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Remedy for the Problem of Least-Cost Optimal Design of Water Distribution Networks

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1. INTRODUCTION

A significant amount of research work has been done on the least-cost design of water distribution networks and considerable achievements were found in terms of the size of network that can be designed and the network components that can be included. But this method of design has got an inherent demerit of changing a looped topology into branched one and hence reducing the reliability of the system. This problem was traditionally overcome by specifying a minimum allowable pipe size. However, this method is generally believed to ensure only connectivity, and not reliability. This paper presents two possible solutions to the problem. First, it introduces a new reliability-based design model of a distribution network, named RBNET, which preserves a looped topology and results in higher system reliability at a relatively lower system cost, and second, based on the results from the new design model, it shows that if the minimum allowable pipe size is selected carefully, the problem of the least-cost design method can be overcome effectively through the traditional approach.

2 ESTIMATION OF NETWORK RELIABILITY

A number of techniques are available to estimate network reliability. In this study, assuming the probability of simultaneous failure of one or more pipes is very low, a single pipe failure scenario minimum cut-set method, coupled with each time network simulation, was used. In this method, the minimum reliability of a network can be given as

$$R_S = 1 - \sum_{i=1}^{M} pf_i \tag{1}$$

Where M is the number of pipes that are minimum cut-sets and pf_i is the probability of failure of pipe i. A pipe is a minimum cut-set if it, when failed, causes a drop in head below the allowable minimum at one or more of the demand points in the network. The probability of failure of a pipe, pf_i is a random variable that can be expressed as a function of the break rate λ and length of the pipe. Historical pipe break records show that the average break rate of a pipe is closely related to its diameter and can be approximated using an equation of the form, $\lambda = a \times e^{b \times D}$ where λ is the break rate per unit length per year, D is the pipe diameter, a and b are constants that can be determined from data and b is always less than zero since larger pipes have lower break rates Using the exponential distribution (for its simplicity), the reliability of a pipe with length L and break rate λ can be expressed as $R = \exp(-\lambda \times L)$. Therefore, the probability of failure of pipe i in equation (1) can be expressed as

$$pf_i = 1 - \exp(-\lambda_i \times L_i) \tag{2}$$

In the normal minimum cut-set method, pipes that, when broken, affect many nodes with large demands are treated equally to those pipes that affect a few nodes with small demands, which is unfair. To address this issue in estimating network reliability, the expression for the probability of failure of a pipe given in equation (2) has been conveniently changed to the following form.

$$pf_i = \frac{[1 - \exp(-\lambda_i \times L_i)]}{P_{tot}} \sum_{j=1}^{NJ} df_j \times P_j \tag{3}$$

Where P_{tot} is the total demand in the network, P_j is the demand at node j, NJ is the total number of junction nodes in the network and df_j is a demand factor for node j, the value of which is ZERO if $h_j \geq hl_j$; $(1 - h_j / hl_j)$ if $0 < h_j < hl_j$; and ONE if $h_j \leq 0$. Here h_j and hl_j are the pressure head when pipe i was under simulation close and the permissible minimum head at node j, respectively.

3. BRIEF DESCRIPTION OF THE NEW DESIGN MODEL

The capacity of the reliability-based design model developed here is to select optimal pipe sizes from a set of commercially available discrete diameters to construct a "best-compromised" pipe network. The model first sets all pipes to maximum values and then reduces them step-by-step, one at a time, until the pressure heads at one or more of the nodes in the network reach the preset minimum values. At each step the pipe to be reduced is selected based on its effect on the cost and reliability of the system when reduced to the next lower. A pipe with the smallest ratio of change in reliability to change in cost is chosen since we want to have large decrease in cost but small drop in reliability. When all pipes are set to maximum values, most or all of them may not be minimum cut-sets and the effect of a single pipe on the reliability of the system cannot be determined, and hence the model will be unable to select the pipe that should be reduced. To overcome this problem the concept of false system reliability, which is calculated from false probabilities of failures of pipes, was introduced. The false failure probability of a pipe, *pff*, is calculated using the same equation (3), but in this case the demand factor $df_j = (1 - h_j / hl_j)$ for all $h_j > 0$. And the false system reliability is calculated using equation (1) by replacing pf_i with pff_i. Note that the false probability of failure of a pipe can have value below zero and the false system reliability can be greater than one.

4. MODEL APPLICATION AND RESULTS

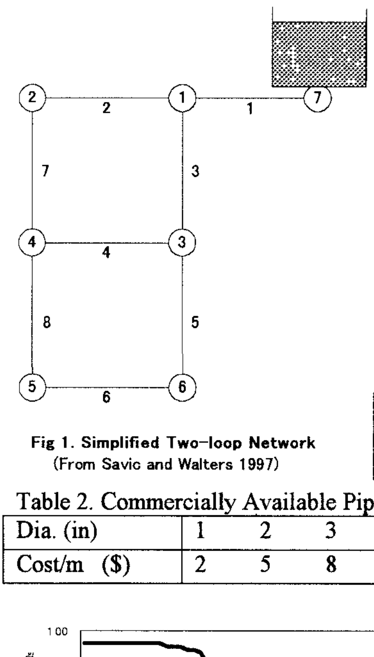

Fig 1. Simplified Two-loop Network (From Savic and Walters 1997)

This simplified two-loop network was first studied by Alperovits and Shamir (1977) and later by many researchers mainly because of its simplicity. For the same reason, it is used here to illustrate the performance of the new reliability-based design model and to study the effect of minimum allowable pipe sizes during least-cost optimal design on the reliability of the network. A minimum pressure of 30m is required at all the nodes. Network nodes and commercially available pipes data are given in tables 1 and 2, respectively. All pipes are 1000m long and the Hazen Williams coefficient C=130 for all pipes. The average break rate expression obtained from City of St. Louis (1985) pipe failure data, $\lambda = 0.5089 \times \exp(-0.1363D)$ where λ is Breaks/km/year and D is in inches, was used to calculate pipe failure probability.

Table 1. Network Node Data

Node No.	1	2	3	4	5	6	7
Ground El. (m)	150	160	155	150	165	160	210
Demand (m^3/hr)	100	100	120	270	330	200	-

Table 2. Commercially Available Pipe Diameters and Costs

Dia. (in)	1	2	3	4	6	8	10	12	14	16	18	20	22	24
Cost/m ($)	2	5	8	11	16	23	32	50	60	90	130	170	300	550

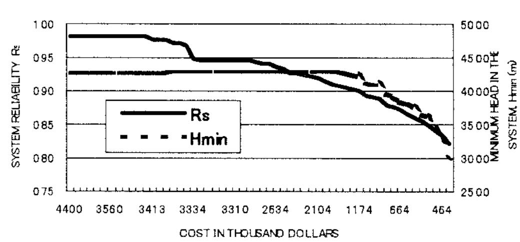

FIG 2 RELIABILITY VS COST GRAPH FOR L-COST OPTIMIZATION

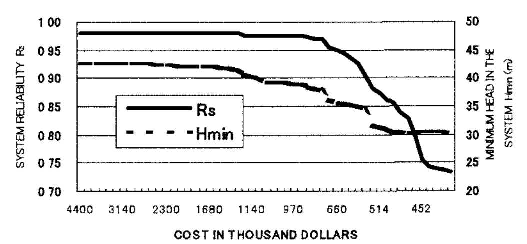

FIG 3. RELIABILITY VS COST GRAPH FOR R-BASED OPTIMIZATION

First initial sizes of all the pipes were set to 24in and the network was designed using RBNET and a least-cost design model that applies a similar one by one reduction method. A reliability subroutine was connected to the least-cost design model to calculate the reliability of the network after each change in pipe size. Figures 2 and 3 show how reliability Rs and head at the most depressed node H_{min} vary with system cost during least-cost and reliability-based optimal designs, respectively. The reliability-based model tries to maintain higher reliability whereas the least-cost design model maintains higher excessive energy at the most depressed node, and we can see that this higher excessive energy does not necessarily mean higher network reliability. Reliability dropped suddenly from 0.98 to 0.95 at early stage of the optimization during the least-cost design. This was the point where the looped network started to operate as *"implicitly branched, non-redundant system"* as described by Goulter et al., (1986). At this point all pipes were still 24in except pipes 4 and 6, which were reduced to 8in and 4in respectively. From this point onwards the reliability of the network depends on the reliability of each pipe (excluding pipes 4 and 6), and not on the network geometry. And this is what we want to overcome by specifying the "right" minimum allowable pipe size

Table 3 shows summary of the results obtained from designing the same network using the least-cost design model by changing the minimum allowable pipe sizes. The last row of this table contains results from RBNET, which are used as a standard to tell whether a specific allowable pipe size is effective or not. From this table, by comparing the figures in rows 2 to 5 with row 1, we can easily observe that specifying minimum pipe sizes from 1in to 6in helped nothing to increase system reliability instead it had disadvantage of increasing system cost. Assume we want to attain a network reliability of 0.9. The result from RBNET tells us it is possible to attain this reliability with a cost of $564,000. If the minimum allowable pipe size is, let's say, one inch in the least-cost design, to attain the same reliability we have to increase the cost to $1,304,000. But with the same least-cost design we can attain the same reliability with a cost of $580,000 if we set the minimum allowable pipe size to 12 or 14in. We can make similar comparisons from the table for other reliability values in the same way and appreciate how selecting the right allowable pipe size during least-cost design helps to attain a desired reliability with a reasonable cost.

Table 3. Summary of Least-Cost Design Results for Different Minimum Pipe Sizes

Pipe	Optimal Values at Hmin = 30m		Cost in thousand Dollars when			
Dia. (in)	Reliability, Rs	Cost (1000$)	Rs=0.85	Rs = 0.9	Rs=0.95	Rs=0.98
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0	**0.8222**	**420**	**550**	**1210**	**3334**	**3382**
1	0.8222	424	554	1304	3334	3382
2	0.8222	430	560	1310	3334	3382
4	0.8222	442	572	1442	3334	3382
6	0.7687	454	622	1672	3339	3382
8	0.8367	471	***529***	658	1276	3382
10	0.8527	480	***480***	590	1016	2184
12	0.8665	530	-	***580***	***870***	***1440***
14	0.9079	580	-	***580***	***900***	***1420***
RBNET	0.7343	438	**487**	**564**	**660**	**1430**

5. CONCLUSION

Reliability is an important issue that needs consideration during optimal design of water distribution networks. In this study a design algorithm that considers reliability explicitly was introduced. Though such an approach is realistic and appropriate for small networks, it usually is computationally infeasible for large ones. If the reliability-based optimal design method is to be used for practical networks instead of the least-cost design approach, there should be some kind of parameter (or reliability index) that shows system reliability implicitly but the estimation of which does not require closing of each pipe one by one and simulating the system. Currently, when dealing with design of large distribution networks, there is no much option other than the least-cost design approach. As we have seen, the problem of this design approach is that it reduces some of the pipes at early steps of the optimization and the looped network starts to operate as implicitly branched system. This reduction is a right and necessary step from cost minimization point of view since those pipes carry very small amount of flows under normal condition, but it has an adverse effect on the network reliability The minimum allowable pipe size we specify, therefore, should prevent this situation from happening. Identifying the right minimum allowable pipe size that can help us to attain the required reliability with a reasonable cost may not be easy especially for large and complicated networks, but it is not impossible.

Reference:

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