RELIABILITY OF WATER DISTRBUTION NETWORKS

Nuri MERZI[1], Metin NOHUTCU, Evren YILDIZ

[1] IWRA Member, Middle East Technical University, Civil Engineering Department, 06531 Ankara, Turkey

SUMMARY

The main objective of this study is to determine relatively weak pipes intersecting at nodes with relatively low reliabilities; it will help to point out the pipes to improve both for an existing water distribution network and a network in the design stage. The improvement can be realized by increasing the size of the concerning pipes and/or better valving of the related pipes; necessary reliability calculations were carried out based on the partially satisfied nodal demands that depend on pressure heads at the nodes of the water distribution network. A case study was conducted to demonstrate the algorithm.

1 INTRODUCTION

A water distribution network should provide, during its economic life, the required quality and quantity of water at required pressures. The system must be able to supply water during unusual conditions such as pipe breaks, mechanical failure of pumps and valves, power outages, malfunction of storage facilities, inaccurate demand projections. The possibility of occurence of these events should be examined to determine the overall performance and the reliability of the distribution system. Reliability is usually defined as the probability that a system performs its task within specified limits for a given period of time; any calculation of the reliability needs the solution of the partially satisfied networks. The reliability of a water distribution system is important because it gives indications about the quality of service which can be closely related to the management practices of the water utility.

Traditionally, water distribution networks have been designed to be completely reliable; however, the scarcity of public money for construction and maintenance causes the reliability to be an important issue. The reliability is calculated by various reliability factors, by predicting the availability of water at deficient nodes. Reliability should be regarded basically as the ratio of actual flow delivered to the required flow. While designing water distribution networks traditionally, it is important that the network supplies the predicted demands with adequate pressures at all nodes of the network; these models assume fixed demands for nodes and they compute corresponding nodal pressures and also pipe flows. Deficient parts of the networks with nodal pressures lower than the the minimum required pressures are then upgraded through necassary modifications. However, there are no comprehensive and generally acceptable methods for calculating the quantity of flow actually delivered by water distribution systems with less pressure than the required.

In this study, the relationship suggested by Germanopolos (1985) was used with some modifications to relate nodal demands and pressure heads. The modified relationship was included in linear theory for the solution of non-linear network equations. A computer program was coded in MATLAB to provide both fixed-demand and pressure-dependent demand solutions for water distribution networks. An existing network in Ankara, N8 pressure zone was simulated with the developed program; furthermore basic reliability calculations (Gupta and Bhave, 1991) were carried out concerning this pressure zone taking into out various loading conditions and existing valving topology (Walski, 1993) using geographic information systems (GIS).

2 PARTIALLY SATISFIED NODAL DEMANDS

Very few studies have been proposed on partially satisfied nodal demands while there is still no generally accepted suggestion for the subject. Germanopoulos (1985) is one of the pioneers that related directly pressure and nodal consumption. In the network model developed, the pressure-consumption relationship for a given node is expressed as,

$$c_i = q_i^{req}(1 - a_i.e^{-b_i.P_i / P_i^*}) \tag{1}$$

c_i: The consumer outflow at node i,

q_i^{req} : The nominal consumer demand,

a_i, b_i *and* P_i^*: Constants for the particular node.

In the above relationship, q_i^{req} is the outflow normally provided to consumers assuming that the pressures in the system are adequate. P_i^* corresponds to the nodal pressure at which a given proportion of q_i^{req} is known to be provided. Germanopoulos (1985) states that field measurements and information from the system operators can be used to determine the values of a_i, b_i *and* P_i^* for each node; *a* and *b* values were taken as 10 and 5 respectively in an application of the model on an existing network, in the absence of detailed field data.

Germanopoulos' model seems to have three parameters (*a*, *b* and P^*); determining *a* and *b* will designate the value of P^*. It should be noted that, P^* corresponds to the nodal pressure at which a given proportion of q^{req} is known to be provided. For example, taking *a* and *b* as 10 and 5 respectively will designate the value of P^* as the pressure that provides 93.2% of the nominal consumer demand q^{req} (when the pressure *P* is equal to the P^* for *a* and *b* as 10 and 5 respectively, the consumption will equal to $0.932\, q^{req}$). For these values, the pressure for which 93.2% of the demand is provided is to be sought for the corresponding demand.

Although the relationship suggested by Germanopoulos (1985) displays the basic characteristics that are expected in a pressure-consumption relation, i.e. a fall in nodal outflow for pressures below a certain limit as well as a leveling out for higher pressures corresponding to the maximum flow that the consumers are likely to require, it has some problems which should be corrected; some modifications will be suggested for Germanopoulos' model. At first, a consumption per demand (c / q^{req}) value, above which the consumption should be considered as equal to the demand, will be selected; a value of 0.995 is considered to be suitable for this value, which means that consumption should be assumed as equal to the demand for consumption values above 99.5% of the demand.

Note that, P^{req} values are known for each node even at the design period of the networks. So, if P^* is replaced with P^{req}, consumption should be equal to the nominal demand. Equation 1 then becomes;

$$c_i = q_i^{req}(1 - a_i.e^{-b_i.P_i / P_i^{req}}) \tag{2}$$

Since equation 2 is a logarithmic one, *c* will never be equal to q^{req}, so it should be considered as equal to demand when the RHS of the equation is equal to 0.995 q^{req}, as described above. Also it is known that consumption will reach this value when the pressure reaches P^{req}. Replacing these values and simplifying it, equation 2 becomes,

$$a_i.e^{-b_i} = 0.005 \tag{3}$$

It is also known that, consumption should be zero for pressure values below P^{min}. If the value of P^{min} could be found, there will be two equations with two unknowns (*a* and *b*). P^{min} usually ranges from 0 to 10 m. It seems reasonable to take P^{min} as 0 m., so to assume H^{min} to be equal to the node elevation, considering the faucets at node level such as the ones for garden watering or in basement floors in the absence of detailed field data. This assumption is not unrealistic considering that the demand for a node includes the leakage in the pipes. Replacing both *c* and *P* with 0, equation 2 becomes,

$$a_i.e^{-b_i.0} = 1 \qquad (4)$$

which gives *a* as 1. Using this value in Equation 3, *b* is found as 5.3. Finally, Germanopoulos' model becomes,

$$c_i = q_i^{req}(1 - e^{-5.3\, P_i / P_i^{req}}), \qquad 0 < P_i < P_i^{req} \qquad (5)$$

$$c_i = q_i^{req}, \qquad P_i > P_i^{req} \qquad (6)$$

which will be called as *Modified Germanopoulos model* from now on. Note that, demand (q^{req}) and minimum required pressure to provide the demand (P^{req}) are known in the design period of the network. Knowing these values, Equation 5 will give consumptions for pressure values between 0 and P^{req}. Graphical representation of Germanopoulos and Modified Germanopoulos models are given in Figure 1.

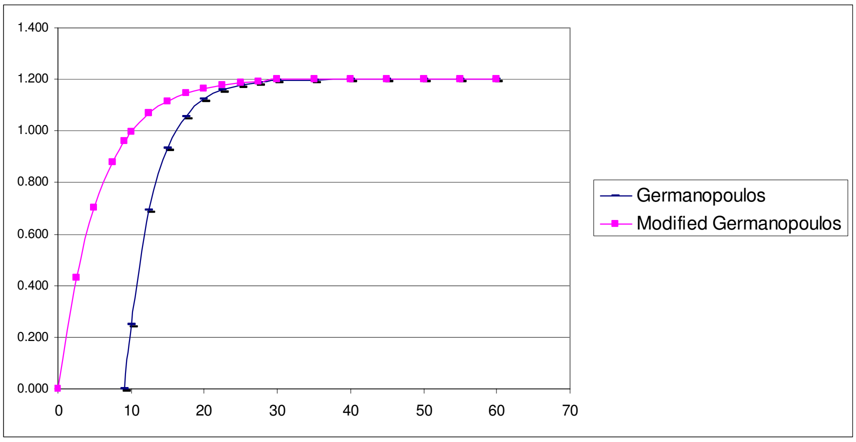

Figure 1. Germanopoulos and Modified Germanopoulos methods

3 INCLUSION OF PRESSURE DEPENDENT DEMAND TERMS

3.1 In linear theory method

Nonlinear equations are obtained by applying the node flow continuity relationship for demand nodes of the network in which nodal heads are taken as the basic unknown parameters in formulating H-equations;

$$\sum_{\substack{\text{i connected} \\ \text{to j through x}}} \left(\frac{H_i - H_j}{K_x} \right)^{1/n} + q_j = 0 \qquad (7)$$

H_i, H_j: heads at upstream node and downstream nodes of pipe x, respectively
K_x: resistance constant of pipe x
q_j: external flow, i.e., supply (inflow) or demand (outflow), at node j

In linear theory method, the nonlinear terms in equations of pipe network analysis are linearized by merging a part of nonlinear terms into the pipe resistance constant,

$$\sum_{\substack{\text{i connected to j} \\ \text{through x}}} C'_x (H_i - H_j) + q_j = 0 \tag{8}$$

in which C'_x denotes the modified conductance of pipe x and given by

$$C'_x = \frac{\left| H_i - H_j \right|^{(1/n)-1}}{K_x^{1/n}} \tag{9}$$

Demand values in equation 7 are not fixed but they depend on the pressure head; in other words they depend on HGL (hydraulic grade line) of nodes for pressure dependent solution methods. Since consumptions are related to pressure head, they must be linearized to be involved according to the linear theory method. A linearization coefficient, D', is defined in order to relate linearly the consumptions and HGL values,

$$c_i = D'_i . H_i \tag{10}$$

Consumption equations are divided and then multiplied by H value in order to express these equations in form of equation 10; accordingly, the consumption equation for Modified Germanopoulos model becomes,

$$c_i = D'_i . H_i = \frac{q_i^{req}(1 - a_i . e^{-b_i . (H_i - elevation_i)/P_i^{req}})}{H_i} * H_i \tag{11}$$

4 RELIABILITY PARAMETERS

Reliability parameters which are Node Reliability Factor, Volume Reliability Factor, and Network Reliability Factor were calculated according to Gupta and Bhave (1991).

5 CASE STUDY

Most of the studies apply reliability considerations on hypothetical networks. However, in this study a real network and actual valve locations were considered. For this purpose N8 pressure zone of Ankara Municipality Water Distribution System was selected as the study area. This zone is a residential area and water consumption in this zone is nearly homogeneous except for the mosques and the schools around; the consumers have same socioeconomic status with lower income. There exists very few commercial and industrial customers. Since the system is fed by one pump station and has one tank, the monitoring of this network is relatively easy. The flow rate passing through the pump, input and output pressure head values and tank levels can be easily observed and saved by the help of Supervisory Control and Data Acquisition System (SCADA) of the water utility (ASKI).

The study area is distributed on two adjacent hills and has a population of 25,000; real network is consisting of 465 links and 373 junction nodes; there is one storage tank having a volume of 5000 m^3 and one pump station. A simple skeletonization process was applied to the N8 network; pipes having a diameter of 150 mm and below were ignored and extracted from the system; therefore, some nodes were carried to the adjacent nodes considering the pipe length using inverse proportionality; finally, 465 pipes were reduced to 125 pipes, and 373 nodes were eliminated to 95 nodes. The valve locations of the system were directly taken from the digital maps of the water utility and they were considered for scenario management. In this study every pipe was considered as if it were broken only once and considering the topology of the valves, a corresponding network layout (a scenario), was obtained. All these possible networks were evaluated considering their related probability of occurrence; breakage rate of the pipes were taken from Kettler and Goulter (1985).

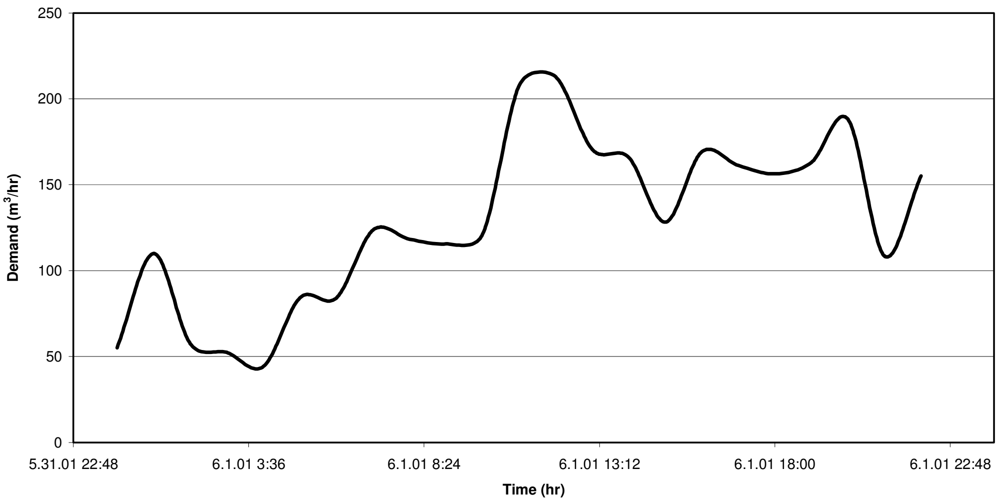

Figure 2. Diurnal curve of June 1, 2001, extracted from SCADA recordings

A prescribed date was selected , June 1st , 2001 (Figure 2) from SCADA recordings and then divided into four equal periods. Using the diurnal curve, average demands were calculated (Table 1). Tank levels were indicated on Table 2.

Table 1. Average demands during appropriate time intervals.

Time Interval	**Average Demand (m^3/hr)**
0 – 6	65.47
6 – 12	135.85
12 – 18	166.58
18 – 24	136.54

Table 2. Assumed tank levels during operation

Time	**Tank Status**
00:00	½ Full
06:00	Full
12:00	½ Full
18:00	Empty
24:00	½ Full

Considering the valve locations, 50 scenarios were extracted. In a scenario it is assumed that an arbitrary pipe was broken and the influenced area was isolated using the related nearby valves.

The duration of a " broken pipe" scenarios is related to the pipe repair time; it was taken as one day as recommended by the water utility staff.; this information indicates that if a pipe is broken, it will be repaired in one day and it will be fully operational the day after. During this period, the isolated area can not take the required amount of water. Other considered scenarios are related to fire condition, and normal condition. Different state groups and corresponding durations are presented on Table 3.

Two topological cases were investigated in this study. In the first case, the system was assumed to be fully valved (at the end of each pipe there is a valve); the reliability factors were very close to unity. In the second case, the system was partially valved – real case – and corresponding reliability values were different than unity. Volume reliability factor was calculated as 0.99623 whereas the network reliability factor was obtained as 0.93373; the network reliability gives a better indication concerning network reliability because it takes into account some threshold numbers regarding the overall behaviour of the individual nodes. Both of these factors give information about the whole network; on the other hand, node reliability factor was found to be varying between 0.95615 and 1.

Table 3. Different State groups and corresponding durations.

Mode	**Description**	**Number of States**	**Total time(days)**	**Cumulative time (days)**
Normal	No shutdown-pipe, normal flow, no fireflow	**4**	**328.217**	**328.217**
Scenarios	Scenarios, normal flow, no fire flow	**200**	**34.283**	**362.5**
Fire	No shutdown pipe, normal flow, fire requirement	**10**	**2.5**	**365**

6 CONCLUSIONS

The main objective of this study is to determine relatively weak pipes intersecting at nodes with relatively low reliabilities; it will help to point out the pipes to improve both for an existing network and a network in the design stage. The improvement can be realized by increasing the size of the concerning pipes and/or better valving of the related pipes. Furthermore, importance of breakage rates of pipes, repair time of the broken pipes, degree of the skeletonization were mentioned.

REFERENCES

Germanopoulos G., "A Technical Note on the Inclusion of Pressure Dependent Demand and Leakage Terms in Water Supply Networek Models", Civil Engineering Systems, 2, September, 1985.

Gupta R., and Bhave, P.R., "Reliability Analysis of Water Distribution Systems", J. of Env. Eng., ASCE, 120 (2), 447-460, 1994.

Kettler, A.J., and Goulter, I.C., "Reliability Consideration in the Least Cost Design of Looped Water Distribution Networks", Proc. of the X. Int. Symp. on Urban Hydrology, Hydraulics and Sediment Control, Univ. of Kentucky, Lexington, Ky., 305-312, 1985.

Walski, T. M., "Water Distribution Valve Topology for Reliability Analysis", Reliability Engineering and System Safety, 42, 21-27, 1993.