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ScienceDirect
Procedia Engineering 89 (2014) 1168 – 1175
Procedia Engineering
www.elsevier.com/locate/procedia

16th Conference on Water Distribution System Analysis, WDSA 2014

Segment-Based Reliability/Supply Short Fall Analysis of Water Distribution Networks

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Abstract

Pipe failure is a major parameter affecting the reliability of a water distribution network (WDN). A WDN consists of isolation valves which are closed to isolate a failed pipe for repairs. Depending up on the location of valves, a group of pipes termed as a segment gets isolated. Herein, reliability is estimated based on supply shortfall considering isolation of an appropriate segment on failure of a pipe. Supply shortfall is obtained using node flow analysis. An existing water main system is chosen as an example to compare the reliability values obtained by considering the actual location of valves and valves in each pipes on either end.

Peer-review under responsibility of the Organizing Committee of WDSA 2014
*Keywords:*Reliability; segment analysis; shortfall analysis; water distribution system.

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1. Introduction

Water distribution networks (WDNs) deliver treated water to the users and aim in fulfilling the varying water demands of the users. The performance of a WDN is affected by several factors such as failure of its components like pipes, valves and pumps, variation in nodal demands, variation in pipe roughness due to deterioration of pipe surface, power failure, etc. How well a WDN can perform under such uncertain conditions can be indicated through its reliability. In general, reliability is defined as the probability that a system performs its mission within specified limits for a given period in a specified environment [1]. A significant amount of research work has been completed on the reliability of water distribution systems in the last three decades. This work is reviewed from time to time by many

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Peer-review under responsibility of the Organizing Committee of WDSA 2014
doi:10.1016/j.proeng.2014.11.244

researchers ([2-4], etc).In order to improve the reliability of a WDN in situations of failure due to mechanical factors, it is necessary to install a system of isolation valves which, during the time of failure, will help isolate the failed component from the sources [5-6]. However, the N and N-1 rule for valve placement is usually not followed. Thus, the failure of a pipe would result in the closure of the part of the network (segment), containing the pipe, so that it is isolated (from the source) and thus can undergo maintenance without disrupting services across the network or in large parts of it [5-6]. Walski [6] defines a segment as the portion of the network that can be isolated by closing valves. Segment based reliability analysis and design of water distribution network is a recent field of research. In the literature there are a number of studies regarding segment identification and the undesired disconnections that occur following the closure of a set of isolation valves e.g., [7-11]. In particular, the methods proposed by Jun and Loganathan [7] and Li and Kao [8] are based on a dual representation of the network, with segments treated as nodes and valves as links to identify the unintended segments. The methods proposed by Giustolisi et al. [9], Creaco *et al.* [10], and Giustolisi and Savic [11],used hydraulic simulations to identify nodes belonging to different segments. Alvisi *et al.*[12] used classic topological incidence matrices to identify the segments. Gao[13] used a method based on the theory of transitive closure of graphs. Kaldenbach and Ormsbee[14] proposed a simple algorithm to identify intended and unintended segments based on a node-node connectivity matrix in which valves are also treated as nodes. This methodology with slight modifications, as explained later, has been used herein to avoid duplication of both nodes and pipes in different segments. Li and Kao [8] carried out segment-based supply short fall analysis by repetitive use of EPANET. Creaco et al [15] showed that water supply shortfalls obtained through complete hydraulic simulation of networks connected to a source using pressure-driven simulations are better than shortfalls obtained as the total sum of water demand not delivered to isolated consumers. Gupta and Bhave[1] suggested a methodology for reliability analysis in which reliability of a WDN is assessed through three reliability parameters - node reliability, volume reliability and system reliability. They considered isolation of each pipe separately by assuming isolation valves at either ends of a pipe. In this paper, an algorithm for segment-based reliability analysis of WDNs is presented with the following assumptions:

- Even though withdrawal points are distributed along links, these points are aggregated and assumed to be concentrated at nodes.
- Nodal demands are known with certainty.
- No storage is considered to be available in the system, whether at the source or at the consumer point.

The methodology of Kaldenbach and Ormsbee[14] is used with slight modifications for the automatic segment identification of a WDN which recognizes the exact location of valves. Node flow analysis of the network is carried out to determine the available flows under pipe failure condition by considering both available pressure and required demand simultaneously using EPANET 2.0 directly by considering additional components at demand nodes as suggested by AbdySayyed et al. [16], thus, avoiding the repetitive use of EPANET [8]. Node, volume and system reliability are then used to quantify reliability as suggested by Gupta and Bhave[1]. , using the parabolic node head-flow relationship [17].

2. Segment analysis model

A method suggested by Kaldenbach and Ormsbee [14] for segment identification is used with slight modifications. The suggested modification avoids the duplication of nodes, pipes and valves in different segments. The suggested modifications in the methodology of Kaldenbach and Ormsbee to avoid duplication of nodes is to search both, the Skip List and the existing Search List, whenever a connection is found instead of searching only the Skip List. Similarly, duplication of pipes and valves can be avoided by checking the Segment's Pipe List and Valve List respectively, whenever a connection is found.

2.1 Identifying segments

A small network serving an area with large commercial/industrial customers ([23]) is selected to explain the algorithm. The network has one source and 16 demand nodes. Ormsbee and Kessler [23] labelled the Source Node as *S* (herein labelled 1) and Demand Nodes 1 through 16 (herein labelled 2 through 17). The network is modified by placing valves at some assumed locations. Valves are placed at mid length of the pipes 1,7,9,10,15,16,17,18 and 19. Thus the total number of pipes is increased from 19 to 28 as valves are considered to be nodes in the network model. The modified network with 17 nodes, 9 valves and 28 pipes is shown in Fig.1. The segment search is run on a node-node connectivity matrix, which is shown in Fig. 2 for the water main system. This is a square, symmetric matrix in which each row and each column represent a node. The nodes are sorted with sources first, then junction nodes, and then valves. If there is a connection between node *i* and node *j*, the *(i,j)* and *(j,i)* elements of the matrix will contain the index number of the connecting pipe. This method introduces the limitation of not being able to keep track of parallel pipes between two junction nodes. Currently, the remedy for this limitation is to introduce another junction node into one of the pipes, thus separating it into two pipes. This is an area for further development.

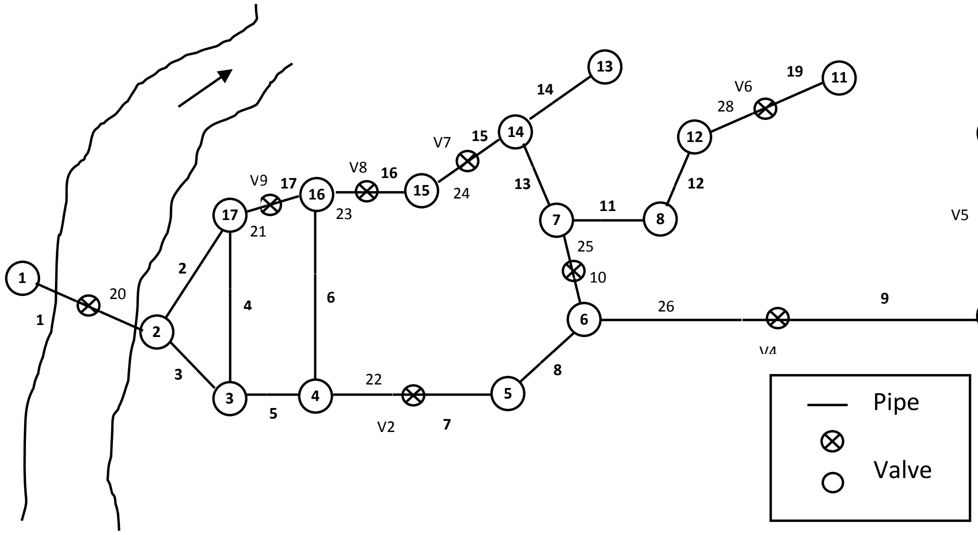

Fig. 1. A water main system with assumed valve locations

The matrix can be broken into four quadrants: source or junction nodes that are connected to other source or junction nodes (Quadrant I); source or junction nodes that are connected to valves (Quadrants II and III); and valves that are connected to other valves (Quadrant IV). The node-node and valve-valve quadrants are also symmetrical. For each segment, the search algorithm identifies each of the contained nodes, pipes and valves. Segments are identified by connected nodes in Quadrant I of the matrix. Valves are identified in Quadrant II. Segments that consist of a length of pipe isolated between two valves which contain no nodes are identified in Quadrant IV. Pipes are identified each time a node-node, node-valve, or valve-valve connection is found. The program performs the search of Quadrants I and II simultaneously to identify the nodes, pipes and valves in each node-containing segment. It then searches Quadrant IV for valve-valve segments.

2.2 Identification of Segment Nodes

The algorithm uses a breadth-first search to find the nodes contained in each segment. The program maintains three lists as it performs the search. The first (Segment List) is the list of nodes that are connected to form the current segment; the second (Search List) is a list of nodes that will be searched for connections within the current segment;

and the third (Skip List) is a list of nodes that have already been searched for all segments. To begin, the first node is added to the Search List and the first Segment's Node List. Quadrant I of the node-node connectivity matrix is then searched for connections on that node's row. If a connection is found, the connecting node is added to the Search List and the Segment's Node List. Once the search of the row is completed, that node is added to the Skip List and deleted from the Search List. The row of the next node in the Search List is then used, and the process continues until the Search List has been emptied. The Skip List is used to avoid duplication. When a connection is found, the program checks the Skip List as well as the existing Search List to make sure that the node has not already been counted. If it has, the node is not added to either list.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	V1	V2	V3	V4	V5	V6	V7	V8	V9
1																		1								
2			3														2	20								
3		3		5													4									
4			5													6			22							
5						8													7							
6					8															10	26					
7								11						13						25						
8							11					12														
9																					9	27				
10																						18				
11																							19			
12								12															28			
13														14												
14							13						14											15		
15																								24	16	
16				6																					23	17
17		2	4																							21
V1	1	20																								
V2				22	7																					
V3						10	25																			
V4						26			9																	
V5									27	18																
V6											19	28														
V7														15	24											
V8															16	23										
V9																17	21									

Quadrant I

Quadrant II

Quadrant III

Quadrant IV

Fig. 2. Example of node-node matrix

2.3 Identification of Segment Pipes and Valves

Once the node list for each segment is created, identifying the pipes and valves in each segment is simple using the node-node connectivity matrix. The row for each node in the segment is searched using Quadrant I and Quadrant II as shown in Fig. 2. Wherever a connection is found, that pipe is added to the Segment's Pipe List. To avoid duplication, the program checks whether the pipe is already present in the Segment's Pipe List. If it is present, the pipe is not added to the Segment's Pipe List. If the connection is found in Quadrant II, the valve for that column is added to the segment's Valve List. To avoid duplication, the program also checks whether the valve is already present in the Segment's Valve List. If it is present, the valve is not added to the list. Single pipe segments that are isolated between two valves are found by searching Quadrant IV. Because this quadrant is square and symmetrical, only the upper diagonal must be searched. If a connection is found, the row valve and the column valve are added to a new Segment's Valve List and the connecting pipe is added to the Segment's Pipe List. The methodology as above is followed to identify various segments as shown in Fig.3.

2.4 Identifying Unintended Isolations

The isolation of one segment has the possibility of disconnecting other sections of pipe from the water supply. There are two ways a segment can be disconnected by the isolation of another segment: as a branch off of the isolated segment, or by being surrounded by the isolated segment [8]. These unintended isolations can be found using the same methodology as was used to identify segments by nodes. Instead of using a node-node connectivity matrix, a segment-segment connectivity matrix is used. Identification of unintended segments helps in removing those segments along with failed segment during analysis of water distribution network. However, analysis can be carried outwithout identifying unintended segments by considering failed segment to determine available flows at different nodes. For nodes in unintended segments, available flows would be zero.

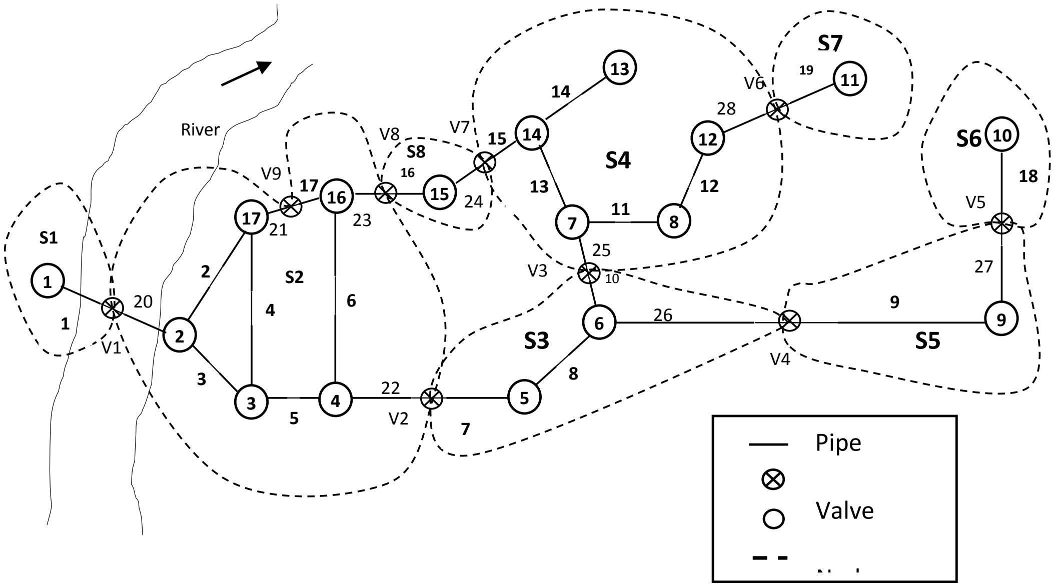

Fig. 3. Identified segments for the water main system

3. Water supply shortfall and reliability analysis

Water supply shortfall is the undelivered water associated with the failure of a pipe or segment. When a pipe or segment of a WDN fails the demands at some nodes may not be satisfied and, as a result, supply shortfall occurs. Available supply under all pipe (or segment) working condition and 1 pipe (or segment) failure condition is estimated using EPANET 2.0 using the methodology suggested by Abdy Sayyed et al. [16] of adding check valve, flow control valve and emitter in series at each node as additional components. Supply shortfall was calculated as the difference between the actual demand and the available supply. Reliability is quantified and obtained by the method suggested by Gupta and Bhave [1]. Three reliability parameters are used: (1). Node reliability parameter, R_n; (2). Volume reliability parameter, R_v; and (3). System reliability parameter, R_s to describe the performance of a network over the period of analysis. Node reliability parameter, R_n, is the ratio of the total available outflow volume at a node to the desired outflow volume at that node for all states during the period of analysis. Volume reliability parameter, R_v, is the ratio of total available outflow volume to required outflow volume of the entire network for all states during the period of analysis. System reliability parameter, R_s, is a single reliability parameter which is a product of volume reliability, node factor and time factor introduced to distinguish reliability values under different situations [1].

4. Illustrative example

The water main system shown in Fig. 1 is chosen to illustrate the methodology. Readers can refer to earlier papers for network details [18, 19]. The reliability of the system is obtained for the known nodal demands, which are considered as Peak Hour Demands (PHD).

4.1 Reliability Analysis considering isolation of a single pipe during its failure

Let us assume that valves are available at either ends of pipes so that isolation of each pipe is possible. Further, demands are assumed concentrated at nodes, so this isolation of pipe would not affect any consumer. In practice, consumers are given connections along the pipe, so isolation of valve will affect those consumers. Flow conditions are classified into two state groups; all-pipes-working-condition (APWC) and 1-pipe-failure-condition (1-PFC). The available flows at each node were then obtained using EPANET 2.0 with the methodology suggested by Abdy Sayyed et al. [16]. Under APWC, there was no demand shortfall, whereas the failure of pipes 1, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18 and 19 causes supply shortfalls at some of the nodes. The results are shown in Table 1. Node reliability (*Rn*), volume reliability (*Rv*) and system reliability (*Rs*) of the network is calculated using the available flows under various states. The resulting system reliability considering the two state groups is 0.997766 (Table 2).

Table 1. Demand shortfall for pipe failure condition

Failed Pipe	Total Available flows, m^3/hr	Supply Shortfall, m^3/hr
0	1259.04	0.00
1	0.00	1259.04
2	1259.04	0.00
3	1259.04	0.00
4	1259.04	0.00
5	1259.04	0.00
6	1259.04	0.00
7	1259.04	0.00
8	1259.04	0.00
9	821.76	437.28
10	1252.95	6.09
11	1143.18	115.86
12	1143.18	115.86
13	1139.79	119.25
14	1173.84	85.2
15	1010.9	248.14
16	988.82	270.22
17	1088.95	170.09
18	906.96	352.08
19	1228.38	30.66

4.2 Reliability Analysis considering isolation of the segment during the failure of any pipe

In the water main system, valves are assumed to be provided at locations shown in Fig. 1. These locations are at mid length of the pipeline. However, it could be anywhere in the pipeline. With the valves in assumed locations (Fig. 1), the network is divided into 8 segments (Fig. 3) using the segment finding algorithm. The segments are labelled as S1, S2, S3, S4, S5, S6, S7, and S8. The nodes, valves and pipes of different segments are in Table 3. This system is required to be analyzed for APWC and 1-PFC. Herein, the total time of failure of different pipes in a segment have been obtained and instead of failure of an individual pipe, failure of an individual segment is considered to reduce computational efforts. Under the all segment working condition there was no demand shortfall whereas the failure of any segment causes supply shortfalls (Table 4). It can be observed from Table 4 that segments 1 and 2 are most critical as their failures cut-off the source from nodes having demands. Failure of segment 7 causes the node 11 to be cut-off from the network and the network is least affected. The nodal and system reliability values are obtained and shown in Table 2 for easy comparison with pipe-based failure and its isolation. It can be observed from Table 2 that node reliability values are much less when segment based failure is considered. The volume and system reliability values are also less for segment based failure.

Table 2. Pipe-based and segment-based system reliability values

Reliability Parameters		Reliability Values	
		Pipe-based failure	Segment-based failure
Node Reliability, *Rn*, at node	3	0.999507	0.996948
	4	0.999508	0.996949
	5	0.999506	0.996405
	7	0.999335	0.995789
	9	0.999014	0.996045
	10	0.998897	0.996024
	11	0.997969	0.995156
	12	0.999245	0.995805
	13	0.999299	0.995800
	14	0.999399	0.995800
	15	0.999436	0.996823
	16	0.999480	0.996949
	17	0.999507	0.996948
Volume Reliability, *Rv*		0.999213	0.996180
System Reliability, *Rs*		0.997766	0.988777

The reliability values at different nodes have marginal difference and are therefore expressed with six figures after decimal. Although critical or vulnerable segments can be obtained by comparing supply shortfall, it is represented herein with reliability parameters. The reliability values are based on the time of different states during the period of analysis; hence, they are more useful when two alternative designs are compared during the design of any network.

Table 3.Segments of the water main system

Segment	Pipes	Nodes	Valves
S1	1	1	V1
S2	2,3,4,5,6,17,20,21,22,23	2,3,4,16,17	V1,V2,V8,V9
S3	7,8,10,26	5,6	V2,V3,V4
S4	11,12,13,14,15,25,28	7,8,12,13,14	V3,V6,V7
S5	9,27	9	V4,V5
S6	18	10	V5
S7	19	11	V6
S8	16,24	15	V7,V8

5. Summary and conclusions

It is a common assumption in the reliability based analysis and design of WDNs that valves are provided at either ends of a pipe and therefore any pipe can be isolated during failure. However, this is not so in practice. Valves are provided at salient locations and a group of pipes are isolated during a failure of any pipe. Herein, the methodology of Kaldenbach and Ormsbee [14] is used for segment identification which recognizes the exact location of valves. The methodology of Gupta and Bhave [1] is used for reliability analysis considering isolation of segments during failure of any pipe. The reliability values are compared under two conditions, and it is observed that isolation of each pipe during failure provides higher than actual values of reliability obtained by considering exact location of valves. This methodology would be useful in comparison of reliability values of several alternative designs, generated by increasing the size of a pipe or segment through the location of additional valves, in iterative selection of pipes/valves for reliability-based design of WDNs.

Table 4. Demand short fall for segment failure

Failed Segment	Total Available Flows (m^3/hr)	Supply Shortfall (m^3/hr)
0	1259.04	0
1	0	1259.04
2	0	1259.04
3	610.50	648.54
4	883.13	375.91
5	821.76	437.28
6	906.96	352.08
7	1228.38	30.66
8	983.86	275.18

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