RELIABILITY-BASED OPTIMAL DESIGN OF WATER DISTRIBUTION NETWORKS[a]

Discussion by TT Tanyimboh[3] and P Kalungi[4]

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A considerable amount of research has been carried out on the reliability analysis and optimal design of water distribution systems, and it has been reported that each of the above problems is very difficult to solve (Wagner et al., 1988; Eiger et al., 1994). The authors are, therefore, to be commended for their work which directly incorporated a sophisticated probabilistic reliability model into an optimization routine. The paper had other interesting and useful aspects which, unfortunately, will not be elaborated upon.

The proposed reliability model was concerned with the “capacity reliability” of water distribution systems, recognizing the possible random variations in demand and uncertainties in pipe roughness coefficients. Unfortunately, the method was limited to predefined configurations of the network and so did not incorporate the effects of random component failures. The authors mentioned the idea that this can be remedied using the expected value formulation (Fujiwara and Tung, 1991), which is worth pursuing further. Although this may appear in theory to require the hydraulic analysis of a large number of configurations, it is possible to reduce the number of system configurations actually simulated.

Tanyimboh and Tabesh (1997a) have shown that quite accurate estimates of the reliability of water distribution systems can be obtained by averaging the upper and lower bound estimates of the reliability, which can be done in a relatively straightforward way (Tanyimboh and Templeman, 2000). Therefore, it might be possible in the above manner to address the concern raised by the authors that such a reliability measure may be inappropriate because it may be incomplete if it does not include all possible failure events.

By contrast, the authors tackled the problem of pipe failures in the cost minimization model by adding an extra capacity reliability constraint for each configuration of the network corresponding to a single critical unavailable link. This approach would appear to be computationally less efficient than the direct inclusion of pipe failure effects in the reliability analysis model. This raises the question of how best to approach failure-tolerant design. Unfortunately, without an exhaustive simulation there is no straightforward procedure for identifying the critical links of a water distribution system. Furthermore, the greater the number of capacity reliability constraints specified for the critical failures, the more difficult it is to solve the cost minimization problem computationally.

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An alternative worth considering might be to define the failure tolerance of the distribution system. If quantified, this measure could provide a single reliability constraint to ensure that the vast majority of the most frequent or severe failure cases are addressed in the optimization. Tanyimboh and Templeman (1998) characterized failure tolerance as the performance of the distribution system, on average, during subnormal conditions ensuing from the unavailability of some components of the system. The formulation has the advantage that it can be obtained while calculating system reliability without any need for additional hydraulic simulations and so its use would not impose a major computational burden. However, the measure did not address possible variations in nodal demands or uncertainties in pipe roughness. The authors' paper underscores the need to investigate this issue along with the possibility of directly incorporating failure tolerance in cost minimization models.

As a possible illustration of the usefulness of realistic failure tolerance measures, the average CPU time of 88 seconds for the authors' Example 2 (Cases 1 to 4) with only 3 critical-failure reliability constraints is 2.5 times the average CPU time of 35 seconds for Example 1 (Cases 1, 6, 7 and 8) with 12 pipe-failure reliability constraints and identical levels of uncertainty. Example 1 had 9 nodes while Example 2 had 16 nodes. Therefore, the computational demands of the optimization model including the evaluation of reliability would appear to be high, from a practicability viewpoint as indicated by the above CPU times for a VAX 6000 mainframe computer. Use of a failure tolerance parameter in the manner suggested herein could limit the number of reliability constraints to 2 (corresponding to the system reliability and failure tolerance) irrespective of the size of the distribution system and could help ensure that the CPU times remain manageable.

A potential weakness of the first order reliability method (FORM), as conceded by the authors, is its computationally very demanding nature despite being able to estimate the reliability of only one node at a time; it has to be repeated for each node whose reliability is required. It follows that the evaluation of the single-value reliability for a multiplicity of system configurations to address the issue of random component unavailability may render the FORM approach excessively time consuming for real distribution systems, especially if a holistic view of system performance is required. Approximately $NN \times NC$ FORM analyses would be required where NN is the number of nodes and NC is the number of configurations considered. The value of NC is commonly equal to the number of components in the system, although it can be a lot larger.

It is worth reiterating a point made by the authors that a prerequisite of the FORM is the determination of the design point, i.e. the most probable failure point on the failure hyperplane. This involves the solution of a constrained non-linear programming problem which in general is very difficult to do. Also, it is interesting to note that the authors did not include a definition of the reliability of the system as a whole in their formulation. However, as the FORM is capable of evaluating nodal reliabilities it may be appropriate in this framework to define the reliability of the system as a whole as the demand weighted average of the nodal reliabilities. Evidence of the equivalence of the above measures can be found in Tabesh (1998). Even though this approach would potentially be time consuming, it has the advantages of providing a reliability value for the entire system and avoiding the complicated task of pre-identifying a critical node for each reduced network configuration.

As mentioned above, the authors took the system reliability as the reliability of the most critical node, which was defined as the probability that both the pressure and outflow at the node in question were fully satisfactory. This is equivalent to estimating system reliability as the probability that all demands are met at adequate pressure. It is questionable whether this is not too conservative a definition of reliability for water distribution systems. This definition does not recognize the concepts of partial failure, which may cause a reduction in the level of service, and system capacity exceedance, due to excessively high demands. In both situations the amount of water delivered may be appreciable (Cullinane et al., 1992; Gupta and Bhave, 1996).

It has been shown that the requirement that all demands at all nodes including the critical nodes be fully satisfied at adequate pressure does not fully recognize the spatial nature of the hydraulic behavior of water distribution systems (Tanyimboh et al., 1999). Deficiencies in performance have a tendency to be rather localized. In other words, the performance can be unsatisfactory in some areas whilst being fully satisfactory elsewhere (Gupta and Bhave, 1996). If such a system with locally insufficient heads is simulated using the demand driven network analysis approach (with all demands fully met), the deficiency will appear to be far more serious and widespread than it is in reality (Tanyimboh et al., 1997b). Therefore, the authors' use of demand-driven network simulation in this way compounds the underestimation effect of assuming that system reliability is the same as the reliability of the least reliable node (Tanyimboh et al., 1999).

It is useful to note that many of the issues highlighted above can be addressed if another commonly used definition of reliability is adopted, i.e. the mean value of the ratio of the flow delivered to the flow required. The main difficulty with approach at present is that it involves the simulation of the system performance using head-driven network analysis, for which software is not readily available. However, it has the following advantages:

1. It is more realistic in that it fully recognizes the concepts of partial failure, reduced service and system capacity exceedance.
2. The reliability of the system as a whole and that of individual nodes can be calculated in a single operation. For each of the *NC* fully connected or reduced network configurations, a single head-driven hydraulic analysis is required to determine the flow delivered. Therefore, a total of *NC* head-driven network simulations would be performed compared to $NN \times NC$ FORM evaluations.
3. There is no need to identify the critical nodes of the network for the various configurations. The identification of the critical nodes in a distribution system is in general not straightforward as observed by the authors. This is particularly true if nodal demands vary randomly, because the spatial distribution of the demands and their relative magnitudes are important factors also.

To conclude, it is quite clear that more research on easy-to-use methods for the optimal design of reliable water distribution systems is needed. As observed by the authors, one area that attention should focus on is the determination of the appropriate probability distributions for nodal demands. Also, there is an urgent need for clarification of the meaning of the term reliability in this context. Head-driven simulation has the potential to resolve several difficulties associated with the reliability analysis of water distribution systems, some of which have been highlighted herein. This area has received little attention. Finally, it would appear that though powerful the proposed FORM based (optimization) approach is best used for estimating (or optimizing) the reliability of only selected nodes of interest as opposed to entire distribution systems.

APPENDIX I. REFERENCES

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