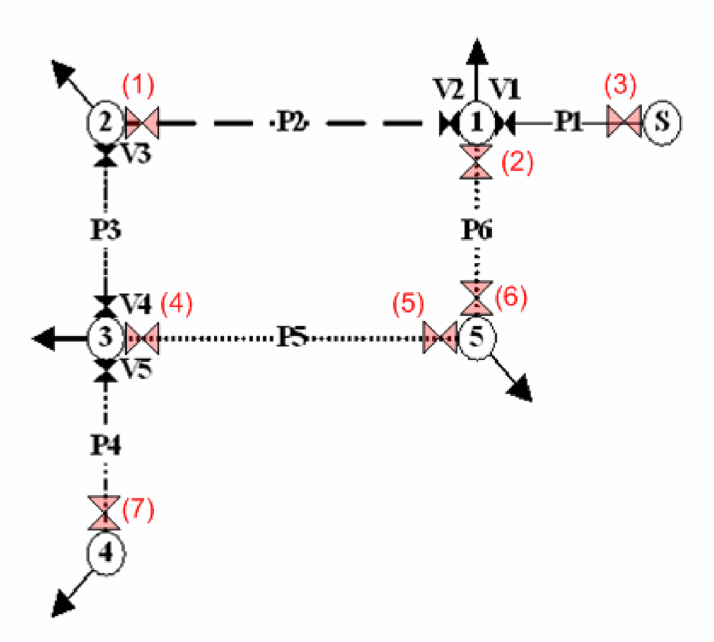
Among these, it is relatively easy to install isolation valves and it can reasonably reduce extent of damage by pipe failures. That is to say, it is the most practicable method which can be used easily. Because of such reasons, the first method is only considered to obtain the structural improvement of a system.

3.2.1. Verification for effectiveness of valve installation through an example

In <Fig. 3-10>, there are 7 positions where isolation valves can be installed on, (1)～(7). The total number of cases is $2\prod 7 = 128$ but cases are simplified by adding one or two valves to isolate a pipe. Cost to install a valve is assumed to 100 (unitless) and each pipes have different reliability respectively as shown in <Table 3-4>.

<Table 3-4> Reliability of each pipe

Pipe ID	Reliability
P1	0.99
P2	0.94
P3	0.97
P4	0.98
P5	0.95
P6	0.98



<Fig. 3-10> Example network

1) Results

Installing isolation valves can reduce probability that additional damage occurs by decreasing the length of isolated pipe to repair the broken pipe. <Table 3-5> shows the results.

The most effective case is installing a valve on (1), through the work, P2 can be excluded from minimum cut sets. Hence, any TOP event, suspension of water supply, unintended isolation and low pressure, does not occur even if P2 is broken.

On the other hand, a unintended isolation occurs when P1 is broken because P1 is still in minimum cut sets even though a valve is installed on (3). The work does not contribute to the system reliability. In the same manner, when P4 is broken, a untended isolation also occurs even though a valve is installed on (7).

In conclusion, if the TOP events(suspension of water supply, unintended isolation, low pressure), when a pipe is broken, do not occur by installing one or more isolation valves on the pipe, it can be said that it is a effective work. Namely, the criterion is whether installing isolation valves can restrain occurrences of the TOP events or not. When installing isolation valves by the criteria, they should be installed on the most delicate one among them.

<Table 3-5> Results of valve installations

Location of Installation	Pipe's ID in MC	System Reliability	Installation cost
X	P1, P2, P4, P5, P6	0.8491	0
(1)	P1, P4, P5, P6	0.9033	100
(2), (6)	P1, P2, P4, P5	0.8664	200
(3)	P1, P2, P4, P5, P6	0.8491	100
(4), (5)	P1, P2, P4, P6	0.8937	200
(7)	P1, P2, P4, P5, P6	0.8491	100

2) Conclusions

From the example, when valves of same number are installed in the system, the system reliability is different according to where they are. It means that clear criteria are needed to improve the system reliability when installing valves additionally.

From the results of the example, the following criteria are derived.

(1) It is not needed to install isolation valves on a pipe which is not in minimum cut sets because the pipe, when failed, does not cause the TOP events.

(2) When installing isolation valves, nodes should be excluded from the extent of damage. Even though nodes are excluded from the extent of damage by installing isolation valves, if the pipe, when failed, still causes the TOP events, it will be more meaningful to decrease failure rate by increasing durability of the pipe than installing isolation valves.

(3) For a segment consisting of two or more pipes, isolation valves should be installed on the weakest pipe among them. However, the pipe having additional valve(s), when failed, must not cause the TOP events. If the pipe, when failed, still cause the TOP events, it will be meaningful to decrease failure rate by increasing durability of the pipe.

3.3. Proposals for improving system reliability

In this chapter, on the basis of conclusions of Ch.3.1 and 3.2, plans applicable in practical affairs are presented for improving the system reliability.

First of all, the type of reinforcement should be determined to apply the proposed plans; installing isolation valves or increasing durability.

In this study, the plans are classified as two rules according to purposes of reinforcement; Rule 1 and Rule 2. They have a different approach respectively. The Rule 1 is focused on the on-off reliability considering total construction cost. On the other hand, the Rule 2 is focused on decreasing extent of damage by pipe failures.

3.3.1. Determination of reinforcement type for each pipe

As stated in the previous chapter, the methods to reinforce pipes are classified as two kinds. The first method is decreasing failure probability by increasing pipe durability. The second method is reducing the length of isolated pipe by installing valve(s) at the ends of the pipe.

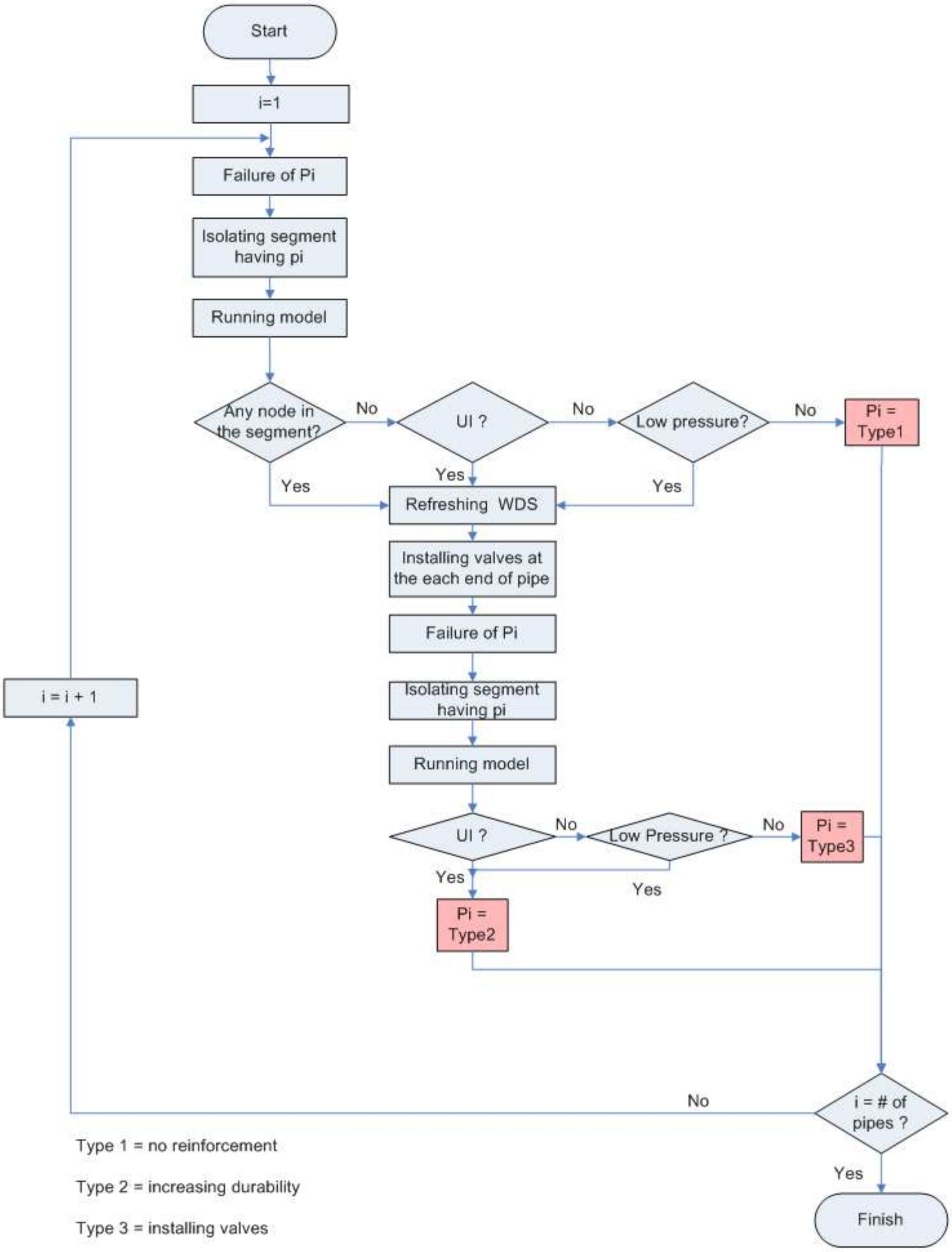
<Fig. 3-1> shows the flow chart to determine the type of reinforcement for all pipes in a system.

P_i is the i_{th} pipe. When P_i is assumed to be broken, the adjacent isolation valves are closed and occurrences of the TOP events are distinguished by EPANET interfaced with Visual Basic. It can be determined that the TOP events occur or not by the following questions: When a pipe is broken, (1) are one or more nodes in the isolated segment? (2) Not case 1, does a unintended isolation happen? (3) Not case 1 and 2, is the pressure of any node in the system under the pressure criterion?

The pipe is classified as the "Type 1" when it is not in the cases, (1)~(3). However, when any one of them happens, a hydraulic simulation is carried out again after installing valve(s) at the ends of the pipe. As s result, it is effective if any TOP event dose not happen, In the case, the pipe is the "Type 3". On the other hand, it is meaningless to do it if one of the TOP events still occurs after installing isolation valves. In such case, increasing durability is a more proper method and the pipe is classified as the "Type 2". This procedure is kept going on until all pipes are considered. <Table 3-6> shows the types of reinforcement.

<Table 3-6> Types of reinforcement

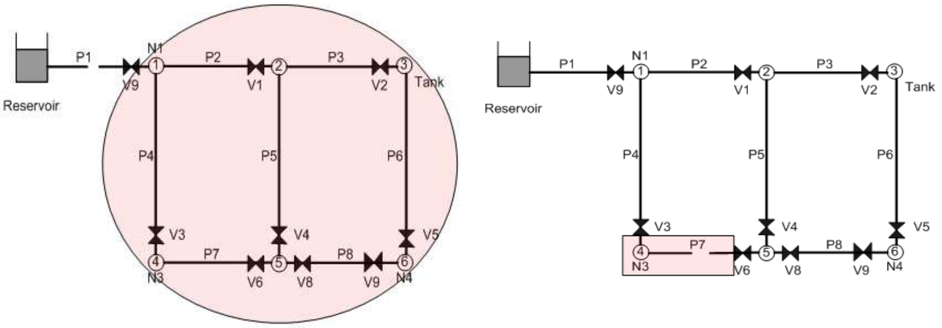
	How to reinforce
Type 1	No reinforcement
Type 2	Increasing durability
Type 3	Installing isolation valves



<Fig. 3-11> Flow chart for determining types of reinforcement

3.3.2. Rules for improving system reliability

The Park's model estimates the on-off reliability of a system. When a pipe in minimum cut sets is broken, the model treats it as the system-off state regardless of size of damage. However, the size might be different greatly depending on conditions regarded as system-off states. <Fig. 3-12> shows it clearly.



(a) Case 1 : size of damage by failure of P1

(b) Case 2 : size of damage by failure of P7

<Fig. 3-12> Size of damage, Case 1 vs. Case 2

For instance, if the reliability of P1 is 0.9 and 100 customers out of service occur when it fails, the expected number of customer out of service can be calculated as (1-0.9)×100=10. In case2, if the reliability of P7 is 0.5 and the number of customers out of service is 10 resulting from the failure of P7, the expected number of customers out of service is 5, (1-0.5)×10=5. That is to say, the damage size of Case 1 is bigger than Case 2 even thought the reliability of P1 is higher than P7.

The Rule 1 takes a role to lower the probability of system-off so that P7 has the priority rank of reinforcement than P1. On the other hand, the Rule 2 has a purpose of reducing the size of damage by pipe failures by reinforcing P1 prior to P7. Namely, they follow the same method to determine the type of reinforcement but different priority orders are applied to them respectively.

1) Rule 1

The Rule 1 is applied to a system by the following procedure.

(1) All pipes in a system are classified from the Type 1 to the Type 3 by the procedure shown in <Fig. 3-11>.

(2) Reliability of each pipe is sorted in ascending order.

(3) For pipes in the Type 3, they are perfectly isolated by installing one or two isolation valves at the ends of the pipe. On this occasion, it makes the reliability of the pipe as 1 (100%) in the model. So, installing isolation valves at all available positions is useful for improving the system reliability.

(4) Increasing pipe durability in the Type 2 costs much money comparing with them in the Type 3 and it is also controled by conditions of construction site. For those reasons, it should be determined by taking the following subjects into consideration. The contents are recorded in the Korea Standards for Water Service Facilities in detail.

- Total construction cost.
- Conditions of construction site: pipe connections, objects being layed underground and so on.
- Velocity constraints to maintain water quality or protect systems.
- Pressure constraints to supply water with proper pressure.
- Distribution of pressure heads at nodes / Diameter constraints

2) Rule 2

The purpose of the Rule 2 is reducing size of damage reasonably. Hence, the priority order of reinforcement is different from the Rule 1.

First of all, it is necessary to quantify the size of damage by pipe failures. When a pipe is broken, the segment having the broken pipe should be isolated to conduct repairs by shutting off adjacent isolation valves and in some cases, a unintended isolation can occur according to the topological structure. The size of damage is closely related with the amount of water being cut off in the isolated zone. In the Rule 2, the priority order of reinforcement should be determined by checking the system segment by segment while it is done pipe by pipe in the Rule 1.

As already stated in the Ch. 2.2.2, a segment is out of order if any pipe in the segment is broken. So to speak, all pipes in the segment should be operational if the segment displays its own function. The probability that a segment is in a normal condition is calculated as follows.

$$S(Seg_i) = \prod_{j=1}^{M} S(P_j) \qquad \text{<3-1>}$$

where $S(Seg_i)$=the probability that the i_{th} segment in minimum cut sets is operational; $S(P_j)$=the probability that the j_{th} pipe in the segment is operational; M=the number of pipes in the segment.

From Eq. <3-1>, the probability that the segment is not operational is calculated as follows.

$$F(Seg_i) = 1 - S(Seg_i) \quad \text{<3-2>}$$

where $F(Seg_i)$=the probability that the i_{th} segment in minimum cut sets is not operational.

The number of customers out of service can be estimated from the actual population in the isolated zones. In the case that related data does not exist, it can be approximately calculated as follows.

$$NCOS = \sum_{k=1}^{O} D_k / AQU \quad \text{<3-3>}$$

where $NCOS$ = the Number of Customers Out of Service; AQU = the Average water Quantity Used per head ($171 gal/day/person$); D_k = the demand at the k_{th} node in the isolated zone; O = the number of nodes in the zone.

The customers out of service can occur when a segment is abnormal. So, the Expected Number of Customers Out of Service ($ENCOS$) is calculated by the following equation.

$$ENCOS = F(Seg_i) \times NCOS \quad \text{<3-4>}$$

The segment having the biggest $ENCOS$ should be reinforced firstly. At the same time, the pipe which have the smallest reliability is the first object to be reinforced in the segment. After determining the priority order of reinforcement, the methods correspond to the contents of the Rule 1.

3) Suggestions for Rule 1 and Rule 2

The rules need to be applied to a system according to what the purpose is because they have different approaches respectively.

For instance, if the purpose is increasing the on-off reliability within limited cost, the Rule 1 will be suitable for the work, while if it is decreasing the size of damage, the Rule 2 will be more suitable.

Regardless of the size of damage, for areas where pipe failures occur frequently the reliability can be improved effectively by doing the presented methods.

When increasing pipe durability, it should be done not relying on the Su's equations but considering situations and purposes. Here are three subjects to be considered for the problems. Firstly, the equations do not take part in determining the type of reinforcement but are only used to obtain the priority order. If there is a more suitable model, it can suggest more practical standards. Secondly, pipe replacement cost is relatively bigger than valve installation cost. Finally, pipe replacement is not simple but related with others such as rehabilitation problems. In conclusions, pipe replacements should be considered carefully in various viewpoints because of such reasons.

Chapter 4. Applications

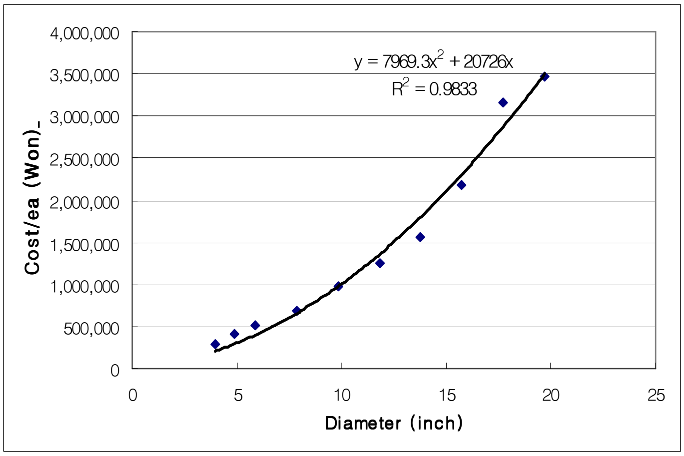
In this chapter, the rules established in the previous chapter are applied to the Cherry Hill network in midium size and the Chester Water Authority network in large size. After that, the results are analyzed.

In these applications, pipe durability is increased by changing a existing pipe with new one having larger diameter. Pipe replacement cost is calculated by <4-1> suggested by the Korea Water Resources Corporation in 1995. The value is converted into prices of 2006 by using the consumer price index. Valve installation cost is calculated from <4-2>, using unit prices and labor costs data in 2006.

$$Pipe\ \ Cost(D,\ L) = (145.33D^2 + 6834.94D + 9859.21) \times 0.4458 \times L \qquad \text{<4-1>}$$

$$Valve\ \ Cost(D) = 7969.3D^2 + 20762D \qquad \text{<4-2>}$$

where D=Pipe diameter (in); L=Pipe length (ft).



<Fig. 4-1> Soft seal valve, valve installation cost with diameter

4.1. Applications (Cherry Hill)

4.1.1. Rule 1

There are 103 pipes in the system. Of these, the number of pipes belonging to minimum cut sets is 90. The pipes are reinforced 10 by 10 from the weakest pipe through the Rule 1(Case1～9). To do the simplification, pipes in the Type2 are replaced with ones that have 2 inch more in diameter to increase their durability respectively.

<Table 4-1> shows the type of each pipe and the cost of each case. <Table 4-2> shows overall results of the application and <Fig. 4-2, 4-3> indicate the system reliability and the total *ENCOS* of each case.

<Table 4-1> Application, Rule 1, Cherry Hill

Case	ID	Diameter (inch)	Length (ft)	Reliability	Failure Rate	Type	No. of valves	Cost (₩)
1	142	8	1821	0.926461	0.073539	Type2		181,192,608
	38	8	1438	0.941465	0.058535	Type2		143,083,455
	52	6	910	0.948484	0.051516	Type3	1	411,251
	157	12	1796	0.951368	0.048632	Type3	2	2,792,582
	133	8	1150	0.952907	0.047093	Type3	2	1,351,686
	40	8	1127	0.953827	0.046173	Type2		112,138,424
	50	12	1703	0.953827	0.046173	Type2		209,984,723
	43	8	1100	0.954908	0.045092	Type2		109,451,878
	126	8	1079	0.955750	0.044250	Type2		107,362,342
	53	8	1072	0.956030	0.043970	Type3	1	675,843
Total							6	**868,444,792**

<Table 4-1> Continued

Case	ID	Diameter (inch)	Length (ft)	Reliability	Failure Rate	Type	No. of valves	Cost (₩)
2	151	12	1533	0.958339	0.041661	Type3	1	1,396,291
	139	8	1007	0.958640	0.041360	Type3	2	1,351,686
	60	8	1000	0.958922	0.041078	Type3	1	675,843
	130	8	887	0.963478	0.036522	Type3	1	675,843
	5	8	870	0.964165	0.035835	Type3	1	675,843
	67	8	838	0.965460	0.034540	Type3	2	1,351,686
	48	8	790	0.967406	0.032594	Type2		78,606,349
	123	8	766	0.968380	0.031620	Type2		76,218,308
	159	8	743	0.969315	0.030685	Type2		73,929,768
	144	12	1102	0.969873	0.030127	Type2		135,879,721
Total							8	**370,761,339**
3	146	8	700	0.971065	0.028935	Type3	1	675,843
	137	8	700	0.971065	0.028935	Type2		69,651,195
	136	8	647	0.973226	0.026774	Type2		64,377,604
	122	12	887	0.975679	0.024321	Type2		109,369,612
	18	8	583	0.975842	0.024158	Type3	1	675,843
	16	8	576	0.976129	0.023871	Type3	1	675,843
	59	12	838	0.977007	0.022993	Type3	1	1,396,291
	135	8	551	0.977153	0.022847	Type3	1	675,843
	128	8	551	0.977153	0.022847	Type2		54,825,441
	21	12	815	0.977631	0.022369	Type3	2	2,792,582
Total							7	**305,116,098**

<Table 4-1> Continued

Case	ID	Diameter (inch)	Length (ft)	Reliability	Failure Rate	Type	No. of valves	Cost (₩)
4	125	8	528	0.978096	0.021904	Type3	1	675,843
	107	8	527	0.978137	0.021863	Type3	1	675,843
	101	8	527	0.978137	0.021863	Type3	1	675,843
	3	8	526	0.978178	0.021822	Type3	1	675,843
	30	12	767	0.978934	0.021066	Type2		94,573,272
	37	8	500	0.979246	0.020754	Type2		49,750,853
	41	12	743	0.979587	0.020413	Type3	2	2,792,582
	134	8	455	0.981096	0.018904	Type3	1	675,843
	115	8	455	0.981096	0.018904	Type2		45,273,277
	129	12	671	0.981546	0.018454	Type2		82,736,200
Total							7	**278,505,401**
5	141	8	431	0.982084	0.017916	Type2		42,885,236
	75	12	647	0.982201	0.017799	Type3	1	1,396,291
	120	12	647	0.982201	0.017799	Type3	2	2,792,582
	55	8	420	0.982537	0.017463	Type3	1	675,843
	56	8	420	0.982537	0.017463	Type3	2	1,351,686
	57	8	420	0.982537	0.017463	Type3	2	1,351,686
	58	8	420	0.982537	0.017463	Type3	1	675,843
	97	12	623	0.982855	0.017145	Type2		76,817,664
	73	12	623	0.982855	0.017145	Type3	1	1,396,291
	113	8	407	0.983073	0.016927	Type2		40,497,195
Total							10	**169,840,319**

<Table 4-1> Continued

Case	ID	Diameter (inch)	Length (ft)	Reliability	Failure Rate	Type	No. of valves	Cost (₩)
6	138	8	407	0.983073	0.016927	Type3	1	675,843
	51	8	400	0.983362	0.016638	Type2		39,800,683
	61	8	400	0.983362	0.016638	Type2		39,800,683
	47	8	400	0.983362	0.016638	Type2		39,800,683
	54	12	600	0.983483	0.016517	Type3	1	1,396,291
	42	12	576	0.984138	0.015862	Type2		71,022,431
	84	8	375	0.984393	0.015607	Type3	1	675,843
	87	8	375	0.984393	0.015607	Type3	2	1,351,686
	90	8	375	0.984393	0.015607	Type3	2	1,351,686
	91	8	375	0.984393	0.015607	Type3	2	1,351,686
Total							9	**197,227,516**
7	65	8	364	0.984848	0.015152	Type3	1	675,843
	64	8	360	0.985013	0.014987	Type2		35,820,615
	17	12	530	0.985396	0.014604	Type3	1	1,396,291
	143	8	335	0.986046	0.013954	Type3	1	675,843
	44	12	479	0.986792	0.013208	Type3	1	1,396,291
	76	12	479	0.986792	0.013208	Type2		59,062,056
	114	8	312	0.986998	0.013002	Type2		31,044,533
	160	8	300	0.987495	0.012505	Type2		29,850,512
	45	8	300	0.987495	0.012505	Type2		29,850,512
	46	8	300	0.987495	0.012505	Type2		29,850,512
Total							4	**219,623,009**

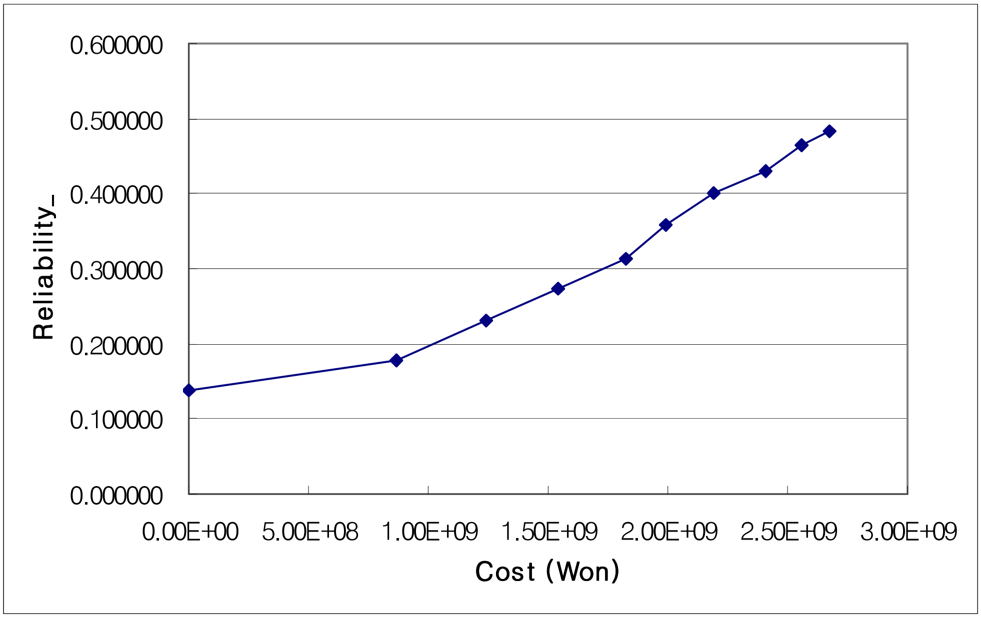
<Table 4-1> Continued

Case	ID	Diameter (inch)	Length (ft)	Reliability	Failure Rate	Type	No. of valves	Cost (₩)
8	11	8	288	0.987992	0.012008	Type3	1	675,843
	25	8	288	0.987992	0.012008	Type2		28,656,492
	22	12	431	0.988107	0.011893	Type3	1	1,396,291
	93	12	400	0.988958	0.011042	Type3	2	2,792,582
	161	12	400	0.988958	0.011042	Type2		49,321,133
	150	12	384	0.989397	0.010603	Type3	1	1,396,291
	35	12	383	0.989425	0.010575	Type3	2	2,792,582
	132	8	250	0.989568	0.010432	Type2		24,875,427
	156	8	216	0.990981	0.009019	Type3	2	1,351,686
	31	12	312	0.991377	0.008623	Type2		38,470,484
Total							9	**151,728,811**
9	72	12	300	0.991707	0.008293	Type3	2	2,792,582
	92	12	300	0.991707	0.008293	Type3	2	2,792,582
	116	12	264	0.992699	0.007301	Type3	1	1,396,291
	71	12	240	0.993360	0.006640	Type3	2	2,792,582
	94	12	240	0.993360	0.006640	Type2		29,592,680
	127	12	240	0.993360	0.006640	Type3	2	2,792,582
	83	12	216	0.994022	0.005978	Type2		26,633,412
	158	12	200	0.994464	0.005536	Type2		24,660,566
	23	8	88	0.996316	0.003684	Type2		8,756,150
	4	12	83	0.997699	0.002301	Type2		10,234,135
Total							9	**112,443,564**

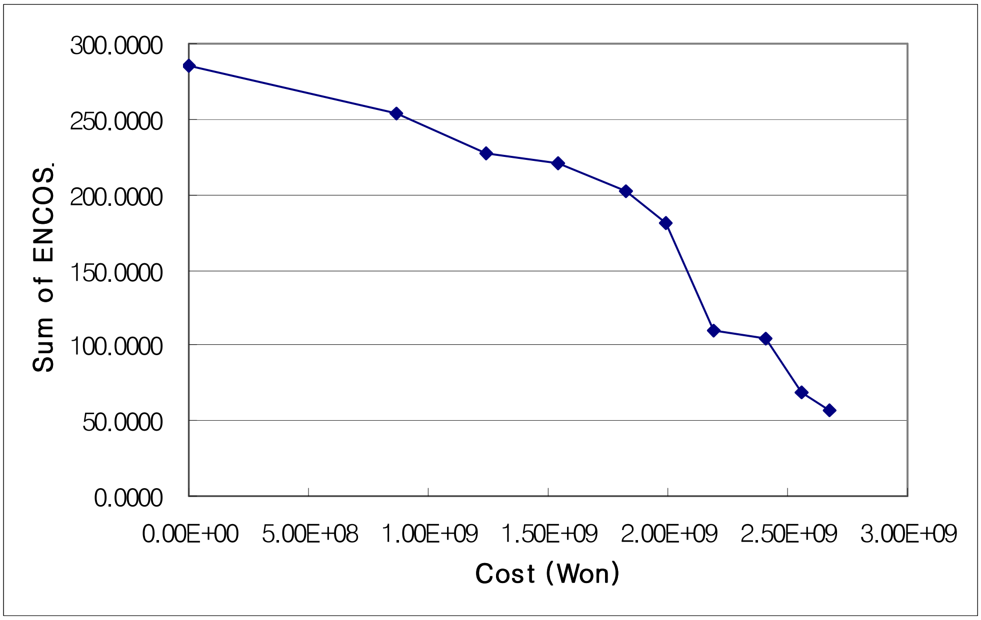
Total no. of valves = 69　　　　*Total Cost = ₩ 2,673,690,848*

<Table 4-2> Result of each Case, Rule 1

Case	Reliability	No. of pipes in MC	No. of segments	Cost (₩)	Sum of cost (₩)	Sum of ENCOS
Case0	0.137310	90	80	0	0	286
Case1	0.178027	86	86	868,444,792	868,444,792	254
Case2	0.230833	80	94	370,761,339	1,239,206,130	227
Case3	0.272747	74	101	305,116,098	1,544,322,229	221
Case4	0.314284	68	108	278,505,401	1,822,827,629	203
Case5	0.359099	61	118	169,840,319	1,992,667,948	182
Case6	0.400560	55	127	197,227,516	2,189,895,465	109
Case7	0.430831	51	131	219,623,009	2,409,518,473	105
Case8	0.463373	45	140	151,728,811	2,561,247,285	68
Case9	0.482660	40	149	112,443,564	2,673,690,848	57



<Fig. 4-2> Reliability with cost for Rule 1



<Fig. 4-3> Sum of ENCOS with cost for Rule 1

The application results are said as follows.

(1) In the final case, the total reinforcement cost is ₩ 2,673,690,848 and the number of installed valves is 69.

(2) The initial reliability of the system is 0.137310 but it is improved to 0.482660 after the reinforcements. This value means that the probability is 48.27% that there is not any suspension of water supply, unintended isolation and low pressure in the system for one year.

(3) Initially, the sum of *ENCOS* is 286 but it is reduced to 57 at the final case.

(4) The number of pipes in minimum cut sets is 90 but it reduced to 40 by adding 69 valves in the system while the number of segment is increased from 80 to 149.

4.1.2. Rule 2

The segment having the biggest *ENCOS* should be reinforced firstly and the pipe which have the smallest reliability is the first object to be reinforced in the segment. They are reinforced 10 by 10 by the priority order of reinforcement(Case1～9), pipes in the Type 2 are replaced with ones that have 2 inch more in diameter to increase their durability respectively.

<Table 4-3> shows the type of each pipe and the cost of each case. <Table 4-4> shows overall results of the application and <Fig. 4-4, 4-5> indicate the system reliability and the total *ENCOS* of each case.

<Table 4-3> Application, Rule 2, Cherry Hill

Case	ID	Diameter (inch)	Length (ft)	Reliability	Failure Rate	Segment ID	NCOS	Type	No. of valves	Cost (₩)
1	84	8	375	0.984393	0.015607	S(20)	1182	Type3	1	675,843
	87	8	375	0.984393	0.015607	S(20)	1182	Type3	2	1,351,686
	90	8	375	0.984393	0.015607	S(20)	1182	Type3	2	1,351,686
	91	8	375	0.984393	0.015607	S(20)	1182	Type3	2	1,351,686
	93	12	400	0.988958	0.011042	S(20)	1182	Type3	2	2,792,582
	92	12	300	0.991707	0.008293	S(20)	1182	Type3	2	2,792,582
	116	12	264	0.992699	0.007301	S(20)	1182	Type3	1	1,396,291
	120	12	647	0.982201	0.017799	S(39)	456	Type3	2	2,792,582
	127	12	240	0.993360	0.006640	S(39)	456	Type3	2	2,792,582
	41	12	743	0.979587	0.020413	S(13)	453	Type3	2	2,792,582
Total									18	**20,090,106**

<Table 4-3> Continued

Case	ID	Diameter (inch)	Length (ft)	Reliability	Failure Rate	Segment ID	NCOS	Type	No. of valves	Cost (₩)
2	35	12	383	0.989425	0.010575	S(13)	453	Type3	2	2,792,582
	67	8	838	0.965460	0.034540	S(24)	383	Type3	2	1,351,686
	75	12	647	0.982201	0.017799	S(24)	383	Type3	1	1,396,291
	156	8	216	0.990981	0.009019	S(24)	383	Type3	2	1,351,686
	72	12	300	0.991707	0.008293	S(24)	383	Type3	2	2,792,582
	71	12	240	0.993360	0.006640	S(24)	383	Type3	2	2,792,582
	4	12	83	0.997699	0.002301	S(24)	383	Type2		10,234,135
	97	12	623	0.982855	0.017145	S(29)	348	Type2		76,817,664
	94	12	240	0.993360	0.006640	S(29)	348	Type2		29,592,680
	133	8	1150	0.952907	0.047093	S(43)	221	Type3	2	1,351,686
Total									13	**130,473,577**
3	129	12	671	0.981546	0.018454	S(43)	221	Type2		82,736,200
	157	12	1796	0.951368	0.048632	S(18)	205	Type3	2	2,792,582
	54	12	600	0.983483	0.016517	S(18)	205	Type3	1	1,396,291
	44	12	479	0.986792	0.013208	S(18)	205	Type3	1	1,396,291
	142	8	1821	0.926461	0.073539	S(71)	180	Type2		181,192,608
	136	8	647	0.973226	0.026774	S(34)	158	Type2		64,377,604
	107	8	527	0.978137	0.021863	S(34)	158	Type3	1	675,843
	30	12	767	0.978934	0.021066	S(14)	146	Type2		94,573,272
	31	12	312	0.991377	0.008623	S(14)	146	Type2		38,470,484
	132	8	250	0.989568	0.010432	S(35)	117	Type2		24,875,427
Total									5	**492,486,603**

<Table 4-3> Continued

Case	ID	Diameter (inch)	Length (ft)	Reliability	Failure Rate	Segment ID	NCOS	Type	No. of valves	Cost (₩)
4	150	12	384	0.989397	0.010603	S(51)	112	Type3	1	1,396,291
	137	8	700	0.971065	0.028935	S(49)	103	Type2		69,651,195
	83	12	216	0.994022	0.005978	S(27)	100	Type2		26,633,412
	50	12	1703	0.953827	0.046173	S(67)	94	Type2		209,984,723
	122	12	887	0.975679	0.024321	S(68)	94	Type2		109,369,612
	113	8	407	0.983073	0.016927	S(36)	85	Type2		40,497,195
	114	8	312	0.986998	0.013002	S(36)	85	Type2		31,044,533
	151	12	1533	0.958339	0.041661	S(25)	84	Type3	1	1,396,291
	139	8	1007	0.958640	0.041360	S(47)	79	Type3	2	1,351,686
	138	8	407	0.983073	0.016927	S(47)	79	Type3	1	675,843
Total									5	492,000,781
5	143	8	335	0.986046	0.013954	S(47)	79	Type3	1	675,843
	73	12	623	0.982855	0.017145	S(26)	75	Type3	1	1,396,291
	65	8	364	0.984848	0.015152	S(23)	75	Type3	1	675,843
	64	8	360	0.985013	0.014987	S(23)	75	Type2		35,820,615
	42	12	576	0.984138	0.015862	S(12)	70	Type2		71,022,431
	55	8	420	0.982537	0.017463	S(21)	60	Type3	1	675,843
	56	8	420	0.982537	0.017463	S(21)	60	Type3	2	1,351,686
	57	8	420	0.982537	0.017463	S(21)	60	Type3	2	1,351,686
	58	8	420	0.982537	0.017463	S(21)	60	Type3	1	675,843
	40	8	1127	0.953827	0.046173	S(15)	58	Type2		112,138,424
Total									9	225,784,506

<Table 4-3> Continued

Case	ID	Diameter (inch)	Length (ft)	Reliability	Failure Rate	Segment ID	NCOS	Type	No. of valves	Cost (₩)
6	37	8	500	0.979246	0.020754	S(54)	58	Type2		49,750,853
	38	8	1438	0.941465	0.058535	S(63)	57	Type2		143,083,455
	126	8	1079	0.955750	0.044250	S(19)	51	Type2		107,362,342
	59	12	838	0.977007	0.022993	S(3)	48	Type3	1	1,396,291
	21	12	815	0.977631	0.022369	S(9)	44	Type3	2	2,792,582
	22	12	431	0.988107	0.011893	S(9)	44	Type3	1	1,396,291
	23	8	88	0.996316	0.003684	S(9)	44	Type2		8,756,150
	52	6	910	0.948484	0.051516	S(5)	44	Type3	1	411,251
	160	8	300	0.987495	0.012505	S(37)	44	Type2		29,850,512
	161	12	400	0.988958	0.011042	S(37)	44	Type2		49,321,133
Total									5	394,120,861
7	125	8	528	0.978096	0.021904	S(31)	41	Type3	1	675,843
	43	8	1100	0.954908	0.045092	S(79)	35	Type2		109,451,878
	60	8	1000	0.958922	0.041078	S(60)	35	Type3	1	675,843
	130	8	887	0.963478	0.036522	S(32)	35	Type3	1	675,843
	46	8	300	0.987495	0.012505	S(57)	35	Type2		29,850,512
	53	8	1072	0.956030	0.043970	S(6)	32	Type3	1	675,843
	48	8	790	0.967406	0.032594	S(46)	32	Type2		78,606,349
	144	12	1102	0.969873	0.030127	S(72)	32	Type2		135,879,721
	16	8	576	0.976129	0.023871	S(7)	32	Type3	1	675,843
	128	8	551	0.977153	0.022847	S(42)	32	Type2		54,825,441
Total									5	411,993,116

<Table 4-3> Continued

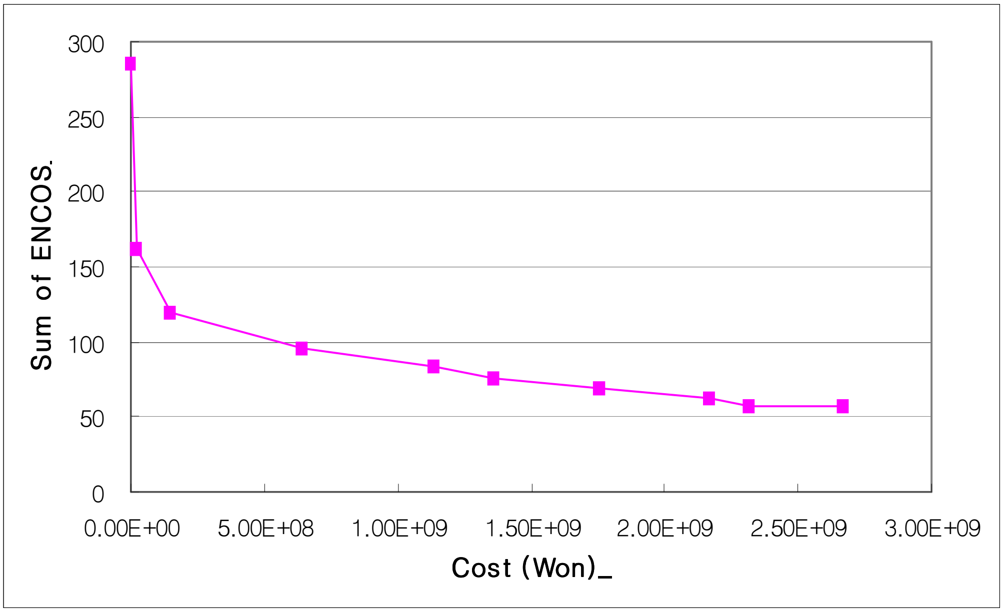
Case	ID	Diameter (inch)	Length (ft)	Reliability	Failure Rate	Segment ID	NCOS	Type	No. of valves	Cost (₩)
8	17	12	530	0.985396	0.014604	S(7)	32	Type3	1	1,396,291
	11	8	288	0.987992	0.012008	S(6)	32	Type3	1	675,843
	5	8	870	0.964165	0.035835	S(4)	28	Type3	1	675,843
	3	8	526	0.978178	0.021822	S(4)	28	Type3	1	675,843
	123	8	766	0.968380	0.031620	S(30)	25	Type2		76,218,308
	135	8	551	0.977153	0.022847	S(45)	25	Type3	1	675,843
	101	8	527	0.978137	0.021863	S(33)	25	Type3	1	675,843
	115	8	455	0.981096	0.018904	S(38)	25	Type2		45,273,277
	134	8	455	0.981096	0.018904	S(45)	25	Type3	1	675,843
	25	8	288	0.987992	0.012008	S(10)	19	Type2		28,656,492
Total									7	155,599,426
9	47	8	400	0.983362	0.016638	S(56)	16	Type2		39,800,683
	159	8	743	0.969315	0.030685	S(52)	13	Type2		73,929,768
	146	8	700	0.971065	0.028935	S(22)	13	Type3	1	675,843
	18	8	583	0.975842	0.024158	S(8)	13	Type3	1	675,843
	141	8	431	0.982084	0.017916	S(48)	13	Type2		42,885,236
	76	12	479	0.986792	0.013208	S(28)	13	Type2		59,062,056
	51	8	400	0.983362	0.016638	S(55)	6	Type2		39,800,683
	61	8	400	0.983362	0.016638	S(59)	6	Type2		39,800,683
	45	8	300	0.987495	0.012505	S(58)	6	Type2		29,850,512
	158	12	200	0.994464	0.005536	S(61)	0	Type2		24,660,566
Total									2	351,141,874

Total no. of valves = 69 *Total Cost = ₩ 2,673,690,848*

<Table 4-4> Result of each Case, Rule 2

Case	Reliability	No. of pipes in MC	No. of segments	Cost (₩)	Sum of cost (₩)	Sum of ENCOS
Case0	0.137310	90	80	0	0	286
Case1	0.157144	80	98	20,090,106	20,090,106	162
Case2	0.180666	73	111	130,473,577	150,563,682	119
Case3	0.206184	69	116	492,486,603	643,050,286	95
Case4	0.236036	65	121	492,000,781	1,135,051,066	83
Case5	0.269401	58	130	225,784,506	1,360,835,572	75
Case6	0.310517	54	135	394,120,861	1,754,956,433	69
Case7	0.378687	49	140	411,993,116	2,166,949,549	62
Case8	0.445672	42	147	155,599,426	2,322,548,975	58
Case9	0.482660	40	149	351,141,874	2,673,690,848	57

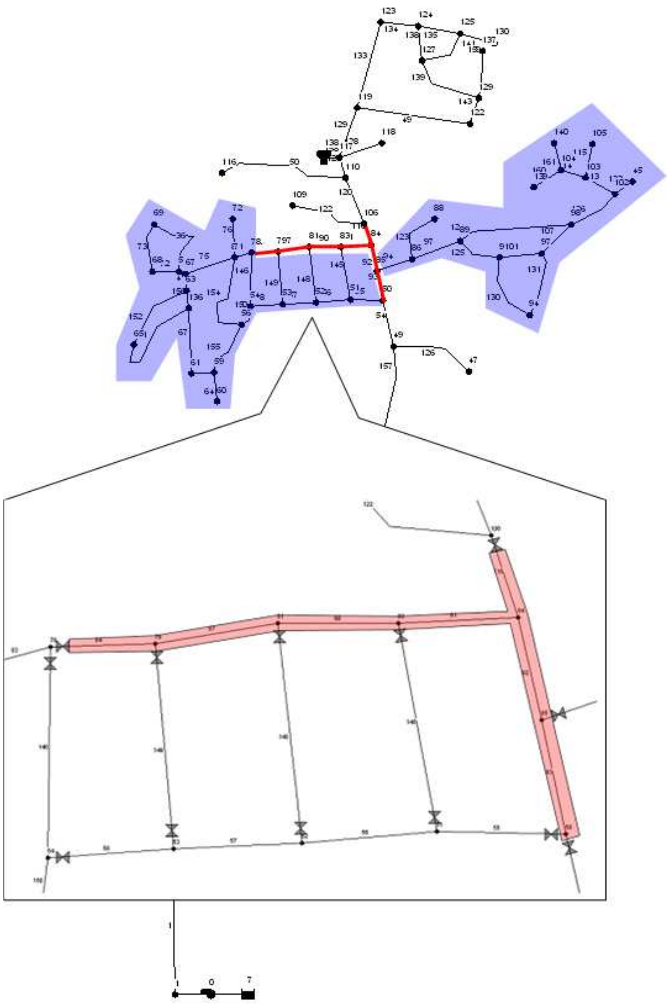
<Fig. 4-4> Reliability with cost, Rule 2



<Fig. 4-5> Sum of ENCOS with cost, Rule2

The results are as follows.

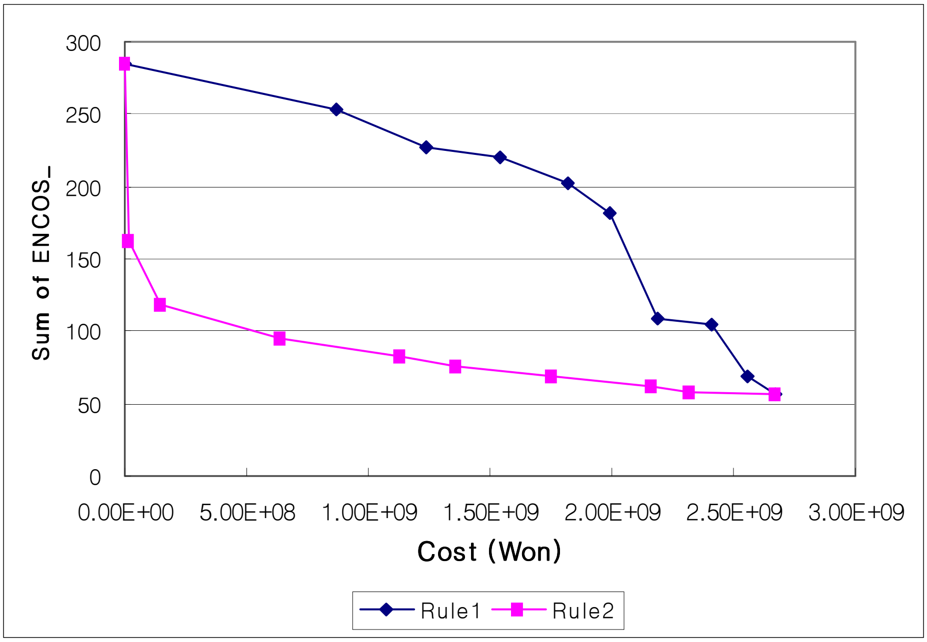
(1) The segment causing the biggest customers out of service is shown in <Fig. 4-6>. It consists of 7 pipes and is isolated by 8 adjacent valves when any one of them fails. The total number of customers out of service($NCOS$) is 1,182, it is a very big number when considering the second one is just 456.



<Fig. 4-6> Vulnerable area in Cherry Hill

(2) All pipes in the segment are the Type 3. The extent of damage coming from failures of the segment can be reduced greatly by installing 12 valves with small cost as shown in <Fig. 4-5>. However, the efficiency is not a common result but arises from the structural vulnerable area shown in <Fig. 4-6>.

(3) <Fig.4-7> shows the sum of *ENCOS* at each case of Rule 1 and Rule 2 respectively. The results indicate that the efficiency of Rule 2 for decreasing the sum of *ENCOS* is greater than the Rule 1.



<Fig. 4-7> Rule1 vs. Rule2, Sum of ENCOS

4.1.3. Practical approaches

Increasing pipe durability needs to be treated carefully in various viewpoints considering situations and purposes. In the previous chapter, pipes in the Type 2 are replaced with ones that have 2 inch more in diameter to increase their durability. Consequently, the system reliability is improved to 0.482660 and the sum of *ENCOS* is reduced to 57 at the final case by investing ₩2,673,690,848.

The total cost calculated by Eq.<3-1> to lay water-pipes underground is $1,224,942 in 1987 and the U.S. dollar rate is ₩792.3 at that time. The cost can be approximately converted to the value of 2006 by using the consumer price index of each year. The value is ₩2,358,569,983. Besides, the valve installation cost for 94 valves in the system is ₩84,039,544. Therefore, the total cost is ₩2,442,609,527.

Namely, the improvements are obtained by investing ₩2,673,690,848 to the system constructed by spending ₩2,442,609,527. The work is hard to be carried out in actuality.

Therefore, practical approaches are performed considering the cost of reinforcement. There are 90 pipes which belong to the minimum cut sets. Of these, 40 pipes are the Type 2 and 50 are in the Type 3. First of all, 69 valves are installed on the pipes in the Type 3 and then only two pipes in the Type 2 that its reliability is lower than 0.95 are replaced with ones which can make it more than 0.95 as shown in <Table 4-5>.

<Table 4-5> Reinforcements of pipes

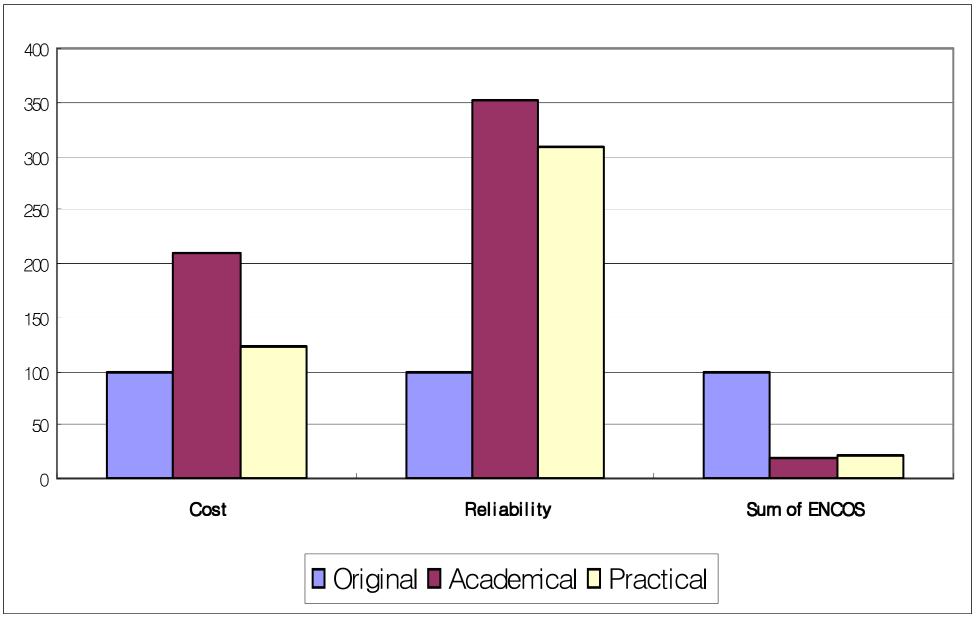
ID	From			To		
	Dia. (in)	Lth.(ft)	Rel.	Dia. (in)	Lth.(ft)	Rel.
142	8	1821	0.926461	12	1821	0.950708
38	8	1438	0.941465	10	1438	0.953403

<Table 4-6> shows the results. the system reliability is improved to 0.423171 and the sum of *ENCOS* is reduced to 64 by investing ₩549,311,024 which is just 22% of the total construction cost.

<Fig. 4-8> shows the values of the approaches relatively when assuming that the original values are 100 respectively. The results say that the effectiveness of installing valves and pipe replacement should be considered carefully in various viewpoints.

<Table 4-6> Academical approach vs. Practical approach

	From	To	
	Original	Academical approach	Practical approach
Cost (₩)	2,442,609,527	+2,673,690,848	+549,311,024
Reliability	0.13731	0.482660	0.423171
Sum of ENCOS	286	57	64



<Fig. 4-8> Academic approach vs. Practical approach

4.2. Applications (Chester Water Authority)

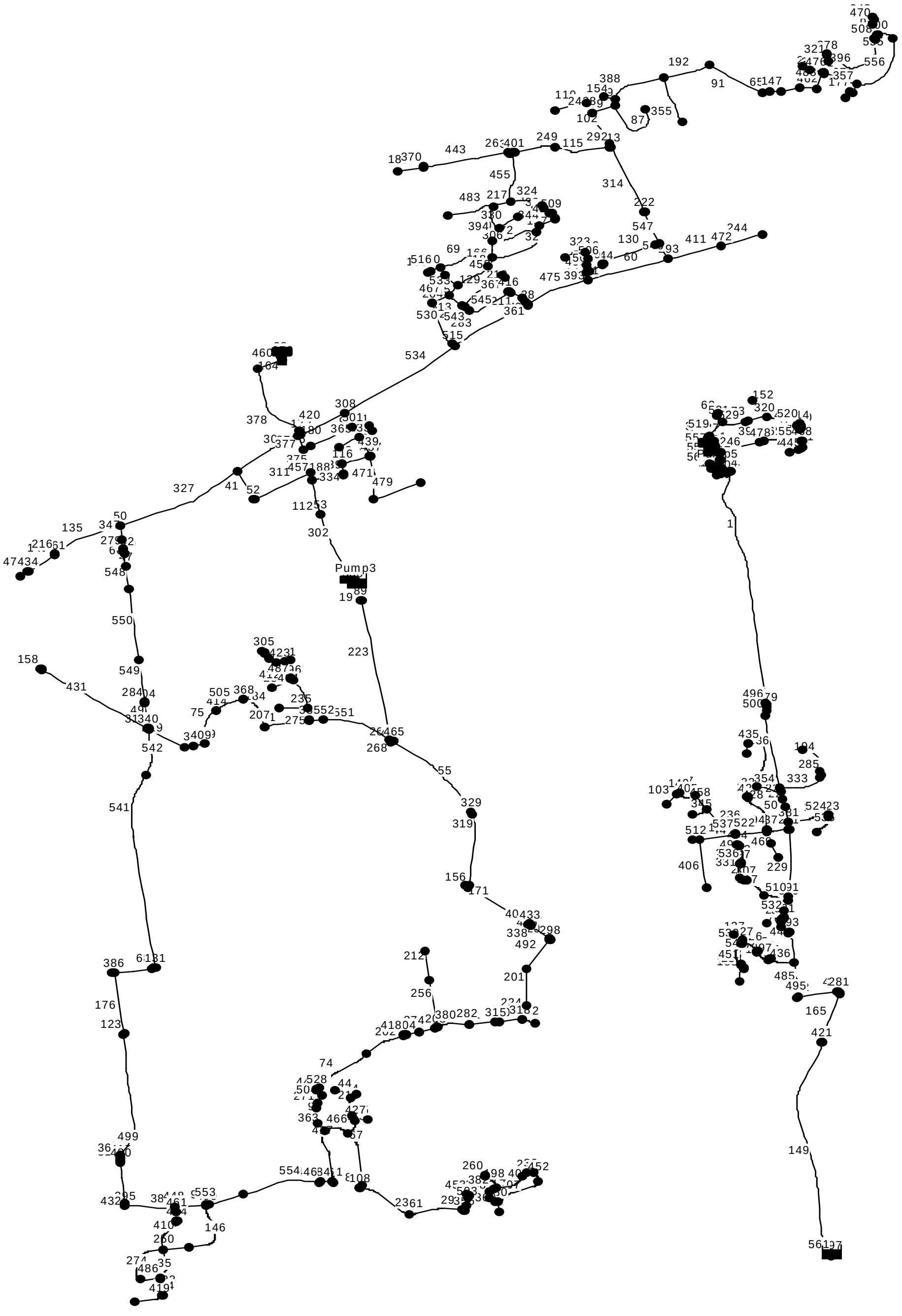
In this chapter, the practical approaches of the rules are applied to the Chester Water Authority network in the state of Pennsylvania, USA.

4.2.1. Overall conditions of CWA

The Chester Water Authority network consists of 2 sources, 2 tanks, 5 pumps, 354 valves, and 560 pipes (4～20 ″) as shown in <Fig. 4-9>. The total length of water pipes is 171,245 ft (52,195 m).

There are 537 pipes which belong to minimum cut sets and the number of segments is 314. The system reliability is 6.7419×10^{-4} that is very low because of the number of pipes in minimum cut sets and the total number of *ENCOS* is 333.

The total cost, calculated by Eq.<3-1> to lay water-pipes underground, is $2,910,729 in 1987 and the U.S. dollar rate is ₩792.3 at that time. The cost can be approximately converted to the value of 2006 by using the consumer price index of each year. The value is ₩5,604,475,236. Besides, the valve installation cost for 354 valves in the system is ₩241,520,543 Therefore, the total cost is ₩5,845,995,479.



<Fig. 4-9> Chester Water Authority network

4.2.2. Rule 1

First of all, the pipes in minimum cut sets are divided into three types (Type1～3). After that, 1～2 valves are installed on the pipes in the Type 3 and then pipes in the Type 2 that its reliability is lower than 0.95 are replaced with ones which can make it more than 0.95 as shown in <Table 4-7>.

<Table 4-7> Application, Rule 1, CWA

ID	Diameter (inch)	Length (ft)	Reliability	Type	No. of valves	Diameter Increment (inch)	Cost (₩)
77032	2	906	0.781275	Type2		6	80,109,515
77034	2	903	0.781914	Type2		6	79,844,252
77162	2	841	0.795233	Type3	1		73,329
76981	6	2260	0.876908	Type2		10	307,412,767
77114	6	2028	0.888812	Type3	1		411,251
95511	4	1223	0.888822	Type3	1		210,413
79704	8	2519	0.899730	Type3	1		675,843
77151	8	2407	0.903966	Type2		10	359,342,236
77122	8	2406	0.904004	Type3	1		675,843
95513	4	956	0.911989	Type3	1		210,413
30323	20	4861	0.916027	Type3	1		3,602,240
126173	2	293	0.923279	Type2		2	19,894,638
P-558	6	1298	0.927335	Type2		4	129,153,216
77004	6	1140	0.935890	Type3	1		411,251
79894	2	243	0.935942	Type2		2	16,499,649
77241	8	1563	0.936542	Type3	1		675,843

<Table 4-7> Continued

ID	Diameter (inch)	Length (ft)	Reliability	Type	No. of valves	Diameter Increment (inch)	Cost (₩)
81719	8	1549	0.937092	Type2		4	172,138,746
76955	8	1507	0.938744	Type3	1		675,843
77016	8	1492	0.939335	Type3	1		675,843
77618	8	1466	0.940360	Type3	2		1,351,686
P-557	8	1444	0.941228	Type3	2		1,351,686
76953	6	1042	0.941235	Type2		2	92,134,785
P-561	8	1404	0.942809	Type3	1		675,843
241226	4	610	0.942910	Type3	1		210,413
77379	8	1388	0.943442	Type3	1		675,843
P-563	8	1342	0.945264	Type3	1		675,843
79651	8	1332	0.945661	Type2			0
76974	8	1331	0.945700	Type3	2		1,351,686
77165	8	1308	0.946613	Type3	1		675,843
238979	8	1262	0.948441	Type2			0
77139	10	1583	0.948827	Type3	1		1,004,190
79700	8	1250	0.948919	Type3	2		1,351,686
77238	8	1215	0.950313	Type2			0
76926	8	1215	0.950313	Type3	1		675,843
241276	4	526	0.950574	Type2			0
77082	6	821	0.953403	Type3	1		411,251
77355	8	1118	0.954187	Type2			0
95109	8	1113	0.954388	Type3	2		1,351,686
77326	8	1112	0.954428	Type3	1		675,843
95567	8	1111	0.954468	Type2			0
88126	4	466	0.956086	Type2			0

<Table 4-7> Continued

ID	Diameter (inch)	Length (ft)	Reliability	Type	No. of valves	Diameter Increment (inch)	Cost (₩)
77069	6	753	0.957179	Type3	1		411,251
229849	8	1043	0.957194	Type2			0
77232	8	1033	0.957595	Type2			0
79668	6	735	0.958181	Type3	2		822,502
81730	8	1010	0.958520	Type3	2		1,351,686
120274	8	1003	0.958801	Type2			0
81533	4	436	0.958854	Type3	2		420,826
77079	6	722	0.958905	Type3	1		411,251
76963	8	986	0.959485	Type2			0
77236	8	978	0.959807	Type2			0
Total					*38*		***1,280,684,776***

The results are as follows.

(1) The Pipes, “77032”, “77034”, “77162”, have low reliability respectively. So, they should be reinforced firstly in the Rule 1.

(2) The number of added valves is 38 and 9 pipes are replaced with ones which can make it more than 0.95 except for pipes that become 0.95 by rounding off the numbers to three decimal places.

(3) After applications, the total cost is ₩1,280,684,776 and there are 507 pipes which belong to minimum cut sets and the number of segments is 352. The system reliability becomes 1.1118×10^{-2} and the sum of $ENCOS$ is reduced to 183.

<Table 4-8> Results, Rule 1, CWA

	From	To
Cost (₩)	5,845,995,471	+1,280,684,776
Reliability	6.7419×10^{-4}	1.1118×10^{-2}
Sum of ENCOS	333	183
No. of valves	354	392
No. of reinforced pipes	-	9

4.2.3. Rule 2

To apply the Rule 2, the segments are sorted in a descending order according to their *ENCOS*. The segment having the biggest *ENCOS* should be reinforced firstly and the pipe which have the smallest reliability is the first object to be reinforced in the segment. In this case, the segments that their *ENCOS* is more than 10 are only considered.

After that, the pipes in minimum cut sets are divided into three types (Type1～3). 1～2 valves are installed on the pipes in the Type 3 and then pipes in the Type 2 that their reliability is lower than 0.95 are replaced with ones which can make it more than 0.95 except for pipes that become 0.95 by rounding off the numbers to three decimal places.

<Table 4-9> Application, Rule 2, CWA

Pipe ID	Dia. (in)	Lth. (ft)	Rel. (Pipe)	Seg. ID	Rel. (Seg.)	Fail. (Seg.)	NCOS	ENCOS	Type	No. of valve	Dia. Inc.	Cost (₩)
2407	8	2407	0.903966	S(202)	0.903966	0.096034	699	67	Type2		20	392,592,024
15	8	15	0.999371	S(207)	0.903436	0.096564	289	28	Type3	1		675,843
2406	8	2406	0.904004						Type3	1		675,843
143	8	143	0.994020	S(77)	0.854236	0.145764	165	24	Type2			0
1215	8	1215	0.950313						Type2			0
706	8	706	0.970821						Type2			0
219	8	219	0.990856						Type2			0
8	8	8	0.999664						Type2			0
1033	8	1033	0.957595						Type2			0
432	8	432	0.982043						Type2			0

<Table 4-9> Continued

Pipe ID	Dia. (in)	Lth. (ft)	Rel. (Pipe)	Seg. ID	Rel. (Seg.)	Fail. (Seg.)	NCOS	ENCOS	Type	No. of valve	Dia. Inc.	Cost (₩)
8	8	8	0.999664	S(11)	0.801102	0.198898	118	23	Type3	2		1,351,686
56	8	56	0.997654						Type2			0
41	8	41	0.998282						Type3	2		1,351,686
13	8	13	0.999455						Type3	2		1,351,686
1331	8	1331	0.945700						Type3	2		1,351,686
743	8	743	0.969315						Type3	2		1,351,686
19	8	19	0.999203						Type3	2		1,351,686
295	8	295	0.987702						Type3	1		675,843
14	8	14	0.999413						Type2			0
1466	8	1466	0.940360						Type3	2		1,351,686
67	8	67	0.997194						Type3	1		675,843
32	8	32	0.998659						Type3	2		1,351,686
16	8	16	0.999329						Type3	2		1,351,686
424	8	424	0.982372						Type3	2		1,351,686
26	8	26	0.998910						Type2			0
736	8	736	0.969600						Type3	2		1,351,686

<Table 4-9> Continued

Pipe ID	Dia. (in)	Lth. (ft)	Rel. (Pipe)	Seg. ID	Rel. (Seg.)	Fail. (Seg.)	NCOS	ENCOS	Type	No. of valve	Dia. Inc.	Cost (₩)
190	8	190	0.992062	S(12)	0.845289	0.154711	128	20	Type2			0
8	8	8	0.999664						Type2			0
150	8	150	0.993728						Type2			0
1118	8	1118	0.954187						Type2			0
653	8	653	0.972981						Type3	1		675,843
355	8	355	0.985220						Type2			0
21	8	21	0.999120						Type2			0
867	8	867	0.964286						Type2			0
6	8	6	0.999748						Type2			0
301	8	301	0.987454						Type2			0
338	8	338	0.985922						Type2			0
1507	8	1507	0.938744	S(156)	0.900711	0.099289	183	18	Type3	1		675,843
986	8	986	0.959485						Type2			0
10	6	10	0.999419	S(171)	0.875889	0.124111	135	17	Type2			0
10	6	10	0.999419						Type2			0
2260	6	2260	0.876908						Type2		16	307,412,767
735	6	735	0.958181	S(39)	0.948154	0.051846	286	15	Type3	2		822,502
181	6	181	0.989535						Type3	1		411,251

<Table 4-9> Continued

Pipe ID	Dia. (in)	Lth. (ft)	Rel. (Pipe)	Seg. ID	Rel. (Seg.)	Fail. (Seg.)	NCOS	ENCOS	Type	No. of valve	Dia. Inc.	Cost (₩)
1332	8	1332	0.945661	S(43)	0.945026	0.054974	195	11	Type2			0
16	8	16	0.999329						Type2			0
12	8	12	0.999497	S(17)	0.938851	0.061149	170	10	Type3	1		675,843
36	12	36	0.999001						Type3	2		2,792,582
69	12	69	0.998087						Type2			0
1455	12	1455	0.960416						Type3	2		2,792,582
695	12	695	0.980893						Type3	1		1,396,291
906	2	906	0.781275	S(30)	0.610890	0.389110	27	10	Type2		8	80,109,515
903	2	903	0.781914						Type2		8	79,844,252
Total										37		887,773,220

The results are as follows.

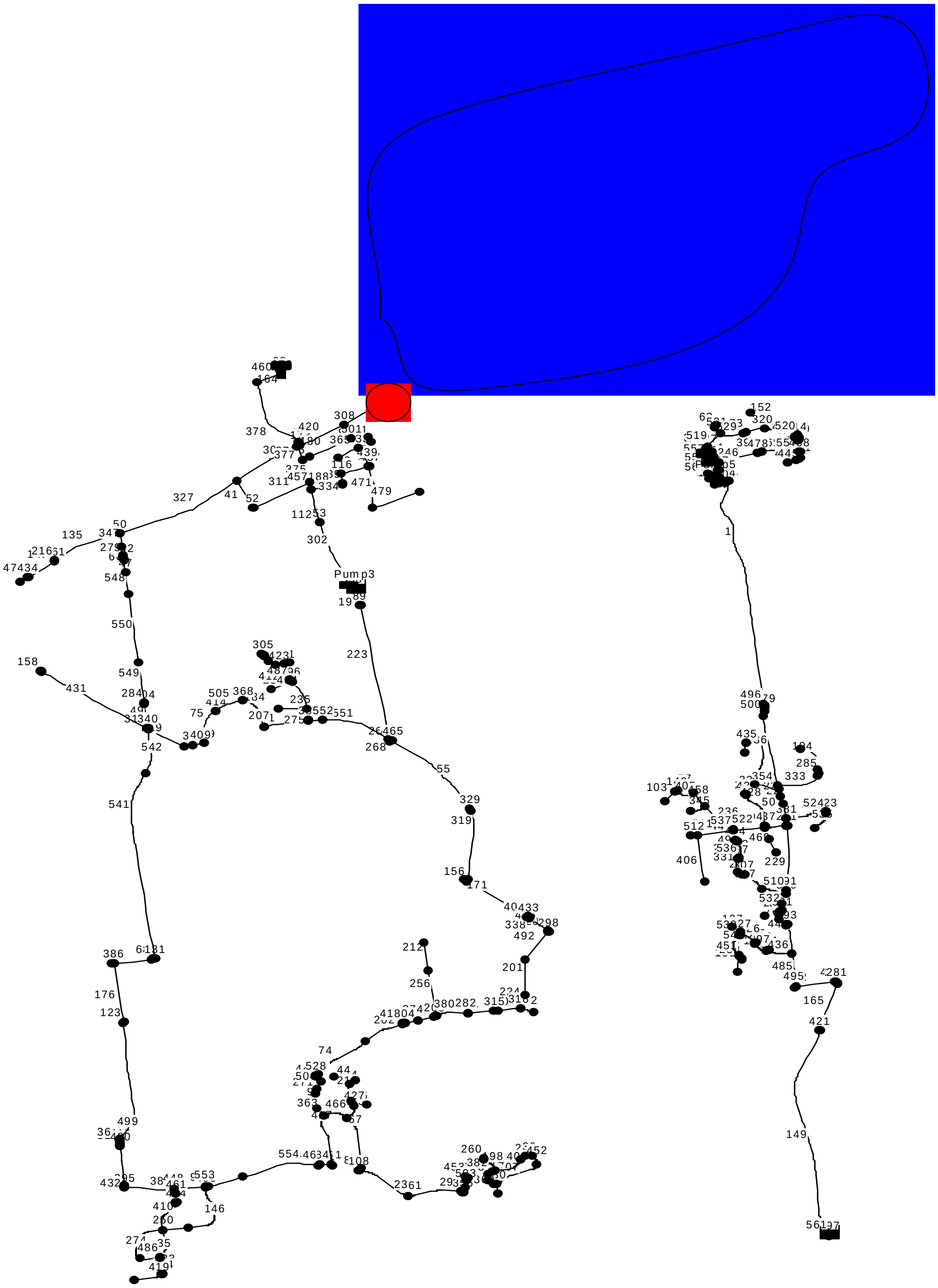
(1) If “2507” is broken, 699 customers will be out of service as shown in <Fig. 4-10>. So, it should be reinforced firstly in the Rule 2.

(2) The number of added valves is 37 and 4 pipes are replaced with ones which can make it more than 0.95.

(3) After that, the total cost is ₩887,773,220 and there are 514 pipes which belong to minimum cut sets and the number of segments is 351. The system reliability becomes 1.9884×10^{-3} and the sum of $ENCOS$ is reduced to 187.

<Table 4-10> Result, Rule 2, CWA

	From	To
Cost (₩)	5,845,995,471	+887,773,220
Reliability	6.7419×10^{-4}	1.9884×10^{-3}
Sum of ENCOS	333	187
No. of valves	354	391
No. of reinforced pipes	-	4

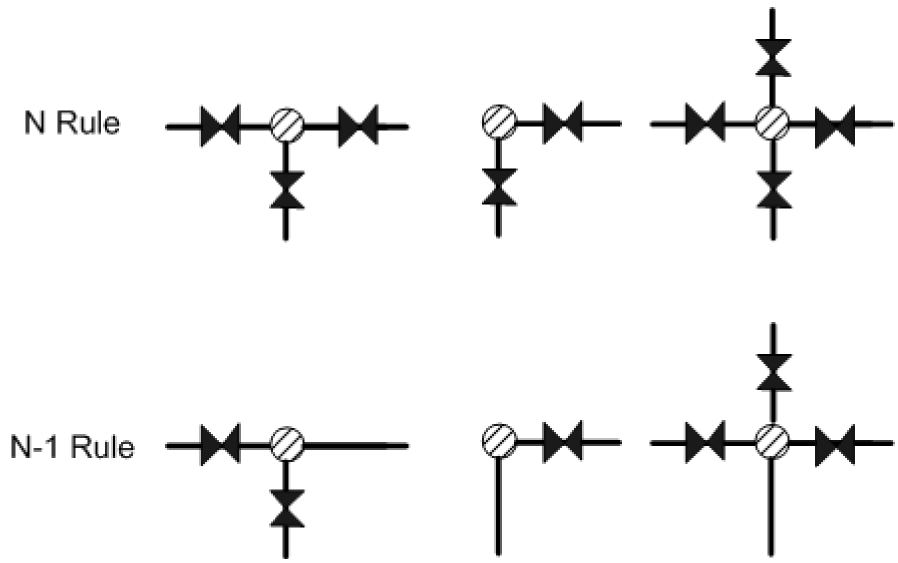


<Fig. 4-10> Vulnerable area in CWA network

4.2.4. Results and comparisons

In this chapter, the efficiency of each case is verified by comparing the rules(Rule 1, Rule 2) with the N-rule. Where the N-rule is installing valves on all pipes connected to a node, while N-1 rule is installing valves on all but one pipe.

<Fig. 4-11> shows the N-rule and the N-1 rule.



<Fig. 4-11> N Rule and N-1 Rule

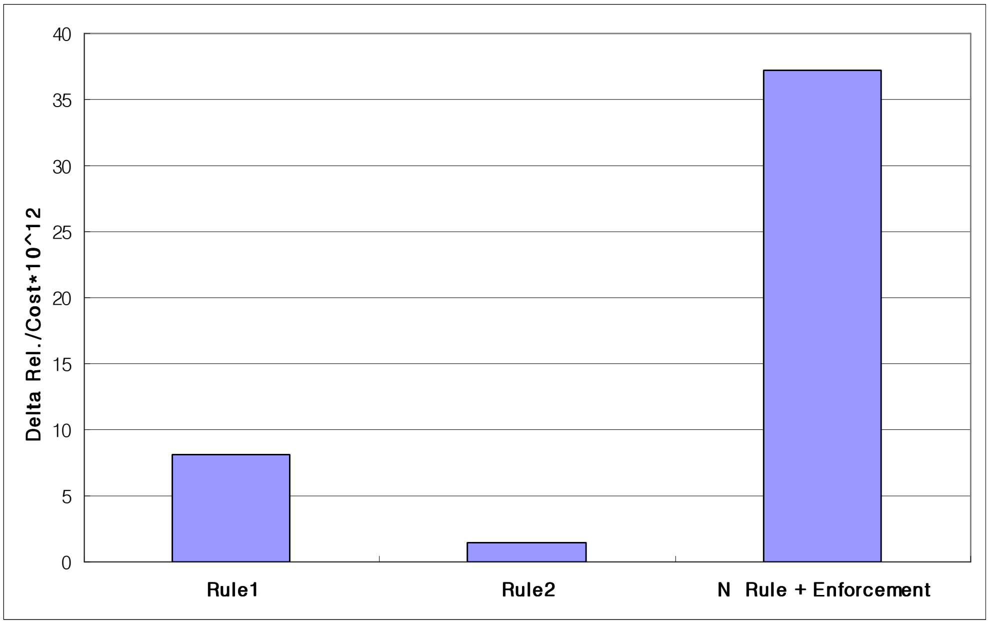
781 valves are added in the network to satisfy the N-rule. As a result, the number of pipes defined as minimum cut sets is 212 and the number of segments is 1,106. 20 pipes in the Type 2 that its reliability is lower than 0.95 are replaced with ones which can make it more than 0.95.

The system reliability is improved to 0.1132 and the sum of *ENCOS* is reduced to 105. The required cost is ₩3,019,319,006.

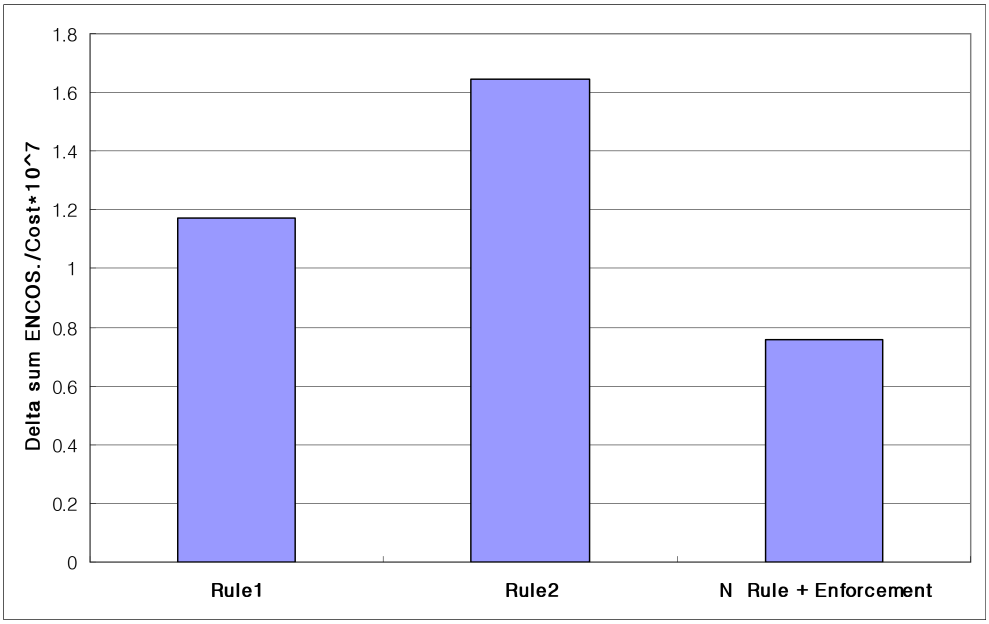
Since the required costs is different respectively, the increment of reliability and the decrement of total *ENCOS* per unit cost are calculated to compare the results relatively. <Table 4-11>, <Fig. 4-11~12> show the results.

<Table 4-11> Comparison of results among Rule 1, Rule 2 and N Rule (CWA)

	Cost (₩)	Reliability	Sum of ENCOS	$\Delta Rel./Cost \times 10^{12}$	$\Delta ENCOS/Cost \times 10^{7}$
Original	5,845,995,471	6.7419E-04	333	-	-
Rule1	+1,280,684,776	1.1118E-02	183	8.15	1.17
Rule2	+887,773,220	1.9884E-03	187	1.48	1.64
N Rule + Reinforcement (20 pipes)	+3,019,319,006	1.1316E-01	105	37.25	0.76



<Fig. 4-12> Increase of system reliability per unit cost



<Fig. 4-13> Decrease of ENCOS per unit cost

From the results, the Rule 1 is more effective than the Rule 2 to increase the system reliability while the Rule 2 is more effective than the Rule 1 to decrease the size of damage. As stated in the previous chapters, the rules should be applied to improvements of system reliability according to the purpose because they have different approaches respectively.

The particular point is that the system reliability is greatly improved by adopting the N rule. The reason is that the extent of damage by pipe failures can be reduced so that additional accidents might not occur comparing with others. From the result, it can be said that the intended goal should be the N rule in viewpoints of maintenance.

In spite of the effectiveness, realistically, the N rule might be a ideal goal because it is burdensome to apply the N rule to a real network. In the case of CWA, the total number of valves becomes 1,135 by adding new valves, 781. In actuality, it is hard to maintain and manage valves of such number even if the valve installation cost is not too high and installing all of them is possible. Because of such reasons, the presented methods can be a practical alternative plan to improve a system.

Although conditions of construction site are not considered in the results perfectly so that it can be said that they are unreal. it is expected that the rules and methods can be guidelines on plans to improve the system reliability according to the level of capability to maintain and manage systems.

Chapter 5. Summary and Conclusions

In this study, new methods are presented to improve the system reliability reasonably.

As the first step, the Park's model is chosen as a tool to analyze systems and study methods to improve the system reliability. The model can estimate the reliability more precisely and effectively than others. The advantages of the model are as follows: (1) The method ,suggested by Jun(2005) to determine the practical extent of damage owing to pipe failures, is used. (2) Calculation errors are minimized by using the "success mode approach". (3) The model can be used easily for large networks.

On the basis of the analysis of the model, the methods to improve the system reliability are summarized as follows. The first method is improving durability of each pipe in minimum cut sets. The second method is reforming a structure by installing valves to reduce additional damage. But increasing pipe durability without structural reforming is not a effective method to arise the system reliability. Hence, the methods should be combined adequately to improve it effectively.

For the work, a method is presented to determine types of reinforcement(Type 1~3). First, pipes in the "Type 1" do not need to be reinforced. Second, in the "Type 2", they are reinforced by increasing durability. Finally, one or two valves are installed on pipes in the "Type 3".

In addition to the method, the "Rule 1" and the "Rule 2" are proposed. they have its own purpose respectively. The "Rule 1" is focused on improvements of the on-off reliability. On the other hand, the "Rule 2" is focused on decreasing extent of damage by pipe failures. The "Rule 1" is more effective than the "Rule 2" to increase the system reliability while the "Rule 2" is more effective than the "Rule 1" to decrease the size of damage. They should be applied according to what the purpose is.

In conclusion, the methods can be guidelines on plans to improve system reliability under restricted conditions.

The follow-up researches which need to be done in the future are as follows.

(1) This study only suggests rough guidelines how to perform reinforcements to improve the system reliability. The Benefit-cost analysis should be performed to determine that reinforcements will be carried out to some degree.

(2) In this study, only installing valves is considered to do the structural reformation of WDSs because of its easy approaches in actuality. However, it is also needed to investigate the other methods; construction of alternative paths or water tanks.

(3) In addition to pipes, the reliability of other components also need to be considered to estimate the system reliability more practically.

(4) The model does not care about size of damage when estimating the system reliability. It is required to develop a model considering size of damage quantitatively.

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