Division of Science, Research and Technology

Research Project Summary

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Susceptibility of Potable Water Distribution Systems to Negative Pressure Transients

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Introduction

The operating conditions of a drinking water distribution system (the network of underground pipes through which water is delivered from a drinking water treatment plant to customers) are rarely at a steady state. Each day, due to constantly changing demand, water pumps start up or switch off and valves open and close, resulting in rapid flow changes. Previous research has established that pressure waves generated by these disturbances can propagate throughout the distribution system. These pressure waves (also called surges or water hammer) have both positive and negative phases as shown in Figure 1.

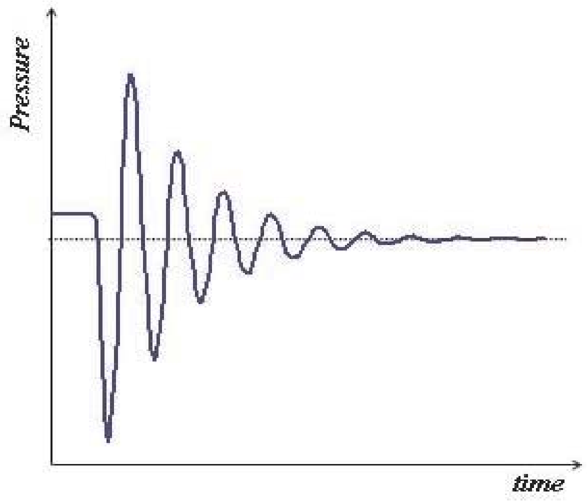

Figure 1. Evolution of a transient pressure wave

Historically, surge control has focused on reducing high-pressure events to prevent pipe fatigue and failure. Concerns regarding negative pressure changes (transients) and their associated public health implications have not received similar attention. Low or negative pressure events create opportunities for external contamination to enter the distribution system. Leakage points in water mains, submerged air valves, cross-connections and faulty seals or joints can all serve as entry portals for external contaminants when the pressure of water surrounding a distribution system main exceeds the water pressure inside the main. As with high pressure events, low and negative pressure transients may also contribute to pipe fatigue and eventual failure if stress fluctuations of sufficient magnitude and frequency occur.

Low water pressure and cross-connections with non-potable water pipes are well-known risk factors for disease outbreaks (Hunter, 1997; Mermin et al.1999; Craun and Calderone, 2001). A survey of over 700 North American systems found that almost all had cross-connections susceptible to backflow by various means (Lee et al. 2003). Thus, all of the systems were susceptible to the introduction of non-potable water through backsiphonage, which could occur with a low or negative pressure transient event. Some epidemiology studies have provided evidence that distribution systems may contribute to increased levels of gastrointestinal illnesses (Payment et al. 1991; Payment et al. 1997; Hunter et al. 2005).

Investigating pressure transients improves understanding of how a system will behave in response to a variety of events such as power outages, routine pump shut downs, valve operations, flushing, firefighting, main breaks and other events that can create significant, rapid, temporary drops in system pressure. This project built upon the work done in previous projects (Kirmeyer et al. 2001; Karim et al. 2003; Friedman et al. 2004; Gullick et al. 2005). It addressed the gap that exists in understanding distribution system characteristics that are conducive to the occurrence of negative pressure transient events. These events were documented in several water systems and mitigation strategies were identified.

Objectives

1. Select five distribution systems that allow a range of distribution system characteristics to be examined.
2. Develop computer models that allow actions resulting in sudden changes of flow (that result in hydraulic

transients) to be examined.

3. Use surge modeling predictions to locate pressure monitors in areas of the distribution system most vulnerable to low or negative pressure events.

4. Based on project results, develop recommendations to minimize the occurrence of and impacts from negative pressure transients.

Methods

1. Distribution System Selection

Five distribution systems that represent a range of utility operations (e.g., system size, operating pressure, number of pumps, topography, network configuration, etc.) were selected for surge modeling (Table 1).

Table 1. Characteristics of Distribution Systems Selected for Surge Modeling.

#	Avg. MGD	Source Type[a]	Elevation Variation	# of Pressure Zones	Service Pressure (max/min psi)		# of floating storage tanks	Primary reasons for selecting system?
1	3.0	GW	Flat	1	130	35	3	flat, 10 inputs into 1 pressure zone
2	12.0	GW	Flat	1	90	40	7	flat, 18 inputs into 1 pressure zone
3	41.0	Both	Moderate	6	110	40	19	multiple inputs; several long, 54-in branching mains
4	39.0	Both	Moderate	13	220	25	17	multiple inputs, complex system
5[b]	29.9	SW	Flat	1	140	25	18	large, no floating storage

[a] SW = surface water; GW = ground water; “Both” indicates system is fed by both groundwater and surface water.

[b] System 5 is located in New York.

2. Surge Modeling Procedure

Calibrated steady-state and extended-period simulation (EPS) models were used to provide initial and boundary (high flow period) conditions for the five system-specific models. A steady-state model simulation predicts behavior during a hypothetical condition where the effects of all changes in system operation have stopped. Extended-period simulations capture pressure and flow changes as customer demands vary over time, as pumps cycle on and off, and as storage tank levels change using a series of steady state simulations linked by an integration scheme for the differential equation describing tank dynamics.

The models were calibrated using field data on pressures, flows, and tank water levels (assumed accuracy of 10%) under known conditions, and adjusted (e.g., pipe roughness factors, tank/pump operational settings, etc.) to agree with field data. A calibrated model was defined as a model of the distribution system calibrated to within ± 5 psi pressure and ± 5% flow at all recorded points for the calibration conditions. Simulated storage tank levels were required to be within +/-2 feet of actual levels at the end of 24 hours.

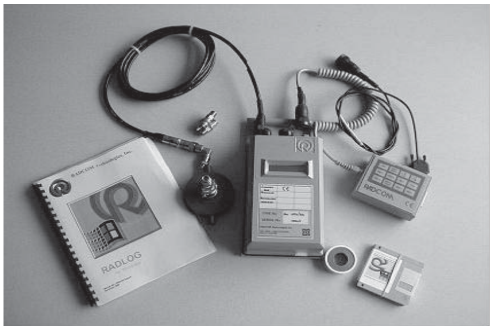

Figure 2 RADCOM electronic pressure monitor assembly.

3. Transient Analyses

The H2OSURGE (MWHSoft, Pasadena, CA) computer program was used for surge modeling. At least three key simulations were performed for each system: 1) complete loss of pumping (e.g., a power outage); 2) a major main break in a key trunk line; and 3) opening a hydrant to fire flow. Additionally, rapid fluctuation of a pressure reducing valve (PRV) was simulated if the system included a PRV.

The wave speed used in all models was assumed to be 3,600 feet per second (ft/s) unless otherwise specified. The model was used to predict the propagation of pressure transients through each system. Based on maximum system size, each simulation was run for at least 120 seconds. The model output showed the results of simulations of transient pressure events, and included analysis of the location and magnitude of low and negative pressure events under the specified conditions.

4. Pressure Monitoring

The primary purpose of pressure monitoring was to determine if low or negative pressure transients would be detected in areas identified during modeling as being vulnerable. Monitoring was conducted at two of the five systems. Several high-speed pressure data loggers were used (RDL1071L/3 Pressure Transient Logger, RADCOM Technologies, Inc., Wobern MA; Figure 2). High speed loggers may be necessary because some pressure transients may last only for seconds and may not be observed by conventional pressure monitoring. Each RADCOM unit can record up to 20 pressure readings per second (capacity, 2 million readings; tolerance, +/- 2.0 - 4.0 pounds per square inch [psi]). However, only one reading per second was obtained so that data could be collected for up to three weeks. Conventional Telog monitors (HPR-31 Hydrant Pressure Recorder, Telog Instruments, Inc, NY) were also used for pressure comparisons.

Monitoring locations (areas vulnerable to low pressure events) in each system were selected based on hydraulic and surge modeling results. Figure 3 shows a schematic of one of the two monitored systems as well as the placement of the pressure monitors at fire hydrants.

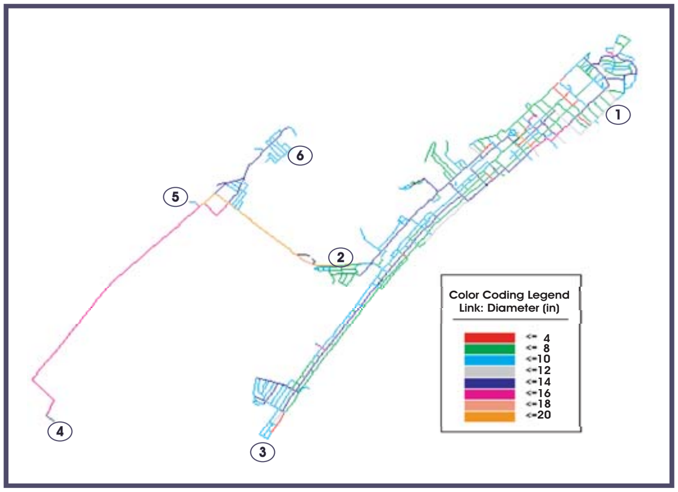

Figure 3. Monitoring locations in System 1. Both RADCOM and Telog monitors were placed at hydrants near Locations 1, 2 and 4. A Telog monitor was placed at Location 6 and RADCOM monitors were placed at Locations 3 and 5.

Water system personnel reported pertinent information related to normal operations during the monitoring periods along with any unusual occurrences. This information included the status of pump operations, power outages that may have shut off pumps, flushing operations (including flow rate and duration), other system demand data and sudden high demands, breaks in pipes, and other information as appropriate. The information was used to ensure the model conditions were set appropriately for comparison of model output to the field pressure data.

Results

1. Pressure Monitoring

For illustrative purposes, Figure 4 shows the resulting low pressure transients at various “junctions”[a] of System 1 that were predicted to occur when a key pump (#9) shuts off.

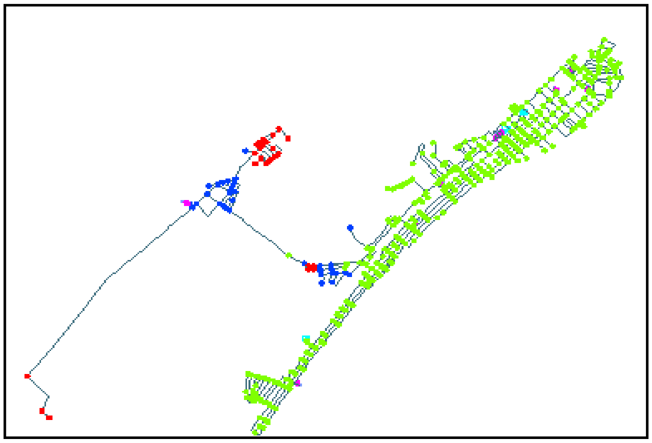

Figure 4. Negative and low pressure nodes[a] resulting from a complete loss of power to pump #9 in System 1. Red = negative pressure; blue = low pressure; green = normal pressure.

Data collected from the six pressure monitoring locations (see Figure 3) revealed low pressures in some locations but not others. Figure 5 shows the pressure profile for one low-pressure location (#4).

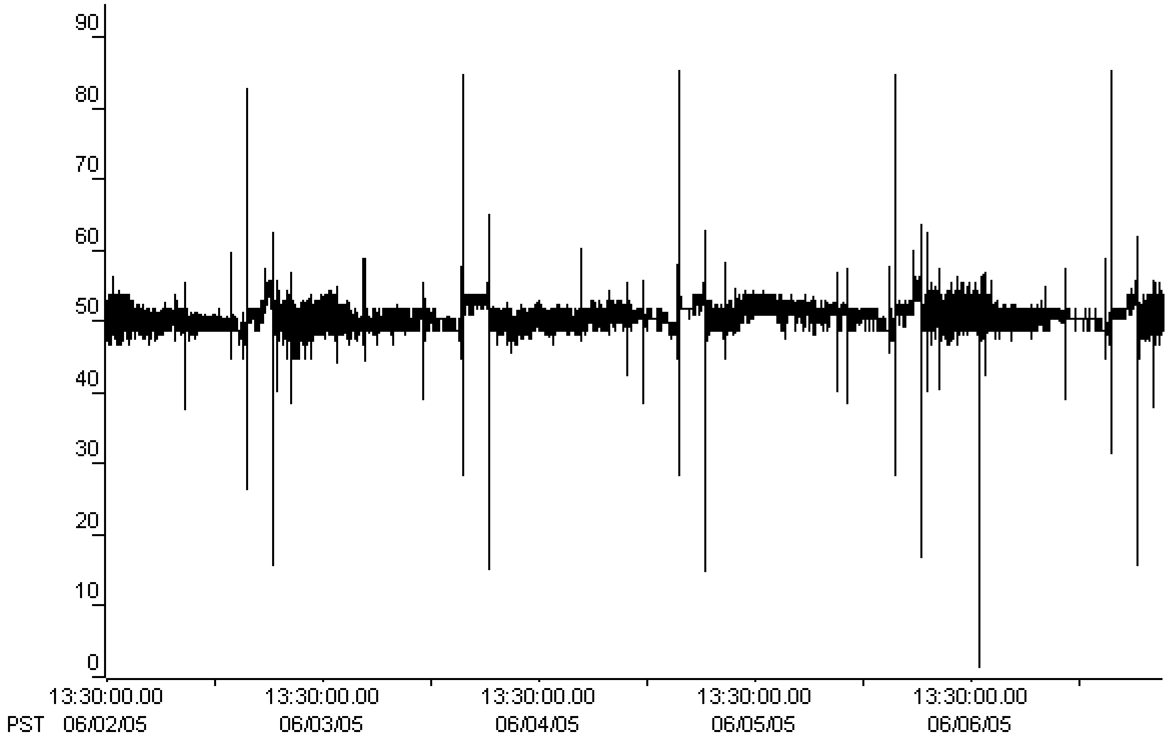

Figure 5. Pressure transients measured at System 1, location 4 (elevation = 25 ft) using a RADCOM data logger. The hydrant was fed by a 16-inch main. Pressure was measured for 5 days. Lowest pressure detected was 1.1 psi.

Modeled and field-measured transient pressure changes were very similar for the two systems examined. Negative pressures were not detected, but low pressures (pressure < 20 psi) were measured in three locations in one system and in one location in the other. The lowest pressure measured was 1.1 psi. The Telog monitors used in this project proved adequate for detecting low pressures in the distribution system. However, such monitors may not be suitable if more detailed information on the transient pattern is required.

2. Comparison of Surge Modeling and Field Monitoring Data

Calibrated EPS models produced surge models that, following wave speed adjustment, adequately assessed distribution susceptibility to low and negative pressures as illustrated in Figure 6 for System 1, location 4.

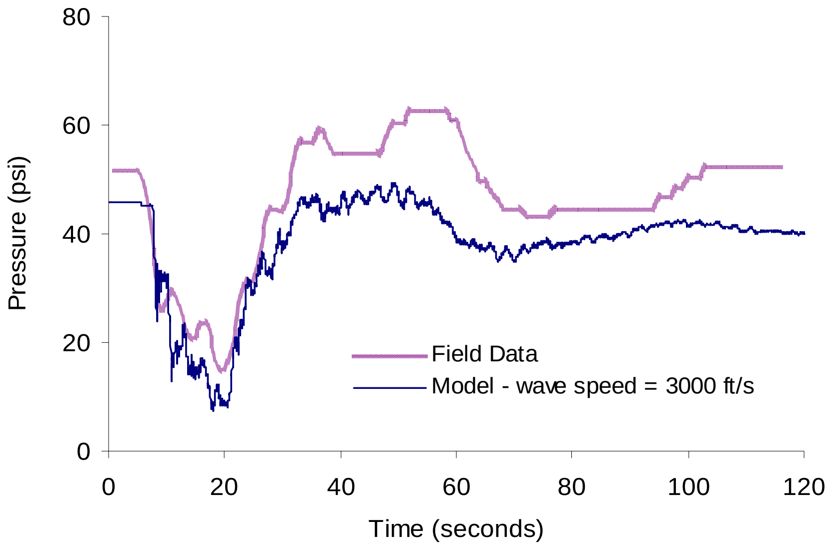

Figure 6. Model and field results for System 1, location 4. Pump #9 shut down in 1 second and with wave speed reduced from 3600 ft/s to 3000 ft/s.

Predicted pressures were lower than monitored values in most cases. The difference was due primarily to the fact that the initial and boundary conditions used during monitoring corresponded to conditions for lower flows than those estimated during surge modeling. Additionally, the timing of transient-producing events (pump shutdown for example) and the wave propagation speed were estimated.

3. System Characteristics Conducive to Low or Negative Pressure Events

Size. System size did not have a significant effect on the occurrence of low and negative pressures. For example, a complete loss of pumping power in a system with 509 miles of main caused negative pressures in approximately 10% of the system, while complete loss of pumping power in another system with 60 miles of main resulted in negative pressures in nearly 70% of the system.

Pump capacity and downstream velocities. Increasing the flow brought to a stop increased the predicted percentage of locations with negative pressures when loss of pumping power occurred. Power loss at pump stations with downstream velocities less than 1.5 ft/s did not result in negative pressures in most of the systems examined. Conversely, the shutdown of pump stations with downstream velocities greater than 3 ft/s almost always created negative pressures in the areas surrounding the station, if "floating"[b] storage facilities or other surge mitigation was absent.

System configuration and topology. Low and negative pressures were more prevalent at or near dead ends and were also more prevalent in regions where local elevations were greater than 30 to 40 ft above immediate surroundings.

Storage facilities. In general, the presence of floating storage[b] significantly reduced the impact of low/negative pressure transients.

Surge relief. The installation of appropriately-sized air vacuum valves reduced negative pressures by as much as 40% in some systems. Hydropneumatic tanks provided the most dramatic reductions, however. For most of the systems examined in this study, if the water main downstream of the pump station was 24 inches or smaller, the installation of one 1,000-gallon hydropneumatic tank was sufficient to prevent negative pressures when a power outage occurred. Systems with larger mains required larger hydropneumatic tanks. Pump bypass piping installed at booster stations was also effective in preventing transients when power loss occurred at the stations.

Conclusions

The purpose of investigating pressure transients is to improve the operator's understanding of how the system will behave in response to a variety of events such as power outages, pump shut downs, valve operations, flushing, firefighting, main breaks and other events that can create significant rapid drops in system pressure and/or low pressure waves. A holistic review of system conditions and utility procedures is recommended to effectively minimize a system's susceptibility to pressure transients. To accomplish this, several key elements should be considered: 1) determination of the occurrence of low pressure surges (including magnitude and duration, as well as locations of lowest pressures); 2) the causes of surges; 3) system response to surges (or system robustness); 4) susceptibility to contamination when surges occur; and (5) means of controlling surges.

Surge models can be used to identify those locations within a distribution system where low or negative pressures are most likely to occur, thus guiding utilities to the most appropriate monitoring locations, and also enabling analysis of alternative mitigation techniques. Modeling can save utilities time and money spent on less fruitful monitoring efforts or less effective corrective actions.

Recommendations for Surge Monitoring and Mitigation

1. Currently available calibrated EPS models can be used to identify susceptible surge monitoring locations. However, pressure monitoring should be performed for a few of the locations to verify the susceptibility of the locations predicted to be vulnerable to low and negative pressures.

2. To best understand the impact of surge in individual systems, the use of calibrated surge models is recommended. If field verification will be performed, then it would be ideal if the model was calibrated so that tank levels, pumping rates and other boundary conditions match the field conditions on the day data is collected.

3. A calibrated EPS model does not equal a calibrated surge model. Once boundary conditions have been verified, critical parameters such as pump inertia, and valve closure times should be verified.

4. Vulnerable areas identified via modeling should be prioritized for maintenance of a disinfectant residual, mitigation via surge control, leak detection and control, and cross connection control.

5. Slowing the rate at which a transient producing action occurs will reduce the magnitude of the surge produced. Increasing pump inertia, slowing the opening and closing of fire hydrants, prolonging valve opening and valve closing times, and avoiding complete pump failure by putting a major pump on a universal power supply are all direct actions that can be taken for surge control.

6. Installing standpipes or hydropneumatic tanks near pump stations is effective for surge mitigation. One way feed-tanks, which only allow flow into the pipe system, can be installed anywhere along the line to reduce negative pressures.

7. For distribution systems still in the planning stages, rerouting pipelines, using larger diameter pipes (or otherwise lowering the flow velocity), changing pipe material, or applying changes in system topology are all direct actions that can be applied

The final choice for surge protection should be based on the initial cause and location of the transient disturbance(s), the system itself, the consequences if remedial action is not taken, and the cost of the protection measure(s).

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Endnotes

[a] A junction is a “node” in a distribution system model where pipes connect. Customer demands are typically represented at this point, although it is possible to have a junction with zero customer demands. A node is a model representation of features at specific locations within the full-scale system. Models have many types of nodal elements, including junction nodes where pipes connect, storage tank and reservoir nodes, pump nodes, and control valve nodes. The terms “node” and “junction” are used interchangeably in the final report.

[b] A storage tank is said to “float” on the system if the hydraulic grade elevation or line (HGL) inside the tank is the same as the HGL in the water distribution system immediately outside of the tank.

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