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RELIABILITY AND SENSITIVITY ANALYSIS OF COMPLEX WATER DISTRIBUTION NETWORKS

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The hydraulic reliability and sensitivity analysis of large scale water distribution systems in presence of uncertainty is considered in this work. The assessment of the network reliability and sensitivity is performed by an efficient Markov chain Monte Carlo method. Prescribed nodal heads of storage tanks, nodal demands and pipe roughness coefficients are modeled as uncertain parameters and described in a probabilistic manner. Failure is assumed to occur when the minimum nodal head in the network is lower than a minimum allowable value. The efficiency of the proposed method is demonstrated with the analysis of a water distribution network consisting of a large number of nodes and pipes.

Keywords: Advanced simulation techniques, Network reliability, Sensitivity Analysis, Water distribution systems.

1 Introduction

One important issue in the analysis of utility networks, such as water distribution systems, is that they are subject to uncertainties. Then, the degree to which the network is able to provide the required service needs to be quantitatively assessed during its design and operation by taking into account these uncertainties explicitly. In general, the reliability of water distribution systems is concerned with two types of failure, specifically, hydraulic failure and mechanical or structural failure. Hydraulic failure considers system failure due to delivered flow and pressure head being insufficient at one or more nodes (Bao (1990)). On the other hand, mechanical or structural failure considers system failure due to pipe breakage, pump failure, power outage and equipment failure in general (Mays (1986), Xu (1998)). Network reliability analysis models based on mechanical, structural or operational failure are well established and they have been developed in the context of many fields. Similarly, a number of studies have been reported on the reliability of water distribution systems based on hydraulic reliability (Torres (2009), Torii (2012)). The previous probabilistic hydraulic models were targeted to small scale water distribution networks. However, one of the intrinsic characteristic features of actual water distribution networks is their very large size. In fact, the complexity of real-world utility networks such as water distribution systems can reach hundreds or thousands of nodes and pipes with a complex topology. In this setting, traditional methodologies such as first/second order reliability methods and standard Monte Carlo simulation methods are not adequate. Then, it is the objective of this work to implement an efficient stochastic framework for the assessment of network hydraulic reliability and sensitivity in the presence of uncertainty. In particular, an efficient Markov chain Monte Carlo method, namely, subset simulation is implemented in the present formulation (Au (2001)).

2 Problem Formulation

It is assumed that the water distribution network is characterized by a vector of uncertain parameters θ. These parameters are defined by a joint probability density function $p(\theta)$, which depends on a certain number of parameters τ. Examples of uncertain system parameters include prescribed nodal heads, nodal demands, pipe diameters, pipe roughness coefficients, pressure head requirements, tanks water surface levels, etc. On the other hand, examples of distribution parameters include the first two statistical moments or other representative value of the system parameters. The performance of the water distribution network is quantified by a utility function $u(\theta)$ through a hydraulic input-output model of the network. This function indicates the degree to which the network provides the required service. Possible utility functions comprise nodal heads (or pressures), nodal flows, water age, chlorine concentration, flow velocities, etc. The network reliability problem consists in computing the probability of failure P_F which is given by the probability integral

$$P_F = \int_F p(\theta)\, d\theta \tag{1}$$

where F is the failure domain defined as the set of system parameters such that

$$F = \{\theta \mid u(\theta) < u^*\} \tag{2}$$

where u^* is the critical threshold. On the other hand, a classical measure for sensitivity is based on the gradient of the quantity of interest. In this context, reliability sensitivity corresponds to the partial derivative of the failure probability with respect to the distribution parameters of the probability density function that characterize the uncertain system parameters. In the framework of networks with a large number of pipes and nodes, the estimation of the probability of failure and its sensitivity is quite challenging due to the dimensionality of the corresponding reliability problem and the complex relationship between the system parameters and the utility function. Thus, the estimation of the network hydraulic reliability and sensitivity has to rely on advanced simulation techniques. Reliability issues related to structural, mechanical or operational failure of system components are not considered in the present formulation.

3 Reliability and Sensitivity Estimation

Among the advanced stochastic simulation methods recently developed, subset simulation (Au (2001), Zuev (2012)) is implemented in the present formulation because of its generality and flexibility. The generality of the method is due to the fact that it is not based on any geometrical assumption about the topology of the failure domain. Validation calculations have shown that subset simulation can be applied efficiently to a wide range of complex reliability problems (Jensen (2007), Schuëller (2007)). The corresponding sensitivity estimation is performed by an approach recently introduced by Jensen (2015). Such approach is a simple post-processing of subset simulation. In other words, the approach does not require any additional water distribution network solution.

4 Example Problem

Figure 1shows the water distribution system analyzed in this work. It consists of 5978 nodes, 5655 pipes (links) and one storage tank.

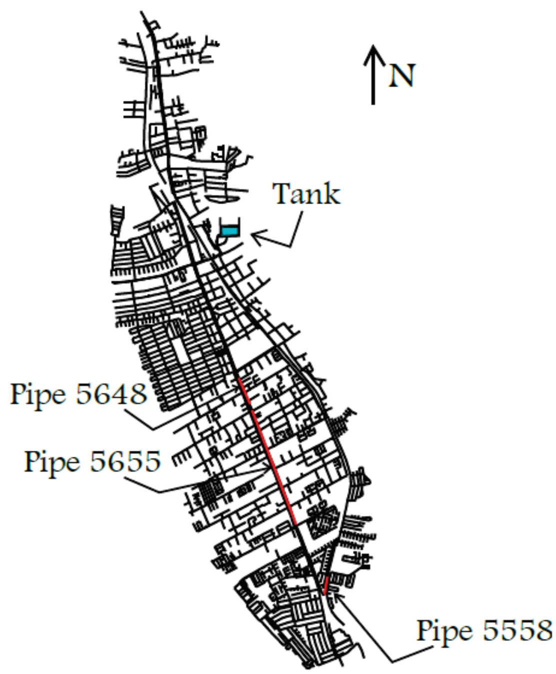

Figure 1. Water distribution network

The length of the network (north-south direction) is about 8300 m. The average total demand of the network is 412.8 l/s and 2848 nodes have no demand. Thus, 3130 nodes are active in the system. The corresponding nominal nodal demands of the active nodes are shown in Figure 2. These nominal values correspond to the ones used in the design stage of the network and represent a standard scenario in terms of the demand pattern. The minimum and maximum nodal demands are 2.0 x 10^{-4} l/s and 3.8 l/s, respectively. The lengths of the pipes in the network vary between 0.28 m and 1636 m, with diameters ranging from 5.7cm to 50.2cm. Pipes of four different materials, namely, high density polyethylene (HDPE), polyvinyl chloride (PVC), asbestos cement (AC) and steel are used in the network. The corresponding nominal roughness coefficients (Hazen-Williams coefficients) are 150, 140, 130 and 100, respectively.

The uncertainty of 8786 parameters corresponding to the nodal demands, pipe roughness coefficients, and prescribed head of the storage tank are considered explicitly in the analysis. The nodal demands are modeled as independent Log-normal random variables with mean values equal to the nominal values, given in Figure 2, and coefficient of variation of 20%. Similarly, the prescribed level of the storage tank is also modeled as Log-normal random variable with mean value equal to 3.2 m and coefficient of variation of 20%. On the other hand, pipe roughness coefficients are described by independent truncated normal random variables with mean values equal to the nominal roughness coefficients values and coefficient of variation of 10%. For reliability purposes failure occurs when the head at some node of the network is lower than its minimum allowable value.

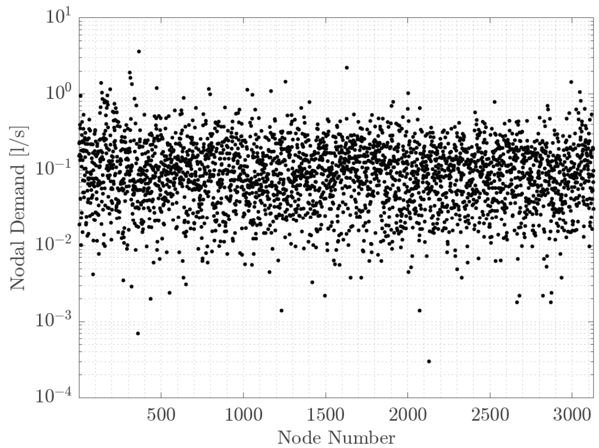

Figure 2. Nominal nodal demands

Figure 3 shows the network probability of failure in terms of the minimum allowable head. Five independent runs are considered in the figure. The hydraulic simulation model EPANET (Rossman (2000)) is used for solving the water distribution system under steady-stare conditions. It is seen that, for example, the probability that the minimum nodal head in the network is lower than 16.5 m is about 2 x 10^{-1}, whereas a probability of 10^{-4} is obtained for a threshold level equal to 14.7 m. Thus, the reliability of the network is highly sensitive to the minimum allowable nodal head. Also, it is interesting to note that the probability of the minimum nodal head being less than 17.18 m (minimum nodal head corresponding to the deterministic network, that is, the system with parameters equal to their nominal values) is about 5 x 10^{-1}, that is, 50%. Therefore, the network characterized in a deterministic manner is quite unreliable under the present uncertain conditions.

As previously pointed out, the standard reliability sensitivity measure is given in terms of the partial derivative of the failure probability with respect to a distribution parameter, i.e., τ_j. Another reliability sensitivity measure is the so-called elasticity, which is given by

$$e_{\tau_j} = \frac{\partial P_F}{\partial \tau_j} \frac{\tau_j}{P_F} \tag{3}$$

This measure is particularly useful to rank the importance of the parameters on the system reliability. Figure 4 shows the elasticity coefficients of the failure probability with respect to the mean value of the most influential parameters in terms of the threshold level. The parameters considered in the figure are the prescribed head of the storage tank and the pipe roughness coefficients (RC) of the most influential pipes, identified as pipe numbers 5558, 5648, and 5655 (see Figure 1).

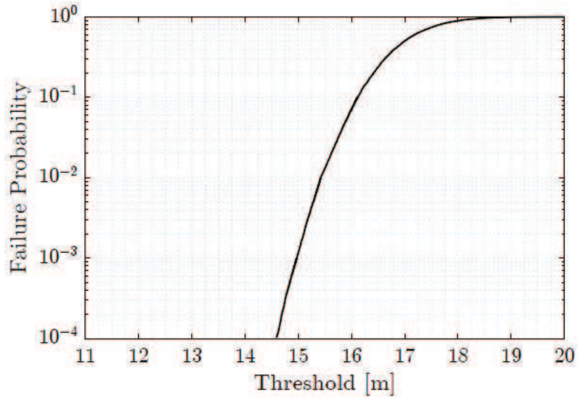

Figure 3. Probability of failure in terms of the threshold

These pipes correspond to some of the longest ones in the network. An average of ten independent runs is considered in the figure. It is seen that the prescribed head of the storage tank plays a significant role in affecting the probability of failure, as expected. It is also observed that the elasticities with respect to the different parameters are negative. Thus, an increase in the values of the prescribed head of the storage tank and pipes roughness coefficients decreases the probability of failure. In fact, an increase in the value of these parameters tends to increase the nodal heads in the network which is reasonable from the physical view point. The previous analyses give a valuable insight into the effect of uncertain system parameters on the reliability and sensitivity of the network.

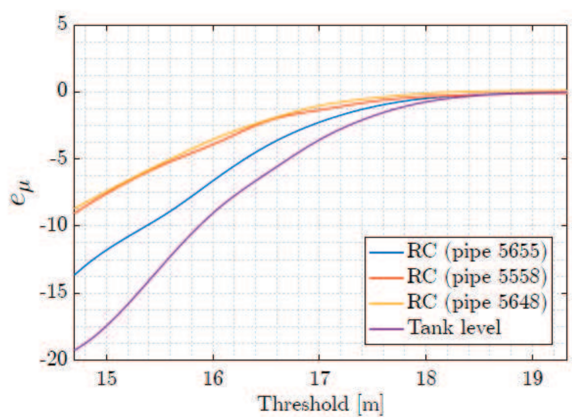

Figure 4. Elasticity coefficient of the failure probability with respect to the mean value of the most influential parameters in terms of the threshold

5 Conclusion

The implementation of an effective stochastic framework for quantifying the hydraulic reliability and sensitivity of large water distribution networks has been presented. The results obtained with the proposed scheme give a valuable insight into the effect of uncertainty on the performance, reliability and sensitivity of large scale water distribution systems. Additional analyses that can be performed within the proposed framework include failure, redundancy, robustness and uncertainty propagation analyses. The information obtained by these analyses can help designers to devise more efficient and robust water distribution networks and to assist water utility managers in making informed decisions on a number of issues related to this class of utility networks.

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