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Development of new computational methods for identifying segments and estimating the risk of water supply interruption for a segment in water pipe networks

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ABSTRACT

In this paper, new algorithms for identifying segments and unintended isolations for water pipe networks were developed. The developed algorithms are based on the two topological relation data that are the connectivity relationships between the nodes and pipes and the location information of valves along pipes. The algorithms for identifying unintended isolation specifically utilized the connectivity relationships between the segments. The developed algorithms employ more efficient processes of finding pipes and nodes that are isolated by valve closure than the previous matrix-based algorithms. Moreover, the size of the matrices has been greatly reduced compared with the previous studies for more efficient calculations. The developed algorithms were implemented as computer programs using the Matlab software and applied to identify the segments and unintended isolation of a case study water pipe network. A new water supply risk estimation method that uses the deterioration scores of pipes, nodal demands, water rate, and average repair time was also presented. The risk estimation method was used to sort and prioritize the segments of the case study system for a further maintenance investment decision.

Keywords: Computational algorithms; Risk; Segment; Unintended isolation; Water pipe network

1. Introduction

The aging of the water pipes and the rise in living standards has resulted in an increase in water supply. As a result, the stability of the water supply network and the reliability in continuous water supply is becoming more important as the existing water pipes become deteriorated. Breakdown of the water pipes constituting the water supply systems occurs frequently, and causes isolation of a portion of the pipe network for repair or replacement after pipe breakage resulting in consumers without water supply until the recovery of the isolated portion of the network.

Disruption of water supply to water users will inevitably bring up the issues of a lack of the system reliability, incur financial losses, and social problems during the recovery period. Since failures of water pipes caused by the deterioration or other various causes are not completely predictable, it is very important to evaluate the risk of pipe failure and subsequent unintended isolation of a portion of pipe network to minimize the losses.

In water distribution systems isolation of a portion of pipe network is carried out by closing valves located a nearby failed pipe section. If the valves are not installed on the failed pipe section, valves installed on other sections of pipe, which are not failed, need to be closed. Closure of valves may cause all of the pipes and demand nodes that are inside the isolated area water supply interruption. Sections of pipes and demand nodes that are isolated in the event of a pipe failure and subsequent valve closure were termed as a 'segment' by Walski [1].

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Since the concept of segment has been established, many studies have been conducted to develop computational algorithms for searching and defining segments in water pipe networks. Previously developed methods utilized matrix operations [2–5] and mix of the matrix operations and hydraulic simulation [6,7].

Jun and Loganathan [2] suggested a method to find the segments using a topological incidence matrix representing the topological relations among pipes and nodes, and to calculate the unintended isolation using the deep search algorithm. Kao and Li [3] estimated the segments using a topological matrix and analyzed the risk. Alvisi et al. [4] developed an algorithm for searching for segments by using the vectors of auxiliary valve matrix and model valves. Gao [5] developed an algorithm to find the segments and unintended isolation of a pipe network including valves that controls the flow only in one direction using a topological incidence matrix. Gupta et al. [6] and Creaco et al. [7] utilized a topological incidence matrix to identify segments and incorporated pressure-driven hydraulic simulation techniques to evaluate the pressure and flow conditions inside an isolated portion of a pipe network.

In addition to the researches for segment retrieval in water distribution pipe networks, many studies on the risk and reliability analysis of water pipe networks were also conducted. Studziński and Pietrucha-Urbanik [8] proposed methods of water supply risk assessment expressed in monetary values under pipe failure conditions. Cubillo and Pérez [9] introduced a technique to assess water supply risk linked to structural elements, risk at consumption points, and overall system risk based on a concept of sector head risk coupled with hydraulic simulation. Sargaonkar et al. [10] calculated the reliability of water distribution network using contaminant ingress and pipe condition assessment models with GIS. To evaluate the reliability of a water pipe network under mechanical pipe failures methods utilizing hydraulic simulation have been applied. Giustolisi et al. [11] estimated the segments using a pressure-driven equation. Creaco et al. [7] reviewed two methods of segment retrieval using a topological incidence matrix as well as the modified version of the NSGA II. Gupta et al. [6] examined the effects of additional installation of valves and pipes to improve the reliability of the water distribution network by hydraulic analysis.

In this paper, new algorithms for identifying segments and unintended isolation for water pipe networks were developed. The developed algorithms are based on the two topological relation data that are the connectivity relationships between the nodes and pipes and the location information of valves along pipes. The algorithms for identifying unintended isolation utilized the developed method for representing connectivity relationships between segments in this study.

The developed algorithms employ more efficient processes of finding pipes and nodes that are isolated by valve closure than the previous matrix-based algorithms. Moreover, the size of the matrices has been greatly reduced compared with the previous studies such as Gupta et al. [6], Jun and Loganathan [2], and Creaco et al. [7] for more efficient calculations. The developed algorithms were implemented as computer programs using the Matlab software.

Also, in this study, a new water supply risk estimation method that uses the deterioration scores of pipes, nodal demands, water rate, and average repair time was also presented. The calculated risk represents the loss of revenue for the water supply system operator due to the water lost during segment isolation. The loss of revenue was calculated as the water rate that is not collected due to segment isolation. The risk estimation method was used to sort and prioritize the segments of the case study system for further maintenance investment decision.

The risk calculation method developed in this study evaluates the risk of water supply interruption for a segment whereas the previous hydraulic simulation-based methods estimated the nodal risks under pipe failure conditions. Also, the previous methods using the mix of matrix operations and hydraulic simulation methods calculated the overall system-wide risks based on the calculated nodal risks under the normal operating condition utilizing fictitious reservoirs [7] and different valve layouts and node flow analysis [6].

2. The segment search algorithm

In the case of pipe failure in a water distribution system the failed section of pipe need to be isolated for repair by closing nearby valves. If the valves are not installed on the failed pipe section, valves installed on other sections of pipe that are not failed need to be closed causing isolation of sections of pipes that are not failed and demand nodes that are inside the isolated area by valve closure. This isolated section of pipe and demands nodes in the event of pipe failure and subsequent valve closure was termed as 'segment' by Walski [1].

Defining pipe segments for a real-world water distribution pipe networks using only eyes are practically impossible due to the enormous size. In this study, a computation algorithm for defining segments in water distribution pipe networks was developed (Fig. 1).

The computational algorithm for searching and defining pipe segments was developed by analyzing the continuity of pipes through nodes without valves. The algorithm requires Node-Pipe number (NP) matrix and Node-Pipe-Valve (NPV) matrix. NP matrix represents pipes that are connected to a node. NPV matrix shows valve installation status for a pipe that is connected to a node by 0 or 1. If a valve is installed on a pipe, the corresponding value in NPV matrix is assigned as 1. NP and NPV matrix for a pipe network shown in Fig. 2 are presented in Table 1.

2.1. Identifying segments using the NP and NPV matrix

The segment search algorithm shown in Fig. 1 starts with a node which has at least one '0' value in the NPV matrix. For example, the sample pipe network shown in Fig. 2, a segment that contains node 2 consists of nodes 2 and 4, and pipes P2 and P5. This segment can be identified by starting with node 2 in the NPV matrix that has a '0' at the third column. The value at the corresponding location, which is the third column, in the NP matrix of this '0' is '2'. This means that pipe P2 is connected to node 2 without a valve, which means that node 2 and pipe 2 together forms a segment.

Then, the algorithm finds a node that is connected at the other end of pipe P2 by searching for another '2' in the

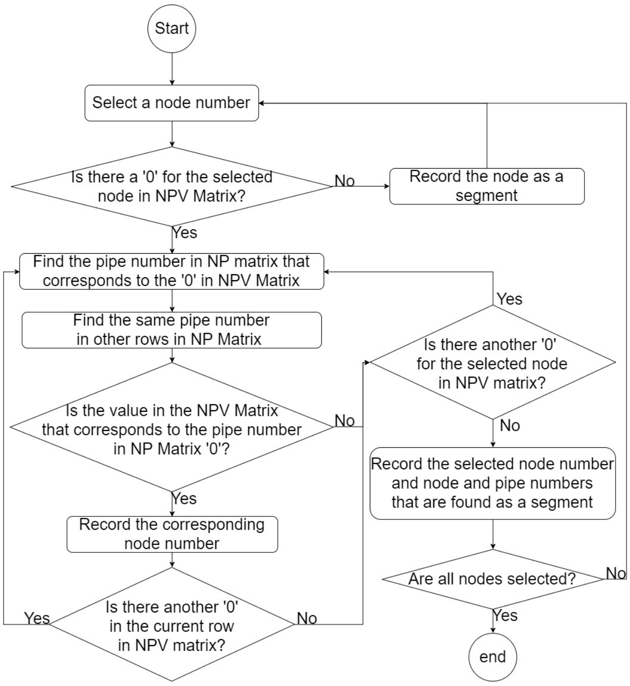

Fig. 1. Algorithm for defining segments in water distribution pipe networks.

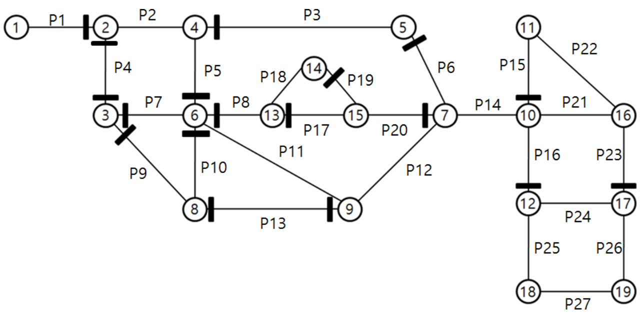

Fig. 2. Sample pipe network for segment and unintended isolation identification.

NP matrix, which is located at row 4 and column 2 in the matrix. The corresponding node for this '2' is node 4. The algorithm checks if there is a valve on pipe P2 adjacent to node 4 by the value at row 4 and column 2 in the NPV matrix, which corresponds to the last location of pipe P2 in the NP matrix. Since this value is '0', the algorithm finds a pipe that is connected to node 4 without a valve by searching for a '0' along the row where node 4 is located in the NPV matrix. The algorithm finds pipe P5 at row 4 and column 4 in the NPV matrix, which corresponds to the location of the '0' other than the already checked '0' in the NP matrix. Then, the algorithm finds a node that is connected at the other end of pipe P5 by searching for another '5' in the NP matrix, which is located at row 6 and column 2. Since the corresponding value for this '5' in the NPV matrix is '1', the algorithm stops searching and reports the collected nodes 2 and 4 and pipes P2 and P5 as a segment. Then, the algorithm begins another search for a segment until all nodes in the network are examined.

Table 1
NP and NPV matrix for the sample pipe network

NP matrix						NPV matrix					
Node no.	Pipe no.					Node no.	Valve status				
1	1					1	0				
2	1	2	4			2	1	0	1		
3	4	7	9			3	1	1	1		
4	2	3	5			4	0	1	0		
5	3	6				5	0	1			
6	5	7	8	10	11	6	1	0	1	1	0
7	6	12	14	20		7	0	0	0	1	
8	9	10	13			8	0	0	1		
9	11	12	13			9	0	0	1		
10	14	15	16	21		10	0	1	0	0	
11	15	22				11	0	0			
12	16	24	25			12	1	0	0		
13	8	17	18			13	0	1	0		
14	18	19				14	0	1			
15	17	19	20			15	0	0	0		
16	21	22	23			16	0	0	0		
17	23	24	26			17	1	0	0		
18	25	27				18	0	0			
19	26	27				19	0	0			

The sizes of the NP and NPV matrix generated during the developed algorithm depend on the number of nodes and pipes connected to a node. If we assume the maximum number of pipes that are connected to a node is six, the size of the NP matrix is ($n \times 6$), which is the same for the NPV matrix.

The size of the similar matrices used in Gupta et al. [6] is $((n + v) \times (n + v))$, Jun and Loganathan [2] ($n \times p$), and Creaco et al. [7] $((n + p + 2v) \times (n + p + 2v))$, where n is the number of nodes, p the number of pipes, and v the number of valves. Therefore, the size of the matrices generated during the calculation process in this study was greatly reduced compared with the previous studies. As a result, the segment search algorithm developed in this study is more efficient in identifying segments in real water supply pipe network in which thousands of nodes and pipes are easily found.

Table 2 shows the S_Node matrix that represents the segments of the sample pipe network identified by the algorithm of Fig. 1 and the corresponding nodes. Table 3 shows the S_Pipe matrix that represents the segments of the sample pipe network and the corresponding pipes. Fig. 3 shows the identified segments for the sample pipe network in color.

2.2. Algorithms for identifying unintended isolation

Closing valves in a water pipe network may incur sections of downstream pipes closed unintentionally. This phenomenon occurs due to the layout of pipe network and location of the valves in it. It is essential to identify these segments of pipes unintentionally closed which are called 'Unintended Isolation' for proper estimation of risks involved in the water pipe network operations and maintenance.

Table 2
S_Node matrix of the sample pipe network

Segment no.	Node no.					
1	1					
2	2	4				
3	3					
4	5					
5	6	7	9	10	11	16
6	8					
7	12	17	18	19		
8	13	14				
9	15					
10						
11						

Table 3
S_Pipe matrix of the sample pipe network

Segment no.	Pipe no.									
1	1									
2	2	5								
3										
4	3									
5	6	7	11	12	14	15	16	21	22	23
6	9	10								
7	24	25	26	27						
8	8	18								
9	17	19	20							
10	4									
11	13									

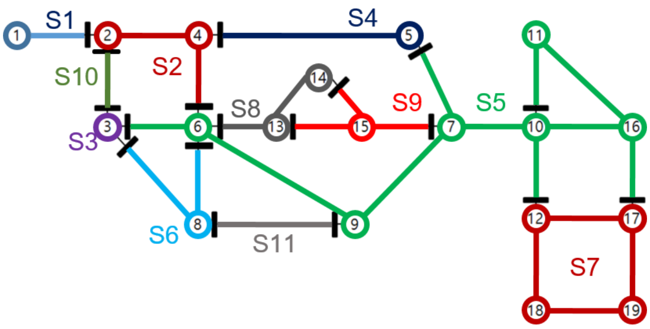

Fig. 3. Identified segments for the sample pipe network.

To identify unintended isolation information on the connectivity of segments is required. Therefore, a computational algorithm for identifying the connectivity of segments shown in Fig. 4 was developed using S_Node matrix, S_Pipe matrix, and NP matrix.

The algorithms shown in Fig. 4 utilize 'Connected Segments (CS) Matrix' which represent operational status of segments for a pipe network. Table 4 shows the connectivity and operational status of the segments, for example, pipe network. The 'Connected Segments Matrix' in Table 4 shows the connectivity of the segments of the sample network by

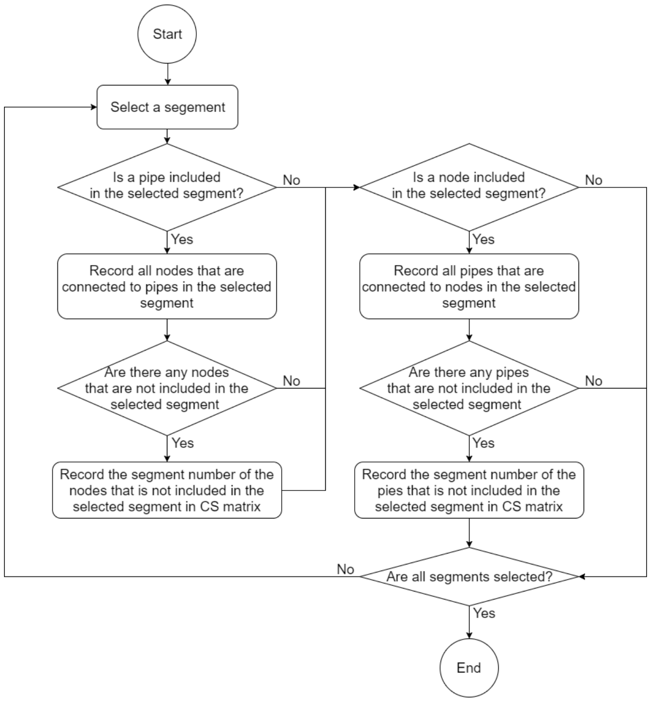

Fig. 4. Algorithms for analyzing the connectivity of segments.

enumerating all of the other connected segments for the segments listed in the left-most column. The '0' values in the 'Operational Status Matrix' represent that water flows through the segments listed under 'Connected Segments'.

A computational algorithm for searching and defining unintended isolation was developed by analyzing the connected segments and operational status matrix up to a water source or sources. The developed unintended isolation of segment search algorithm is shown in Fig. 5.

The unintended isolation algorithm utilizes the segment relation such as the one shown in Table 4. The algorithm starts by assuming a no-flow condition for a segment in Table 4, which occurs in the case of a leak and corresponding repair activities. For example, the sample pipe network shown in Fig. 5, if segment 5 is closed, the values for segment 5 in operational status matrix is replaced with '1' such as shown in Table 5.

Using Table 5 unintended isolation for segment 5 can be identified for the sample pipe network in which segment 1 includes the water source. Each segment listed in the left-most column of Table 5 is examined to determine whether the segment is an unintended isolation of segment 5. For example, whether segment 2 is an unintended isolation of segment 5 or not can be examined as follows. Segment 2 is connected to the source by noting the '0' value in operational status matrix which is found at the corresponding location of segment 1 in the connected segments matrix. Therefore, segment 2 is not an unintended isolation of segment 5.

Applying the same procedure reveals that segments 3, 4, and 6 do not become an unintended isolation of segment 5. On the other hand segment 7 is connected only to segment 5, which is closed in this case, resulting in an unintended isolation of segment 5. After examining the connectivity to the source for all segments in Table 5, the unintended

Table 4
Connected segments and operational status matrix

Segment no.	Connected segments matrix								Segment no.	Operational status matrix							
1	2								1	0							
2	1	4	5	10					2	0	0	0	0				
3	5	6	10						3	0	0	0					
4	2	5							4	0	0						
5	2	3	4	6	7	8	9	11	5	0	0	0	0	0	0	0	0
6	3	5	11						6	0	0	0					
7	5								7	0							
8	5	9							8	0	0						
9	5	8							9	0	0						
10	2	3							10	0	0						
11	5	6							11	0	0						

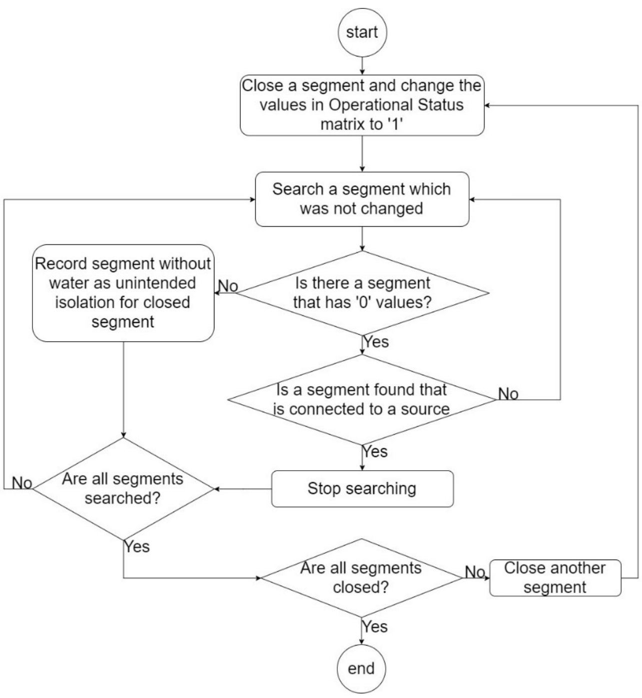

Fig. 5. Algorithms for identifying unintended isolation.

isolation of the sample pipe network for a segment is shown in Table 6. As a result, it was found that all of the segments downstream of segment 2 are unintended isolation of segment 2, and segments 7, 8, and 9 are unintended isolation of segment 5.

Table 7 shows a hierarchy tree of the sample network for representing the connectivity of the segments including unintended isolation. Each segment in a segment hierarchy tree can be regarded as an upstream segment if it has downstream segments.

2.3. Estimation of the risk of segments

In general risk is defined as Eq. (1).

$$\text{Risk} = \text{probability of failure} \times \text{effects of failure} \tag{1}$$

In this study, the risk of water supply interruption was estimated for a segment in a pipe network. Since the water supply risk for a segment is to be estimated, the probability in Eq. (1) should represent the probability of a malfunction of a segment. The effects of failure in Eq. (1) represent the negative effects of a malfunction of a segment. If a segment does not cause unintended isolation, which means it is at the last stratum of the segment hierarchy, the effects of failure are restricted to the negative effects of malfunction of the segment itself. On the other hand, if a segment causes unintended isolation, which means it is above the last stratum of the segment hierarchy, the effects of failure occurred in unintendedly isolated segments downstream must be considered.

The probability of a malfunction of a segment can be obtained by taking the average of or the highest value among the pipe failure probabilities in a segment. The effects of failure can be estimated as a form of a financial loss, volume of water lost, loss of revenue, or number of consumers affected by water supply interruption.

In this study, the risk of water supply interruption for the case study pipe network was evaluated for each segment as Eq. (2).

$$\text{Risk of segment} = \text{average of deterioration scores for the pipes in the segment and the corresponding upstream segments} \times \text{loss of revenue due to segment isolation} \tag{2}$$

If a segment is an unintended isolation of a segment, the deterioration conditions of the pipes in the upstream segments must also be considered since, if there exists isolation of upstream segment due to a pipe failure, the water supply in downstream segment is inevitably interrupted.

The average pipe deterioration scores were used in place of the probability of pipe failure to provide the managers of water supply systems with a more practical method to calculate the risk of water supply interruption. Considering the lack of detailed data required for estimating the effects of pipe failure in the case study area and to facilitate the calculations of the effects of pipe failure in calculating the risk of segments, the effects of pipe failure were evaluated as the loss of revenue for water supply system operator due to segment isolation using Eq. (3).

Table 5
Segment relations for the case of closing segment 5 in the sample pipe network

Segment no.	Connected segments matrix								Segment no.	Operational status matrix							
1	2								1	0							
2	1	4	5	10					2	0	0	1	0				
3	5	6	10						3	1	0	0					
4	2	5							4	0	1						
5	2	3	4	6	7	8	9	11	5	0	0	0	0	0	0	0	0
6	3	5	11						6	0	1	0					
7	5								7	1							
8	5	9							8	1	0						
9	5	8							9	1	0						
10	2	3							10	0	0						
11	5	6							11	1	0						

Table 6
Unintended isolation for the sample pipe network

Segment no.	Unintendedly isolated segment no.									
1	2	3	4	5	6	7	8	9	10	11
2	3	4	5	6	7	8	9	10	11	
3										
4										
5	7	8	9							
6										
7										
8										
9										
10										
11										

Table 7
Segment hierarchy tree of the sample network

Rank	Segment no.							
1	1							
2	2							
3	3	4	5			6	10	11
4			7	8	9			

Loss of revenue (US$) = nodal demands in a segment and the corresponding downstream segments (m^3/h) × water rate (\$/m^3) × average repair time (h) (3)

Eq. (3) represents the amount of the value of water that is not collected by the water supply system operator during the downtime of a segment.

2.4. Applications to the case study pipe network

The case study water supply system is consisted of one water supply source and 242 pipes which amounts 30.414 km of total length. The number of nodes and valves in this system is 239 and 38, respectively. An EPANET hydraulic simulation computer file for the system was available to obtain the average daily nodal demands in the system. Fig. 6 shows the pipe network map of the case study water supply system presented by the EPANET program.

The connectivity relationships between nodes and pipes and the location information of valves along pipes of the case study system were organized as Table 8 and used as a sample of the input file of the developed Matlab computer program. The valve locations data shown in Table 8 represent the node number to which a valve is located close.

As a result, 30 segments for the case study system were identified. The program also identified unintended isolations in the system. Fig. 7 shows a sample result of the identified segments and corresponding unintended isolations in the case study system. The identified unintended isolations showed that there are eight ranks in the hierarchy of the segments of the system.

The water supply interruption risks of the segments in the case study system were evaluated based on Eqs. (2) and (3). For example, the water supply interruption risk of segment 19, which is US$602.2, was obtained using Eq. (4) by multiplying the average of the deterioration scores of the pipes in segment 19 and the upstream segments (segments 1 and 3) and the total loss of revenue for segment 19 and the unintendedly isolated segments that are segments 4, 5, 6, 28, and 7.

$$\text{Risk of segment 19} = \{(ADS\_19 + ADS\_1 + ADS\_3)/3\} \times (LR\_19 + LR\_4 + LR\_5 + LR\_6 + LR\_28 + LR\_7) \quad (4)$$

where ADS represents the average deterioration score of the pipes in a segment and LR the loss of revenue for a segment.

The ADSs for the pipes in Eq. (4) was obtained from the Pipe Network Performance Evaluation Report [12] for the case study system. In reference [12], the pipe deterioration scores were calculated based on the point assignment scheme for water pipes that utilizes the numerical values assigned for each pipe depending on various characteristics and the surrounding environment of pipes such as soil type, water pressure, and pipe material and size. The range of the pipe deterioration scores for the case study system is from 0 to 1.

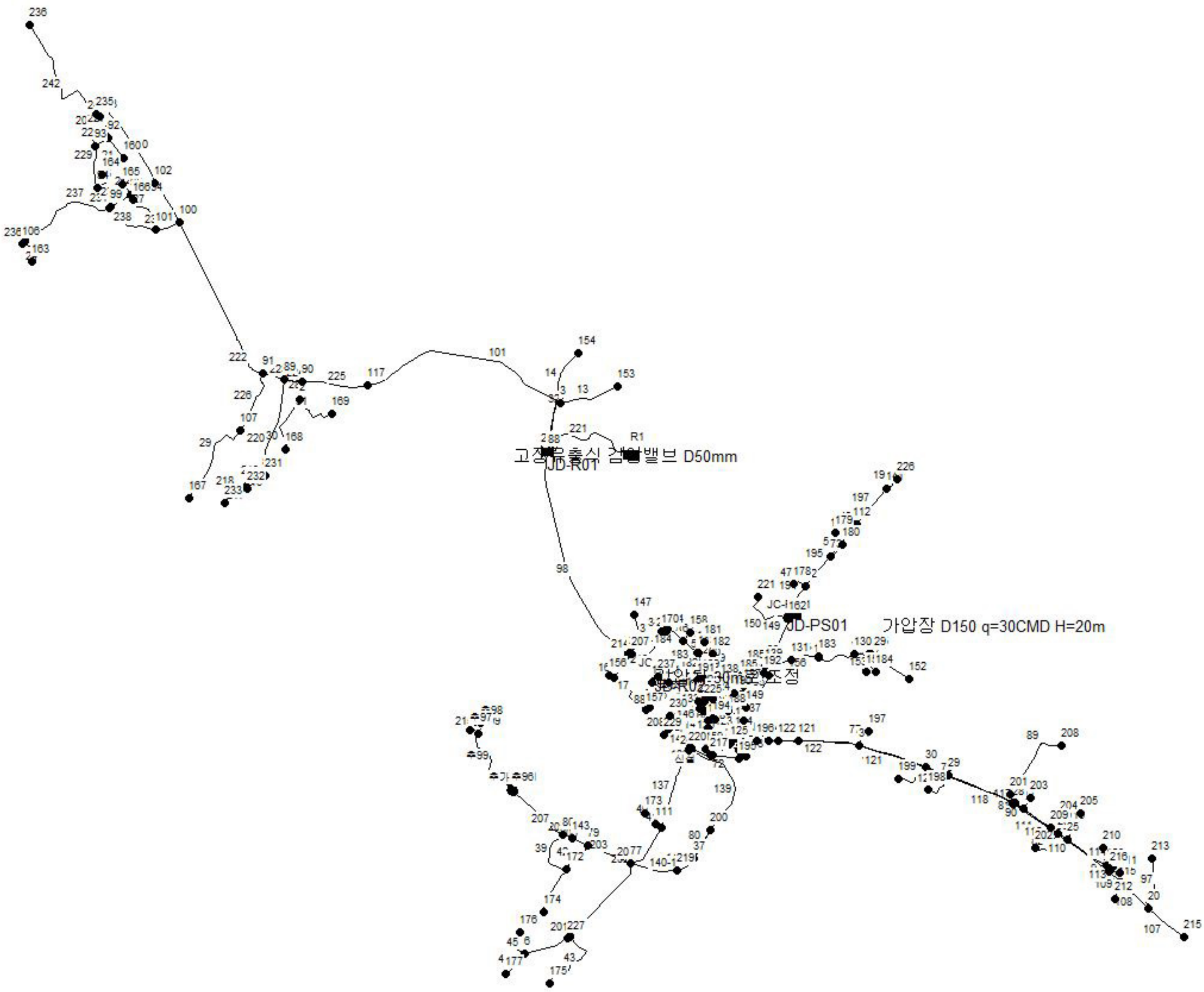

Fig. 6. The pipe network map of the case study water supply system presented by the EPANET program.

Table 8
Input file of the developed Matlab program to determine segments of the case study system

Pipe no.	Pipe ID	Start node	End node	Valve location	
229	JC/JC/01/042/2	95	99	99	0
230	JC/JC/01/043/2	102	95	102	0
231	JC/JC/01/045/2	100	102	100	0
232	JC/JC/01/040/2	96	106	0	0
233	JC/JC/01/039/2	98	96	0	0
234	JC/JC/01/038/2	97	98	97	0
235	JC/JC/01/149/2	101	99	91	0
236	JC/JC/01/148/2	100	101	100	0
237	JC/JC/01/095/2	102	145	102	145

In calculating the loss of revenue in Eq. (4) the nodal demands in segment 19 and the downstream segments (segments 4, 5, 6, 28, and 7) were obtained from the EPANET program of the case study system. The water rate was used as US$1/m^3 and the average pipe repair time was assumed as 5 h for the case study system. Table 9 represents a portion of the segment hierarchy with the calculated risks for the case study system.

In Table 9, the numbers outside the parentheses represent the ID of the identified segments and the numbers inside the parentheses the estimated risk of the corresponding segment. Fig. 8 shows the frequency histogram of the estimated water supply interruption risks of the segments for the case study system. The range of the calculated risk is from US$0 to US$10,874.

28 segments had the risk lower than US$1,000. Among the 30 segments found, three segments were found to have zero risk since these segments were consisted of only one node and no pipes. Fig. 9 shows the histogram of the estimated risks for the segments under $700.

It is considered that the segments with higher risk should be assigned higher maintenance priority. Table 10 shows the segments sorted for the prioritization of the maintenance according to the magnitude of risk.

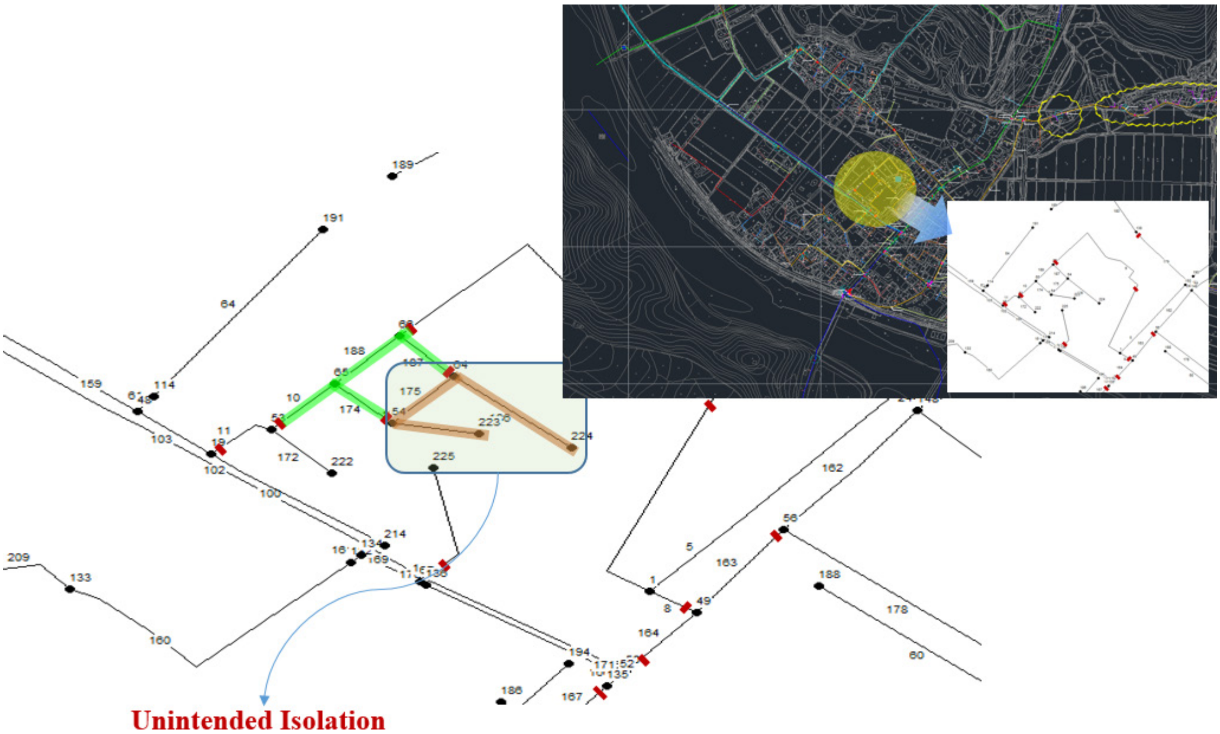

Fig. 7. Sample result of the identified segment and corresponding unintended isolation.

Table 9
Sample of the calculated risk of segments organized as a hierarchy for the case study system

Rank	Segment no. [risk (US$)]						
1	1[10,873.9]						
2	3[3,521.8]			8[105.6]	22[15.3]	24[3.0]	26[209.6]
3	9[38.9]	19[602.2]	21[24.6]				18[215.8]
4		4[560.5]					2[210.1]
5		5[544.3]					10[171.4]
6		6[481.8]					
7		28[419.1]					
8		7[394.9]					

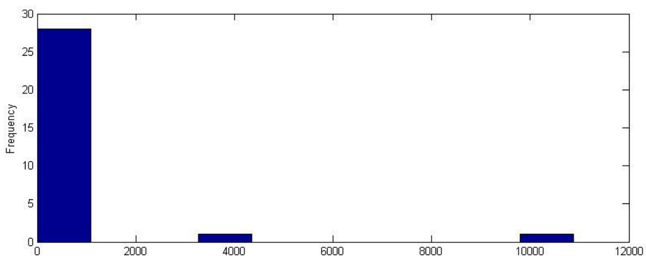

Fig. 8. Frequency histogram of the estimated risks.

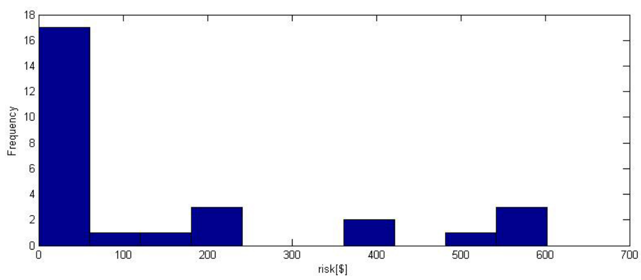

Fig. 9. Frequency histogram of the estimated risks under $700.

3. Conclusions

In this study, computational algorithms were developed to search and identify the segments and unintended isolations of water distribution pipe networks. The developed algorithms employ much smaller matrices, which are generated during the processes of finding the segments, than the ones used in the previous methods resulting in more efficient calculations of identifying the segments and unintended isolations.

Table 10
Segments sorted for the maintenance prioritization according to the magnitude of risk

Maintenance priority	Segment no.	Risk ($)	Maintenance priority	Segment no.	Risk ($)
1	1	10,873.9	16	9	38.9
2	3	3,521.8	17	11	34.2
3	19	602.2	18	21	24.6
4	4	560.5	19	22	15.3
5	5	544.3	20	13	12.3
6	6	481.8	21	20	4.7
7	28	419.1	22	12	4.6
8	7	394.9	23	15	3.8
9	18	215.8	24	24	3.0
10	2	210.1	25	16	2.9
11	26	209.6	26	25	2.8
12	10	171.4	27	14	1.6
13	8	105.6	28	17	1.0
14	29	59.3	29	27	0.0
15	23	55.5	29	30	0.0

The developed algorithms were programmed using the Matlab software and applied to a real-world water distribution pipe network. As a result, 30 segments and eight ranks of unintended isolations in the hierarchy of the segments were found in the case study system. The hierarchy of the segments established for the system may provide the water supply system managers with a visual assistant for a holistic understanding the water supply interruption risk of the network.

In this study, a method for calculating the water supply interruption risk of the segments that can present the risk as a monetary value was also suggested. The method utilizes data such as pipe deterioration scores that are relatively easier to obtain than the individual pipe's failure probability which is generally very difficult to estimate. The characteristics of the distribution of the risks in the system were analyzed and the priority of maintenance among the segments was established using the new risk estimation method.

The risk estimation method used in this study is expected to provide the water supply system managers and operators with a more practical meaning for using the estimated risks in more efficient maintenance of their pipe networks. The probability of working conditions of valves may well be considered in the future study for estimating more realistic risks of water supply interruption.

Acknowledgment

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References

[1] T.M. Walski, Water distribution valve topology for reliability analysis, Reliab. Eng. Syst. Saf., 42 (1993) 21–27.
[2] H. Jun, G.V. Loganathan, Valve-controlled segments in water distribution systems, J. Water Resour. Plann. Manage., 133 (2007) 145–155.
[3] J. Kao, P. Li, Segment-based vulnerability analysis system for a water distribution network, Civil Eng. Environ. Syst., 25 (2008) 41–58.
[4] S. Alvisi, E. Creaco, M. Franchini, Segment identification in water distribution systems, Urban Water J., 8 (2011) 203–217.
[5] T. Gao, Efficient identification of segments in water distribution networks, J. Water Resour. Plann. Manage., 140 (2014) 04014003.
[6] R. Gupta, A. Baby, P.V. Arya, L. Ormsbee, Upgrading reliability of water distribution networks recognizing valve locations, Procedia Eng., 89 (2014) 370–377.
[7] E. Creaco, M. Franchini, S. Alvisi, Optimal placement of isolation valves in water distribution systems based on valve cost and weighted average demand shortfall, Water Resour. Manage., 24 (2010) 4317–4338.
[8] A. Studziński, K. Pietrucha-Urbanik, Risk indicators of water network operation, Chem. Eng. Trans., 26 (2012) 189–194.
[9] F. Cubillo, P. Pérez, Water distribution system risk assessment method, Procedia Eng., 89 (2014) 355–362.
[10] A. Sargaonkar, S. Nema, A. Gupta, A. Sengupta, Risk assessment study for water supply network using GIS, J. Water Supply Res. Technol. AQUA, 59 (2010) 355–360.
[11] O. Giustolisi, Z. Kapelan, D. Savic, Algorithm for automated detection of topological changes in water distribution networks, J. Hydraul. Eng., 134 (2008) 435–446.
[12] Korea Environment Corporation (KEC), Taebaek Area Waterworks Pipe Network Optimum Management System Building Basic Plan Report, 2010, pp. 873–887.