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Reliability Model Of Water Distribution Network Using Minimum Cut Set Approach Based On Rayleigh Distribution

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ABSTRACT: *One of the factors impacting water shortage is the inhibition of water flow in broken pipelines. Therefore, to anticipate future problems, it is necessary to analyze the reliability of the water distribution network in order to assess the durability in a particular situation. This analysis also discusses the hazard model in analyzing the failure rate of a component. The objective of this research is to explain the application of the water distribution network reliability model based on Rayleigh distribution using the minimum cut set method approach, determining the number of paths from the water distribution network for each valve of the disposal node so that they can be calculated for each node with an adjacency matrix. The results of data analysis of the pipeline data for DMA of Buring 3F obtained three stages of reliability in regulating the flow of water in pipelines. The percentage of pipeline network reliability with the minimum cut-set method is in the first stage 96.43% for the sink node valve 9, in the second stage 99.42% for the sink node valve 43 and the final stage for the valve node 9 and 43 is 99.97%. So to solve the issue of clean water catchment it is necessary to consider the reliability of the water distribution network.*

KEYWORDS - Reliability Analysis, Water Distribution Network, Adjacency Matrix, Minimum Cut-set, Rayleigh Distribution

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I. INTRODUCTION

The main components of a water distribution network systems include container basins, container handling, pipes and water distribution networks [1]. The expansion and development of a water distribution network system without regard to the quality and durability of an uncontrolled water distribution network resulted in the failure of pipeline systems and concurrent pipe damage. Therefore, when designing a water distribution network special consideration must be given to the analysis of the expected, estimated durability of the network system. One aspect of this is a reliability analysis that is tested in specific circumstances. Tests in reliability analysis are related to network systems and typically use data related to reliability time, length, size of a network and other factors that affect the reliability value of a network system. The reliability model was divided into three factor parameters, namely node reliability, volume reliability, and network reliability in network distribution system design [2]. Furthermore, this model was developed using three parameters to calculate the ratio of marginal increase in reliability to marginal increase in cost for each pipe by changing its size to next higher one [3]. Reliability testing of water distribution networks requires various methods in order to effectively reduce the rate of the failure that occurs by expanding the reliability model based on the Poisson distribution function for the water distribution system and using the minimum cut-set method to reduce the failure of pipeline network components by cutting off the pipeline pipes that are not operating from the network [4]. This paper builds on a previous study of reliability models using the minimum cut-set method and the availability model of urban water distribution network to calculate the network reliability value of the amount of water flowing in the pipeline [5]. The expansion of the hydraulic reliability model was developed using the adjacent matrix method approach to determine the minimum number of cut sets from the water distribution network [6]. From the explanation above, it is necessary to use Rayleigh distribution, which is a special form of Weibull distribution, as a probability function in the analysis of the water distribution network reliability model using the minimum cut-set approach. This paper aims to explain the application of the reliability model based on Rayleigh distribution of a water distribution network using the minimum cut-set method.

II. METHODOLOGY

2.1 Design

The methodology for this study is literature review and case study. This includes works from the library and data which was obtained by observation when determining a good model of the water distribution network reliability model while using minimum cut-set method based on the Rayleigh distribution.

2.2 Location

The location which was chosen to obtain data of a specific water distribution network is the precinct of Malang city, which has several District Meter Areas (DMA). For this study, researchers chose the DMA of Buring 3F, located in district of Kedungkandang. The water source of the DMA is a water reservoir called Buring III which is 484 meters above sea level and has a capacity of 2000 cubic meters. This location was chosen because the piped water distribution network is quite complex so it requires a mathematical model to analyse the problems that occur in the distribution of water.

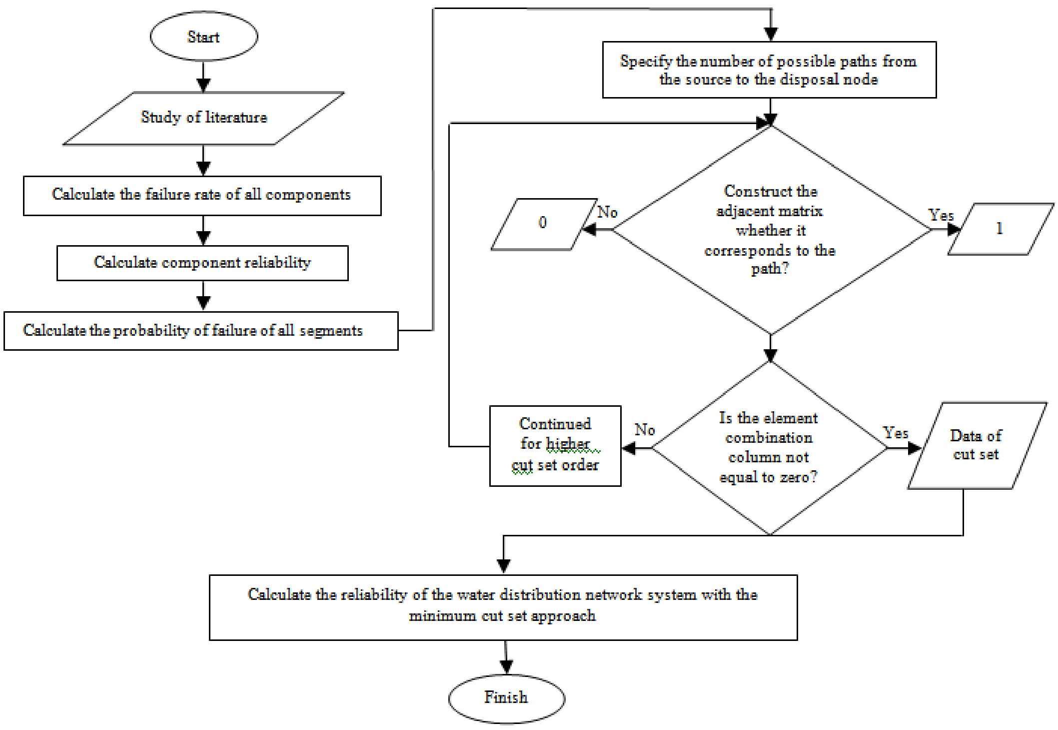

Figure 1: Flowchart

2.3 Implementation Procedures

The implementation procedure is divided into several stages:

1. Calculate the failure rate of each component with the following equation:

$$\lambda_c = \frac{N(t)}{L\Delta t} \tag{1}$$

in which λ_c is the component of failure rate, $N(t)$ is the number of failures that occur during time t, component length and Δt the period between installation and analysis time [7].

2. Calculate the reliability components based on the Rayleigh distribution, as follows:

$$R(t)_c = e^{-\frac{k}{2}t^2}$$
$$= e^{(kt)\frac{1}{2}t} \tag{2}$$

in which $R(t)_c$ is a component of reliability probability, kt is the component of failure rate in time t in equation (1). So the failure rate of each independent component is:

$$h(t) = \lambda_c$$
$$= \frac{N(t)}{L\Delta t} \tag{3}$$

3. Calculate the reliability which is composed of the main components such as pipes, valves, meter gauge and others. From equation (4.2) is obtained as follows:

$$R_{seg} = \sum_{i=1}^{n} R(t)_c w_i \tag{4}$$

in which i is the main component (pipe, valve, meter gauge), n is the number of components and w_i is the relative weights of the components expressed in (5) as follows:

$$w_i = \frac{Weight\ of\ component\ ke\ i}{Sum\ of\ weights\ of\ all\ components}$$

[8].

4. Calculate the probability of segment failure which is the complement of the segment reliability so it can be expressed as follows:

$$Q_{seg} = 1 - R_{seg} \tag{5}$$

in which Q_{seg} is the probability of segment failure [9].

5. Identify the minimum cut-set of a water distribution network with several stages below:

1) Change the structure of water distribution network into the graphs arranged in nodes and arcs.
2) Determine the number of paths which are formed in the water distribution network.
3) Construct the adjacent matrix from a known path to determine one or more segments that are cut sets [10]. The adjacent matrix of a graph G, the matrix that connects the node to the other nodes. In other words, if the matrix of path $\boldsymbol{A} = [a_{ij}]$, then:

$a_{ij} = 1$, if the segment is part of the path
$a_{ij} = 0$, if the segment is not part of the path

6. Calculate network reliability using the minimum cut-set method based on Rayleigh distribution. As follows:

$$Q_S = \sum_{i=1}^{n} Q(MC_i) \tag{6}$$

in which

$$Q(MC_i) = \prod_{j=1}^{k} Q_j\,, \qquad for\ j = 1,2, \ldots k \tag{7}$$

Q_j is the probability of failure of the component (segment) to j and k is the number of cut sets of components (segments) corresponding to the minimum cut set. The probability of failure Q_j which is the cumulative function of the probability distribution used in this study is the Rayleigh distribution.

Thus from equation (7) is obtained:

$$\begin{aligned} R_S &= 1 - Q_S \\ &= 1 - \sum_{i=1}^{n} Q(MC_i) \end{aligned} \tag{8}$$

$Q(MC_i)$ is the probability of failure of the minimum cut-set of the i (MC_i).

III. APPLICATION OF RELIABILITY MODEL BASED ON RAYLEIGH DISTRIBUTION FOR A WATER DISTRIBUTION NETWORK USING MINIMUM CUT-SET METHOD

This section discusses the application of the reliability model based on Rayleigh distribution with minimum cut-set method for a distribution network case in DMA of Buring 3F located on district of Kedungkandang, Malang city, East Java.

DMA of Buring 3F is composed of three main types of components i.e.: pipes, valves, and gauge meters. Table 1 shows the relative percentage of the various components that make up the water distribution network in the DMA of Buring 3F. From the data which was obtained from the Drinking Water Company of Malang city for the DMA of Buring 3F there are 646 main components consisting of 632 distribution pipes, 10 valves (one way) and 4 meter gauges (only 2 meters gauges operating?) as shown in Figure 2.

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TABLE 1: Percentage of Component

Main component	Percentage (%)
Pipes	97.83
Valves	1.55
Meter Gauges	0.62
Total	1

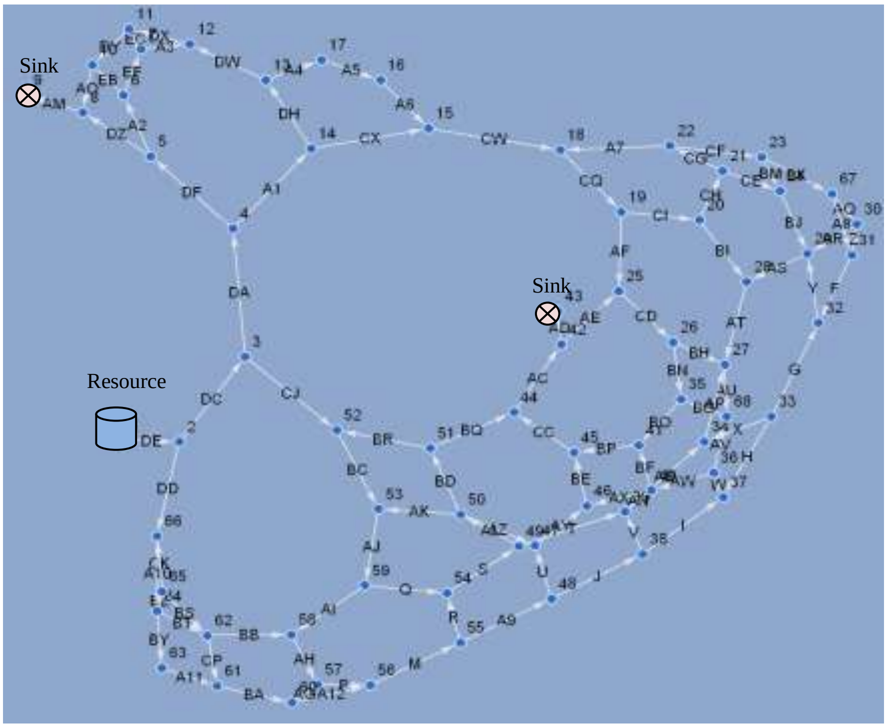

Figure 2: DMA Buring 3F Water Distribution Graph Model

In Figure 2, there are 134 segments and 68 nodes that make up the water distribution graph. Next we will determine the number of paths for both the node sinks 9 and 43. Both nodes are used as water drains for residual water discharges and also as gauges and pressure regulators in the pipeline network for DMA Buring 3F. Table 2 presents the result data for segment reliability calculations and the probability of failure of the DMA of the Buring 3F water distribution network system segment. The calculation data is derived from equations (1), (2), (3), (4) and (5).

TABEL 2: Data on Calculation Result (R_{seg}) and (Q_{seg})

Age (yr)	Comp.	Seg.	No. of failures	Pipe length (m)	Segmen length (m)	Comp mate.	Diam. of comp. (mm)	Failure rate (λ)	Comp. relia. (R)	Percentage Of Comp.	Rel. Weight of comp.	Seg. Relia (R_{seg})	Failure probab. (Q_{seg})
19	Pipa	A	0	4.371	85,416	PVC	50	0	1	0.978	0.167	1	0
19	Pipa	A	0	4.896		PVC	50	0	1	0.978	0.167		
19	Pipa	A	0	31.789		PVC	50	0	1	0.978	0.167		
19	Pipa	A	0	31.789		PVC	50	0	1	0.978	0.167		
19	Pipa	A	0	6.286		PVC	50	0	1	0.978	0.167		
19	Pipa	A	0	6.286		PVC	50	0	1	0.978	0.167		
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

There are 134 paths which are formed from the water distribution network for both nodes and these are used as a reference to determine the number of segment cuts. Therefore, we will determine the number of cut sets for the corresponding segments of each path by using the adjacent matrix. The next step is to calculate the value of the network system reliability for each node sink in three stages: first for node sink 9, second node sink 43, and third for all nodes sinks, with the assumption that when the water is distributed to each demand node from the source (node 1), there are enough active sink nodes for the first and second stage. Because if the two sink nodes are active at the same time then the flow of water distributed throughout the network is not completely even. The cause of the problem is a small build up of air pressure that decreases the flow of water.

3.1 Reliability of Water Distribution Network of Node Sink 9 using the Minimum Cut-Set Method

There are five paths in the water flow from node 1 to node 9 as shown in Figure 1 that can determine the adjacent matrix. Table 3 illustrates the number of cut sets of several paths that allow the flow of water to end at node 9.

TABLE 3: Adjecent Matrix from Node 1 to Node 9

No	DE	DC	DA	AO	A2	A1	A3	DF	DH	DW	DX	DY	DZ	EB	EC	EF	AM
1	1	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	1
2	1	1	1	1	1	0	0	1	0	0	0	0	0	1	0	0	1
3	1	1	1	1	0	1	0	0	1	1	1	1	0	0	0	0	1
4	1	1	1	1	1	0	0	1	0	0	0	1	0	0	1	1	1
5	1	1	1	1	1	0	1	1	0	0	1	1	0	0	0	1	1

Table 3 shows that all the elements in the segment {DE}, {DA} and {DC} are worth 1. Therefore, segment {DE}, {DA} and {DC} are cut sets for order 1 which means the system of water flow from node 1 to node 9 will fail if segment {DE}, {DA} and {DC} are cut. Table 3 shows the number of first order set cuts with the segment failure value (Q_{seg}) obtained from Table 2 so that using equation (7) results in the following:

$$Q_{DA}(MC_1) = \prod_{j=1}^{1} Q_{DA}$$
$$= 0.0357$$

Since the Q_{seg} values for {DE} and {DC} in Table 2 are zero, then the cut set for order 1 is Q_{DA}. Next, the cut set for order 2 is determined by combining two segments that still have the value 0 in the column. This will obtain value 1 in the combination column [11]. As a note, if the second order combinations for two segments are still zero in the combination column then look at the calculations for order 3 and so on.

TABLE 4: The first cut set order of matrix from Node 1 to Node 9

No	DE	DC	DA
1	1	1	1
2	1	1	1
3	1	1	1
4	1	1	1
5	1	1	1
Q_{seg}	0	0	0,0357

TABLE 5: The second cut set order of matrix from Node 1 to Node 9

No	AO+DZ	A1+DF	DH+DF	DX+DF	DW+DF	DY+DF	AO+DF
1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	2
3	1	1	1	1	1	1	1
4	1	1	1	1	1	2	2
5	1	1	1	2	1	2	2
Q_{seg}	0	0	0	0	0	0	0

TABLE 6: The third cut set order of matrix from Node 1 to Node 9

No	A2+A1+DZ	A2+DH+DZ	A2+DW+DZ	A2+DX+DZ	A2+DY+DZ	EB+DY+DZ
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	1	1	1	1	2	1
5	1	1	1	2	2	1
Q_{seg}	0	0	0	0	0	0

TABLE 7: The fourth cut set order of matrix from Node 1 to Node 9

No	A1+DZ+EB+EF	DH+DZ+EB+EF	DW+DZ+EB+EF	DX+DZ+EB+EF	DX+DZ+EB+EC
1	1	1	1	1	1
2	1	1	1	1	1
3	1	1	1	1	1
4	1	1	1	1	1
5	1	1	1	2	1

Q_{seg}	0	0	0	0	0

TABLE 8: The fifth cut set order of matrix from Node 1 to Node 9

No	A1+A3+DZ+EB+EC	DH+A3+DZ+EB+EC	DW+A3+DZ+EB+EC
1	1	1	1
2	1	1	1
3	1	1	1
4	1	1	1
5	1	1	1
Q_{seg}	0	0	0

The results of Tables 5, 6, 7 and 8 for cut sets of order 2, 3, 4, and 5 are zero so that the reliability of the water distribution system using the minimum cut set method for node 9 is obtained from equations (6), (7) and (8) with the number of cuts set n = 24 as follows:

$$R_{S_9} = 1 - Q_{S_9}$$

in which

$$Q_{S_9} = \sum_{i=1}^{24} Q(MC_i)$$
$$= Q_{DA}(MC_1) + Q_{DE}(MC_2) + Q_A(MC_3) + Q_{AO+DZ}(MC_4)$$
$$+ \cdots + Q_{DW+A3+DZ+EB+EC}(MC_4)$$
$$= 0.0357 + 0$$
$$= 0.0357$$

so

$$R_{S_9} = 1 - 0,0357$$
$$= 0.9643$$

Thus, the percentage of water distribution network reliability when only the exhaust valve is activated for node 9 is 96.43%.

3.2 Reliability of Water Distribution Network for Node Sink 43 using the Minimum Cut-Set Method

This section determines the network system reliability value with nodes 9 and 43 terminal simultaneously active. It is assumed that the water flow distributed from node 1 (source) has reached nodes 9 and 43. In other words, the third stage is a further calculation of the first and second stages. From 134 paths, there are several segments that failed, as shown in Table 2. They are segments {EA}, {EB}, {Z}, {U}, {T}, {K}, {DS}, {DL }, {D}, {D}}, {D}}, {DA}, {CU}, {CT}, {CP}, {CO}, {CF}, {BY}, {BV}, {BQ}, {BK}, {BG}, {BF}, {BB}, {AP}, {AF}, {AE}, {AC} and {AN}}. So apart from these 28 segments there is no failure, in other words Q_{seg} is zero. From equation (7) we will calculate the value of the cut set for order 1 to order k. From the result of the combination of segments for 134 paths there are only 2 segments for the second order cut set, which aresegments {AC, DA} resulting in an unequal cut set value with zero as follows:

$$Q_{AC}(MC_1) = \prod_{j=1}^{1} Q_{AC}$$
$$= 0.0059$$

This is because in Table 2 the value for cut set order 1 for the water flow from node 1 to node 43 only has a segment of {AC} which has value not equal to zero. Furthermore, for cut sets of order 2 to k contains a combination of segments in which one or more of the probability of failure of a segment is equal to zero as in the third cut set order for the combination of cut set {DD + CJ + DA}, so that from (7):

$$Q_{\mathrm{DD+CJ+DA}}(MC_i) = \prod_{j=1}^{3} Q_{\mathrm{DD+CJ+DA}}$$
$$= Q_{\mathrm{DD}} \cdot Q_{\mathrm{CJ}} \cdot Q_{\mathrm{DA}}$$
$$= 0 \cdot 0 \cdot 0.0357$$
$$= 0$$

The reliability value of the water distribution system using the minimum cut-set method for node 43 is obtained from equations (6), (7) and (8) as follows:

$$R_{S_{43}} = 1 - Q_{S_{43}}$$

in which

$$Q_{S_{43}} = \sum_{i=1}^{n} Q(MC_i)$$
$= Q_{DE}(MC_1) + Q_{AC}(MC_2) + \cdots Q_k(MC_n)$
$= 0 + 0{,}0059 + \cdots + 0$
$= 0.0059$

so
$R_{S_{43}} = 1 - 0{,}0059$
$= 0.9941$

Thus, the percentage reliability of the water distribution network when only the disposable valve was activated for the node 43 is 99.41%.

3.3 Reliability of Water Distribution Network for Node Sink 9 and 43 using the Minimum Cut-Set

IV. METHOD

This section determines the network system reliability value with nodes 9 and 43 terminal simultaneously active. It is assumed that the water flow distributed from node 1 (source) has reached nodes 9 and 43, in other words the third stage is a further calculation of the first and second stages. From 134 paths, there are several segments that failed, as shown in Table 2 are segment {EA}, {EB}, {Z}, {U}, {T}, {K}, {DS}, {DL }, {D}, {D}}, {D}}, {DA}, {CU}, {CT}, {CP}, {CO}, {CF}, {BY}, {BV}, {BQ}, {BK}, {BG}, {BF}, {BB}, {AP}, {AF}, {AE}, {AC} and {AN}}, so apart from the 28 segments there is no failure, in other words Q_{seg} is zero. From equation (7) we will calculate the value of the cut set for order 1 to the order k, from the result of the combination of segments for 134 paths there are only 2 segments for the second order cut set is segments {AC, DA} resulting in an unequal cut set value with zero as follows:

$$Q_{AC+DA}(MC_i) = \prod_{j=1}^{2} Q_j$$
$= Q_{AC} \cdot Q_{DA}$
$= 0.0059 \cdot 0.0357$
$= 0.00021243$

Furthermore, the reliability value of the water distribution system using the minimum cut-set method for nodes 9 and 43 is obtained from equations (6), (7) and (8) as follows:
$R_{S_{9+43}} = 1 - Q_{S_{9+43}}$
in which

$$Q_{S_{9+43}} = \sum_{i=1}^{n} Q(MC_i)$$
$= Q_{AC+DA}(MC_i)$
$= 0.00021243$
$= 0.00021243$
so
$R_{S_{9+43}} = 1 - 0.00021243$
$= 0.99978757$

Thus, the percentage of end-stage water distribution network reliability when the disposal valve for nodes 9 and 43 is activated simultaneously of 99.97%.

V. CONCLUSION

The reliability of the water distribution network system of the combination between node sinks 9 and 43 has the highest reliability percentage value, i.e. 99.97%, which is greater than at sink nodes 43 and 9, which have 99.41% and 96.43% respectively. This means the percentage chance of network water distribution system failure for the combined node sinks of nodes 9 and 43 is the smallest. Thus, the reliability of the most viable water distribution system (i.e. the selection of the combined nodes 9 and 43) is improved by the final step of regulating the air pressure of the pipelines so that water can be distributed smoothly and evenly to consumers. This addresses the problem of distribution network damage water by considering the overall reliability of the water distribution network. In this paper, the failure rate of pipes and other components greatly affects the reliability of the network system so that accuracy of the data is necessary and also the parameter of failure rate is based on a single parameter. It is anticipated that further research would need to be carried out on failure rates, such as the age of the pipelines, to assist in evaluating the reliability of water distribution network systems more accurately than is possible with the available data.

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