Locating Leaks in Water Distribution Systems Using Network Modeling

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Water distribution systems can experience high levels of leakage resulting in major financial, supply and pressure losses. Locating and repairing system leaks can drastically reduce the amount of water that is lost, as well as reduce the costs for obtaining, treating and pressurizing water distribution systems to meet current and future demands. This chapter describes an efficient step-testing network modeling approach that solves the leakage detection problem using a direct application of network modeling and field testing. The technique involves bracketing the test area with excessive leakage into a tight branched network with a flow meter installed on its input main. Working from the valve furthest away from the flow meter, the size of the area is systematically reduced by closing valves to cut off different pipe sections in succession (so that less and less of the test area is supplied through the meter), at the same time recording changes in flow rate at the meter and comparing with model results. The sequence of closing valves is followed working backward towards the flow meter until the meter is reached (when the flow becomes zero). A disproportionate change in flow discrepancy between two successive steps indicates a leak in the section of pipe that was last shut off. The sequence is repeated by opening valves in reverse order. The method can effectively narrow down leaks to specific pipe segments of the distribution system. It is normally carried out at night before the morning high demand to minimize supply interruption and inconvenience to customers. An example application is used to illustrate the

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proposed approach. The method should prove useful to any water utility attempting to locate excessive pipe leaks in distribution systems and conserve such a precious natural resource as water. It is modeling complexity through simplicity.

21.1 Introduction

One of the major contributors to water loss is underground leaks in water distribution systems. These systems can experience high levels of leakage resulting in major financial, supply and pressure losses. Leakage occurs in different components of the system including transmission and distribution mains, service connection lines, valves, joints, and fire hydrants. It can originate from many sources such as the deterioration of aging pipes and fittings, material defect, changes in water pressure (water hammer), high population density, heavy traffic volumes, movement of above ground pipelines, aggressive soil conditions, and corrosion (AWWA, 1999). Excessive leakage can also cause contaminant intrusion events, which can lead to detrimental or fatal water quality episodes. The EPA estimates that water utilities in the US will need to spend US\$6 billion per year over the next twenty years to rehabilitate failing water distribution pipes (Lansey and Boulos, 2005; Boulos et al, 2006).

Locating and repairing system leaks can drastically reduce the amount of water that is lost, the implementation of drastic conservation policies during droughts, adverse risk of contamination, and water outage events, as well as reduce the costs for obtaining, treating, and pressurizing water supplies. Other benefits for water utilities and their customers include more efficient use of existing supplies, improved water conservation measures, environmental quality, and system operational efficiency, integrity, reliability, performance and fire fighting capability, as well as extended useful life of existing facilities, increased services to new developments, and delayed treatment plant capacity expansion and construction of new sources of water supply (Lauber, 1977).

System (water) audits and leak detection programs can help utilities reduce water losses (AWWA, 1999). Water audits involve detailed accounting of the distribution system inflows and outflows. They provide an overall picture of the distribution system efficiency and water losses and identify areas of the system experiencing excessive leakage. The overall goal is to identify, quantify, and verify water and revenue losses. These audits do not provide information about the precise location of leaks. Leak detection

programs identify and prioritize the areas of high leakage using step-testing. The principal objective of step-testing is to continuously isolate portions of the distribution system where leakage is measured quantitatively (WHO, 2001). Localizing leaks can also be carried out using acoustic listening devices (sounding). The exact locations of leaks can then be determined using leak noise correlators (leak noise correlation).

Acoustic loggers are normally installed on pipe fittings and are used to identify suspected leakage areas by listening for leak characteristics. By recording and analyzing the intensity and consistency of noise, the loggers are able to determine the likely presence of a leak. Noise is created by the leak as it escapes from the pressurized pipe. Similar to the traditional sonic equipment, the correlator relies upon the noise generated by a leak. The main difference, however, is in how the leak noise is detected. A correlator works by detecting the sound from the leak when it arrives at two sensors (installed on pipe fittings) on the pipe, either side of the suspected leak position. The difference in the arrival time of the leak noise at each sensor (time delay), combined with knowledge of the distance between the two sensors and the velocity of the sound in the pipe, enables the correlator to calculate the leak position. Normally, acoustic equipment is effective for metal pipes as the leak signals transmit for relatively long distances but could be problematic for plastic piping as the signals only transmit for only very short distances. In general (Hunaidi et al, 2000), leak noise correlators are more efficient and more accurate than listening devices. Leaks can also be located with non-acoustic technologies such as tracer gas, termography, and ground-penetrating radar. The use of these techniques is, however, still very limited and their effectiveness not well established (Hunaidi, 2000).

Step-testing is one of the most effective and practical tools of identifying and quantifying leakage within specific areas (step areas) of the distribution system. This is an activity whereby the step area is subdivided by the systematic closing of valves during the period of minimum night flow and recording the reduction in flow. Disproportionate drops in flow define the pipes with suspected leakage. The method is particularly suited to identifying areas of high leakage and to use on plastic pipes, where leak noise is absorbed and conventional acoustic methods are less effective. It also minimizes the use of detection required by sonic equipment and correlators. Having localized the leaks using step-testing, the correlators can be used to pinpoint the precise locations of the leaks along the pipes, and repairs can then be carried out. The sequence of step testing and leak detection and repair is continued until an acceptable level of leakage in each step area is recorded.

The main drawbacks of the traditional step-testing approach are the requirement of detailed maps of the distribution system, showing all water facilities (pipes, valves, pumps, tanks and reservoirs), and the need to determine the proper sequences of valve closing to cut off different pipe sections in succession. In addition, the method requires consumption to be relatively stable and its efficacy is limited by the lack of database support and user-friendly interfaces for data manipulation, hardcopy reporting (i.e. detailed field implementation manual), and graphical output display. These requirements suggest the need for an integrated network modeling approach to step-testing.

This chapter presents a rigorous and efficient step-testing modeling approach that overcomes these limitations. It combines hydraulic network modeling with field testing. The network model contains all pertinent water system facilities and is used to delineate the step area, provide the necessary flow and consumption characteristics, and to compute the optimal patterns of systematic closing of valves. In addition, the method is less sensitive to the structure of the network and to the variation in demands. These capabilities provide a consistent modeling environment to assist water utilities in planning, designing and implementing cost-effective and reliable leak detection programs. The method is illustrated by application to an example water distribution system and conclusions are stated.

21.2 Methodology

The proposed step-test network modeling approach narrows down leaks to specific pipe segments of the water distribution system. It involves network modeling and field testing. Network modeling determines how to define and subsequently subdivide the step area with the systematic closing of valves, and computes the total flow into the step area associated with each distinct valve closing operation. Field testing involves taking flow readings while performing required valve operations (Figure 21.1). At each step, the flow reading (at the flow meter) is taken and compared to the modeled value, and the difference in flow rate is recorded. Any leakage isolated in a particular pipe segment sequence is shown as a drop/change in the difference in flow (flow discrepancy) between two successive steps. The flow discrepancy also represents the suspected leakage in the associated pipe segment sequence.

Figure 21.1 Field operation for step-testing.

The method involves bracketing an area with excessive leakage into a tight zone (step area) with a flow meter installed on the input main to each zone to record flow into the zone. The step area must be fed via only one source (e.g. storage tank, pipe interconnection) and must not contain any loops (tree or branched network). The step area thus becomes a tree-like structure that is supplied through a single meter and isolated from the rest of the system by closing all boundary and circulation valves. This can be accomplished by:

- closing boundary valves to isolate the step area from the system (only one source of supply)
- closing circulating valves to remove loops and create a tree network
- placing a data logger to the flow meter

Figure 21.2 shows the schematic of a sample step area. The initial area is depicted in Figure 21.2a while the final tree-like step area, obtained after closing boundary and circulating valves, is shown in Figure 21.2b. It is also important to identify all step valves that can be used during the test and all other valves that should be excluded from operation (not to be used during the test) such as boundary valves and inoperable (e.g. broken) valves. Identification of the latter group of valves is important to avoid mistakenly opening those valves during the test.

Working from the farthest valve (away from the meter), the size of the zone is systematically reduced by closing valves to cut off different pipe sections in succession (so that less and less of the test area is supplied

through the meter), at the same time recording changes in flow rate at the meter and comparing with modeled results. Each step must be shut long enough to see the flow impact at the meter. The sequence of closing valves is followed until the flow meter is reached (when the flow becomes zero). A significant discrepancy in flow rate between two successive steps indicates a leak in the section of pipe that was last shut off. The sequence is repeated by opening valves in reverse order. The opening and closing of valves should be performed slowly to avoid unwanted surges and breaks. Step-testing is normally carried out at night before the morning high demand when the consumption is lowest and relatively unchanged (static), and to minimize supply interruption and inconvenience to customers. Flushing may be required prior to step-testing a targeted area of the distribution system to alleviate potential water quality problems resulting from valve operation (WHO, 2001).

Figure 21.2 Sample step-test area definition.

Step-testing can be summarized as follows:

1. Step-test at night during period of low/slack demand;
2. Define step area with suspected high leakage;
3. Close all boundary valves (to establish a tight area);
4. Close all circulating valves to remove loops and create a tree network;

5. Attach data logger to the flow meter installed on the main supplying the step-test area;
6. Start at the pipe/valve farthest from the flow meter;
7. Close step valves in succession such that less and less of the step area is supplied via the flow meter and record measured flow values;
8. Follow the sequence of closing valves (as determined by the network model) back towards the meter, when the reading is zero;
9. Keep each step long enough to notice a reading impact at the meter; and
10. Reopen the step valves in reverse order.

It should be noted that depending on the topological structure of the step area, more than one arrangement of step sequences could be possible. For example in the sample step area shown in Figure 21.3, the following distinct sequences are feasible:

(V8,V7,V6,V5,V4,V3,V2,V1), (V8,V7,V3,V2,V6,V5,V4,V1),
 (V8,V7,V6,V5,V3,V2,V4,V1), (V3,V2,V8,V7,V6,V5,V4,V1),
 (V3,V2,V6,V5,V8,V7,V4,V1), (V6,V5,V8,V7,V4,V3,V2,V1),
 (V6,V5,V8,V7,V3,V2,V4,V1), (V6,V5,V3,V2,V8,V7,V4,V1).

The network model can identify all possible step sequence arrangements and the desired sequence selected by field personnel based on optimal route.

Figure 21.3 Example of feasible step sequences.

21.3 Illustrative Example

A worked out example is presented here to illustrate the calculation steps of the network modeling approach for leak detection. The step-test area is shown in Figure 21.4. The test area comprises 6 pipe sections and 6 demand nodes. Two leaks (of one flow unit each) are assumed for pipes P2 and P4.

Figure 21.4 Illustrative step-test modeling example.

Figure 21.5 Flow step results towards the meter for sample test area.

Figure 21.5 gives the flow results for each step sequence back towards the flow meter. Moving from right to left in Figure 21.5, field crews will sequentially shut valves. With each valve closure, the flow rate is reduced at the monitoring point on the left side of the figure. The valve closing operations at valve V2 and valve V4 result in two distinct flow discrepancies, indicating the presence of a leak in pipes P2 and P4.

Figure 21.6 Complete step-step flow results for sample test area.

Figure 21.6 shows the flow results for the entire step-test. It should be noted that the symmetry along the Y-axis will only be valid when the demand loadings (and associated patterns) and operating conditions over the step-test period remain unchanged (static). However, the step discrepancies (the additional flow from leaks) will not change depending on the demand loading changes. This observation is key for this method, as the redundancy of measurements provides a stable and efficient experimental design that can be reproduced under any demand conditions. The flow calculations for the example network are summarized in Table 21.1.

Table 21.1. Step-test calculations for sample test area.

Step	Time	Valve	Flow	Flow	Flow	Step	Comment
Seq.	(a.m.)	Operation	Measured	Modeled	Difference	Discrepancy	
0	12:10	--	14 units	12 units	2 units	--	
1	12:20	V1	12 units	10 units	2 units	0 unit	No leak
2	12:30	V2	9 units	8 units	1 unit	1 unit	1 unit leak
3	12:40	V3	7 units	6 units	1 unit	0 unit	No leak
4	12:50	V4	4 units	4 units	0 unit	1 unit	1 unit leak
5	1:00	V5	2 units	2 units	0 unit	0 unit	No leak
6	1:10	V6	0 unit	0 unit	0 unit	0 unit	No leak

21.4 Leak Location

Once leakage has been localized to specific pipes within a step area, leak noise correlation can be effectively used to identify precisely where the leak is located along each pipe. In this method, two sensors are installed on either side (usually hydrant or valve) of the suspected leak position. The location of the leak (X) can then be computed using a simple algebraic relationship (based on the principle of correlation) between the difference in the arrival time of the leak noise at each sensor (Δt), which is measured from the cross-correlation of the leak signals, the distance between sensors (L), and the propagation of sound waves in the pipe (V) as:

$$X = (L - (V\Delta t)) / 2 \quad (21.1)$$

This approach is illustrated in Figure 21.7.

Figure 21.7 Principle of correlation for leak detection.

21.5 Conclusions

Step-testing is the process of localizing leakage into specific pipe segments of the distribution system for subsequent replacement or repair. This chapter has presented an efficient approach to optimally identifying pipes with suspected leaks by combining field testing with network modeling. The leak in a pipe segment is determined by analyzing the rate of change in the discrepancy between field measured and modeled flow values. The method is well suited to bracket high leakage areas in the system and is applicable to any pipe materials. In addition, it is less sensitive to the topological structure of the network and to the variation in consumption than the traditional step-test field approach.

The method can be further enhanced with linkage to a geographic information system (GIS). The GIS can be used to store, locate, manage and display all pertinent water system facilities and produce comprehensive maps of the step areas. The data from the GIS environment are fed into the network model that produces the optimal step-testing sequences, which in turn can be evaluated by the GIS to provide utility personnel with a detailed field step-testing implementation manual detailing the proper sequences of valve operations. The resulting geospatial step-test modeling approach will help to effectively communicate the schedule/progress information to field personnel, because they will be able to see in detail the temporal sequences of valve operations alongside the modeling results (Boulos, 2006). It is modeling complexity through simplicity.

References

- AWWA (1999). "Water Audits and Leak Detection." Manual of Water Supply Practices No. M36, 2nd Edition. American Water Works Association, Denver, CO, 99 pages.
- Boulos, P. F. (2006). "InfoWater LDM – A Comprehensive GIS-Centric Network Modeling Program for Leak Detection." MWH Soft Pub., Pasadena, CA.
- Boulos, P. F., Lansey, K.E. and Karney, B.W. (2006). "Comprehensive Water Distribution Systems Analysis Handbook for Engineers and Planners." Second edition, MWH Soft Pub., Pasadena, CA, 660 pages.
- Hunaidi, O., Chu, W., Wang, A. and Guan, W. (2000). "Detecting Leaks in Plastic Pipes." Journal American Water Works Association, 92(2), pp. 82-94.
- Hunaidi, O. (2000). "Detecting Leaks in Water Distribution Pipes." Construction Technology Update No. 40, Institute for Research and Construction, National Research Council of Canada, pp. 1-6.
- Lansey, K.E., and Boulos, P.F. (2005). "Comprehensive Handbook on Water Quality Analysis for Distribution Systems." MWH Soft Pub., Pasadena, CA, 448 pages.

- Lauber, C.E. (1997). "Leak Detection Cost-Effective and Beneficial". *Journal American Water Works Association*, 89(7), pp. 10.
- World Health Organization (2001). "Leakage Management and Control – A Best Practice Training Manual." World Health Organization.