Skeletonization is the process of representing a water distribution system model by only selected pipes. Skeletonized models normally are adequate for master planning and energy studies, but the degree of skeletonization that is acceptable for surge analysis is an often-raised question. Most of the guidelines used for skeletonizing hydraulic network models do not apply for surge modeling. Replacing two or more pipes in parallel or series into an equivalent pipe with the same carrying capacity and trimming dead-end mains can be readily applied for steady-state analysis with virtually no effect on the resulting flows and pressures, but their effect on the system transient response can be significant. Moreover, the ratio of the pipe diameters greatly affects the transient pressure wave attenuation. In addition, dead ends, which may be caused by closure of check valves, lock pressure waves into the system in a cumulative fashion, and wave reflections will double both positive and negative pressures. The rules of skeletonization ignore the transient interaction of transient pressure waves in the different components and pipe properties of a water distribution system. In this article, case studies highlight the pitfalls of skeletonization in pressure surge analysis and support the conclusion that surge analysis requires a detailed model to accurately estimate transient pressure extremes in a water distribution system. A highly skeletonized model may overlook critical locations that are vulnerable for intrusion of potentially contaminated water.

Pitfalls of water distribution model skeletonization for surge analysis

BY BONG SEOG JUNG,
PAUL F. BOULOS,
AND DON J. WOOD

Rapid changes in pressure and flow conditions (e.g., rapid valve closures or pump stoppages, hydrant flushing), whether caused by design or accident, can create pressure surges of excessive magnitude. These transient pressures are superimposed on the normal static pressures present in the water line at the time the transient occurs and can degrade the integrity of the water distribution system. The total force acting within a pipe is obtained by summing the steady-state and transient pressures in the line. Therefore, the severity of transient pressures must be accurately determined so that the water mains can be properly designed to withstand these additional loads. In fact, pipes are often characterized by their pressure ratings, which define the pipes' mechanical strength and significantly influence their cost.

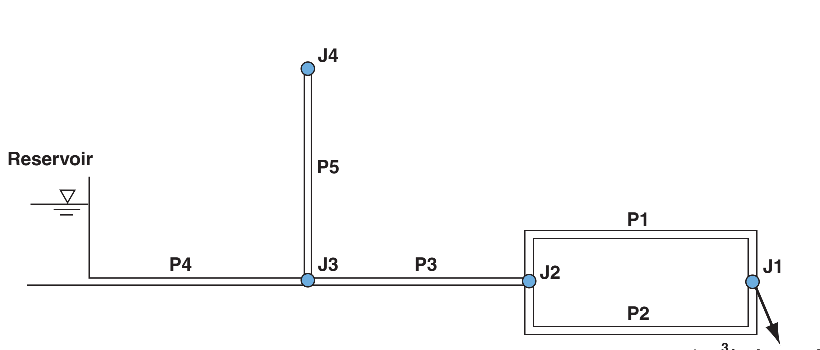
BACKGROUND

Transients. Transients have been responsible for equipment failure, pipe rupture, separation at bends, and the backflow of dirty water into the distribution system via intrusion. High-flow velocities can remove protective scale and tubercles and increase the contact of the pipe with oxygen, all of which will increase the rate of corrosion. Uncontrolled pump shutdown can lead to the undesirable occurrence of water column separation, which can result in catastrophic pipeline failures as severe pressure rises following the collapse of the vapor cavities. Vacuum conditions can create high stresses and strains that are much greater than those occurring during normal operating regimes. Vacuums can cause the collapse of thin-walled pipes or reinforced concrete sections, particularly if these sections were not designed (i.e., pipes with a low pressure rating) to withstand such strains.

Cavitation occurs when the local pressure is lowered to the value of vapor pressure at the ambient temperature. At this pressure, gas within the water is gradually released and the water starts to vaporize. When the pressure recovers, water enters the cavity caused by the gases and collides with whatever confines the cavity (i.e., another mass of water or a fixed boundary), resulting in a pressure surge. In this case, both vacuum and strong pressure surges are present, a combination that may result in substantial damage. The main issue here is that accurate estimates are difficult to achieve, particularly because the parameters describing the process are not yet determined during design. Moreover, the vapor cavity collapse cannot be effectively controlled. In less drastic cases, strong pressure surges may cause cracks in internal lining, damage connections between pipe sections, and destroy or cause deformation to equipment such as pipeline valves, air valves, or other surge-protection devices. Sometimes the damage is not realized at the time but results in intensified corrosion that, combined with repeated transients, may cause the pipeline to collapse in the future (Boulos et al, 2006; Boulos, 2005).

Transients have been responsible for equipment failure, pipe rupture, separation at bends, and the backflow of dirty water into the distribution system via intrusion.

FIGURE 1 Case 1: A small water pipeline system



J—junction, P—pipe

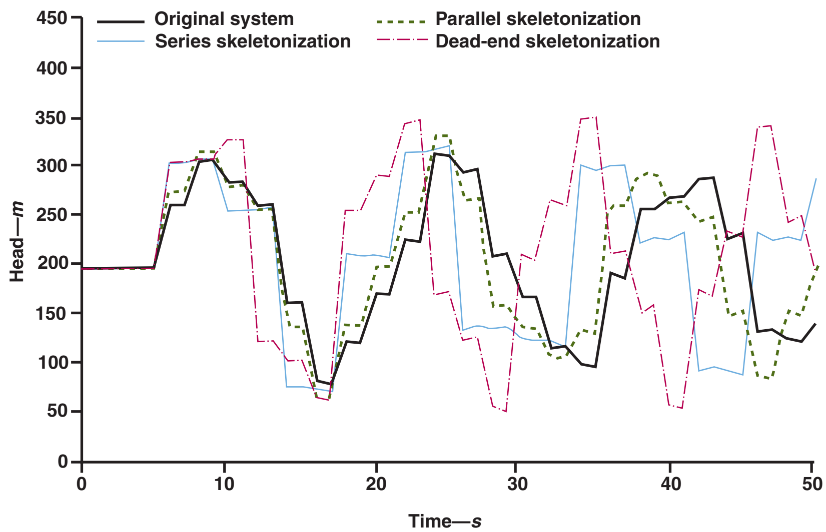
Health and water quality implications. Transient conditions can have significant water quality and health implications (Boulos, 2005; Boulos et al, 2005). Transients can generate high intensities of fluid shear and may cause resuspension of settled particles as well as biofilm detachment. Moreover, low-pressure transients may promote the collapse of water mains; leakage into the pipes at loose joints, cracks, and seals under subatmospheric conditions; and backsiphonage and potential intrusion of untreated, possibly contaminated groundwater in the distribution system. Pathogens or chemicals close to the pipe can become a potential contamination source. Studies have confirmed that soil and water samples collected immediately adjacent to water mains can contain high fecal coliform concentrations and viruses (Karim et al, 2003; Kirmeyer et al, 2001).

Other researchers reported the existence of low- and negative-pressure transients in several distribution systems (LeChevallier et al, 2003). In a study of intrusion occurrences in actual distribution systems, 15 surges were observed that resulted in a negative pressure (Gullick et al, 2004). Recent research confirmed that negative-pressure transients can occur in the distribution system and that the intruded water can travel downstream from the site of entry (Friedman et al, 2004). Locations with the highest potential for intrusion were sites experiencing leaks and breaks, areas of high water table, and flooded air-vacuum valve vaults.

In the event of a large intrusion of pathogens, the chlorine residual normally sustained in drinking water distribution systems may be insufficient to disinfect contaminated water. Indeed, intrusion of as little as 0.05% sewage contamination can cause substantial chlorine decay and would require a correspondingly substantial increase in time in order to inactivate pathogens (Baribeau et al, 2005). For this reason, water utilities should never overlook the effect of pressure surges in their distribution systems. Any optimized design that fails to properly account for pressure-surge effects is likely to be, at best, suboptimal and, at worst, completely inadequate.

Low water pressure in distribution systems is a well-known risk factor for outbreaks of waterborne disease (Hunter, 1997). In 1997, a massive epidemic of multidrug-resistant typhoid fever was reported in the city of Dushanbe, Tajikistan; affecting about 1% of the city's population, the outbreak caused 8,901 cases of typhoid fever and 95 deaths. Low water pressure and frequent water outages had contributed to the widespread increase in contamination within the distribution system (Hermin et al, 1999). More recently, a *Giardia* outbreak was reported at a New York trailer park in April 2002, causing six residents to become seriously ill (Blackburn et al, 2004). Contamination was attributed to a power outage, which created a negative-pressure transient in the distribution system. This allowed contaminated water to enter the system through either a cross-connection inside a mobile home or a leaking underground pipe that was near sewer crossings. During the same period (February 2001 to May 2002), a large-scale control study of the risk factors for sporadic cryptosporidiosis found a strong association between self-reported diarrhea and reported low water pressure (Hunter et al, 2005).

FIGURE 2 Pressure head profile at junction J1 with three levels of skeletonization



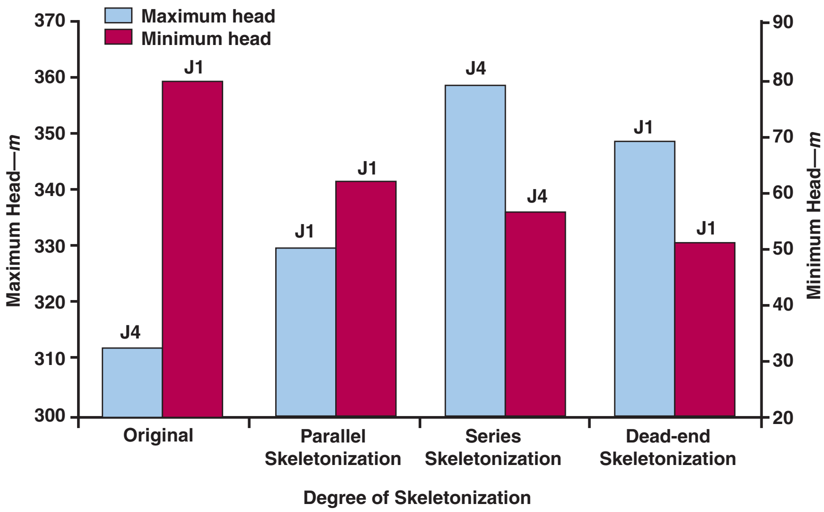
Causes of pressure surge. Transient conditions that can allow intrusion to occur are caused by sudden changes in water velocity attributable to loss of power, sudden valve or hydrant closure or opening, a main break, fire flow, or an uncontrolled change in on/off pump status (Boyd et al, 2004). Although not all intrusions are caused by pressure transients, transient-induced intrusions can be minimized by knowing the causes of pressure surges, defining the system's response to surges, and estimating the system's susceptibility to contamination when surges occur (Friedman et al, 2004). Pressure transients in water distribution systems are usually most severe at pump stations and control valves, in high-elevation areas, in locations with low static pressures, and in remote locations that are at a distance from overhead storage (Friedman et al, 2004).

Additionally, the water distribution system must sometimes deliver large fire demands at adequate pressure. Although these fire demands occur infrequently, they may be a highly constraining factor in pipeline design. Therefore, design procedures should evaluate the ability of the system to meet fire-fighting demands at all relevant hydrant locations. Even though the occurrence of simultaneous fires at all possible locations is not realistic, an array of fire-fighting demand patterns must still be considered. Under transient conditions, it is important to anticipate both the establishment of fire flows and their ultimate curtailment, a process that often unfolds rapidly in time and can create significant transient pressures, particularly if fire crews receive little training or instruction (Jung & Karney, 2004b). Accurate modeling is essential in this case because neglecting some influences could lead to wrong conclusions and poor decisions.

Transient conditions can have significant water quality and health implications.

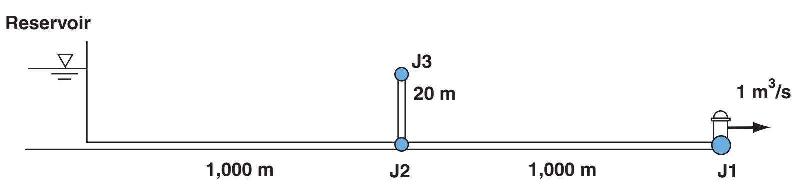
Controlling transients. Several devices can be used to control transients in pipeline systems (Boulos et al, 2006; 2005; Wood et al, 2005a). Devices to control pressure surge operate on the general principles of storing water or otherwise delaying the change of flow or discharging water from the line so that rapid or extreme fluctuations in the flow regime are minimized. Devices such as pres-

FIGURE 3 Maximum and minimum heads and their corresponding locations



J—junction (location)

FIGURE 4 Case 2: A sample system with a dead end



J—junction

sure-relief valves, surge-anticipation valves, surge vessels, surge tanks, pump-bypass lines, or any combination thereof are commonly used to control maximum pressures. Minimum pressures can be controlled by increasing pump inertia or by adding surge vessels, surge tanks, air-release/ vacuum valves, pump-bypass lines, or any combination of these components. The overriding objective is to reduce the rate at which flow changes occur.

Recent studies have included a detailed transient flow chart that provides a comprehensive guide selecting components for surge control and suppression in water distribution systems (Boulos et al, 2006; 2005). These devices offer the only practical opportunity to protect the public from potential intrusion of contaminants caused by low or negative pressure. Other researchers used optimization theory to determine the optimal placement and sizing of open surge tanks and pressure-relief valves to control hydraulic transients in a pipeline system (Jung & Karney, 2006). A comprehensive surge analysis should be performed on a representative network model of the distribution system to properly locate and size the most effective combination of surge-protection devices.

Computer modeling. Although looped networks are generally less susceptible to objectionable pressure transients than are single, long transmission main systems, they must still be protected against low- or negative-pressure transients. Computer-based mathematical models offer the most effective and viable means of analyzing hydraulic transients in water distribution systems. These models provide a powerful tool for determining the extent of pressure wave attenuations within the water distribution system environment and calculating their effect on the resulting flows and pressures. The models can be used to develop and evaluate design and operational alternatives that address the needs and deficiencies identified in the hydraulic transient analysis and to prepare contingency plans. In a recent study identifying several of the misconceptions or limitations of simplified rules for surge analysis, the authors concluded that only systematic and informed surge analysis can be expected to resolve complex transient characterizations and adequately protect distribution systems from the vagaries and challenges of rapid transients (Jung et al, 2007).

Skeletonization techniques are widely used to simplify the reduction of large water distribution network models to a manageable size for analysis. They make use of database management and hydraulic equivalency theory to reduce excessive pipe segmentation while maintaining the hydraulic behavior of the larger original model. Applications include merging series pipes and/or consolidating parallel pipes into a single hydraulically equivalent pipe with the same carrying capacity, removing pipes less than a specified diameter, trimming dead-end mains, and eliminating hydrant leads.

However, the application of skeletonization for surge analysis is questionable. Hydraulic equivalency theory is predicated on steady-state equilibrium and ignores the interaction of transient pressure waves in the different pipe properties of a distribution system. The ratio of the pipe diameters has a significant effect on the transient pressure wave attenuation. Smaller-diameter pipes connected to larger mains amplify the surge waves and become more susceptible to the presence of water column separation and subsequent collapse. The collapse of vapor cavity can result from flow reversal because of higher hydraulic head from a nearby storage tank. It can create extremely high-pressure spikes that can damage the pipeline and the seals, leaving the system even more vulnerable to low-pressure conditions. At any discontinuity of pipe, wave reflections and transmissions occur, which often magnify or attenuate the transient pressure wave. The wave speed is also a function of the pipe material, diameter, and thickness.

Any optimized design that fails to properly account for pressure-surge effects is likely to be, at best, suboptimal and, at worst, completely inadequate.

Limited published work has addressed the relationship between the degree of model skeletonization and the accuracy of the surge modeling results. Martin (2000) warned that oversimplified models may introduce error. Davis (2001) confirmed that excessive pressure surges can occur in the distribution system piping in addition to the large transmission mains. Walski and colleagues (2004) downplayed the importance of model skeletonization for systems with relatively small changes in ground elevation and as long as the reduced model size exceeded 10% of the original system. The sample example used in their study, however, assumed that no water column separation occurs. More recently, other researchers have discouraged the use of skeletonized models for surge analysis of water distribution piping systems (Boulos et al, 2005; Wood et al, 2005b).

Focus of this article. This article addresses the issues associated with water distribution model skeletonization for surge analysis. Case studies are presented to demonstrate the sensitivity of pressure-surge accuracy to different levels of model skeletonization. The authors show that model skeletonization can introduce significant error in estimating pressure extremes and can overlook water column separation and subsequent collapse at vulnerable locations in the distribution system. These shortcomings can lead to poor design and operation as well as inadequate protection of water distribution systems and added maintenance costs.

MODEL SKELETONIZATION

Models are only approximations of the real world. Capturing every component and characteristic of a water distribution system is difficult and can result in tremendous amounts of data to manage. Skeletonization is the process of reducing the network model (i.e., producing a skeleton model) by removing pipes not considered essential to the analysis (e.g., pipes with insignificant carrying capacity and pipes that serve relatively few customers). Skeleton models normally include all hydraulically significant pipes. However, skeletonization can sometimes have a negative effect on accuracy.

The degree or level of skeletonization normally depends on the purpose of the model, its intended use, and the size and complexity of the overall network. Master planning studies (such as long-range capital improvement program development) may require only pipes with diameters greater than 12 in. (304.8 mm). Pump stations typically are designed with models of large transmission mains. Water quality modeling applications normally require a more detailed model to accurately represent the flow and velocity pattern and distribution, especially for identifying localized water quality problem

FIGURE 5 Case 2: Transient head profiles at the hydrant

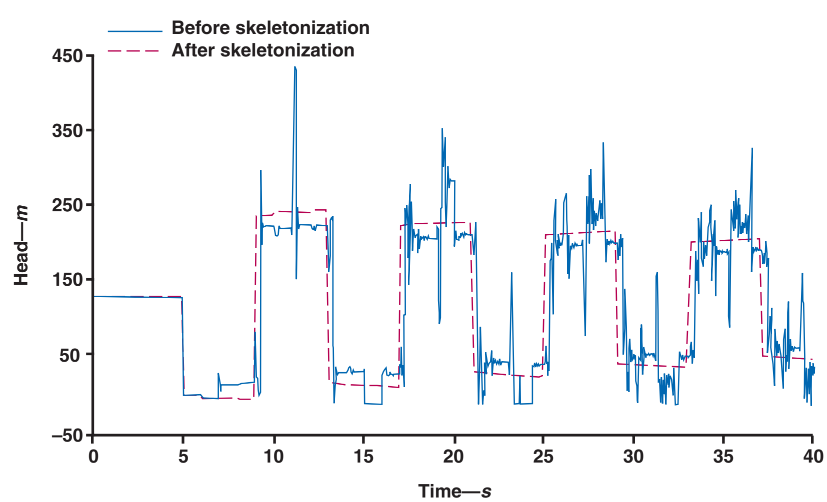
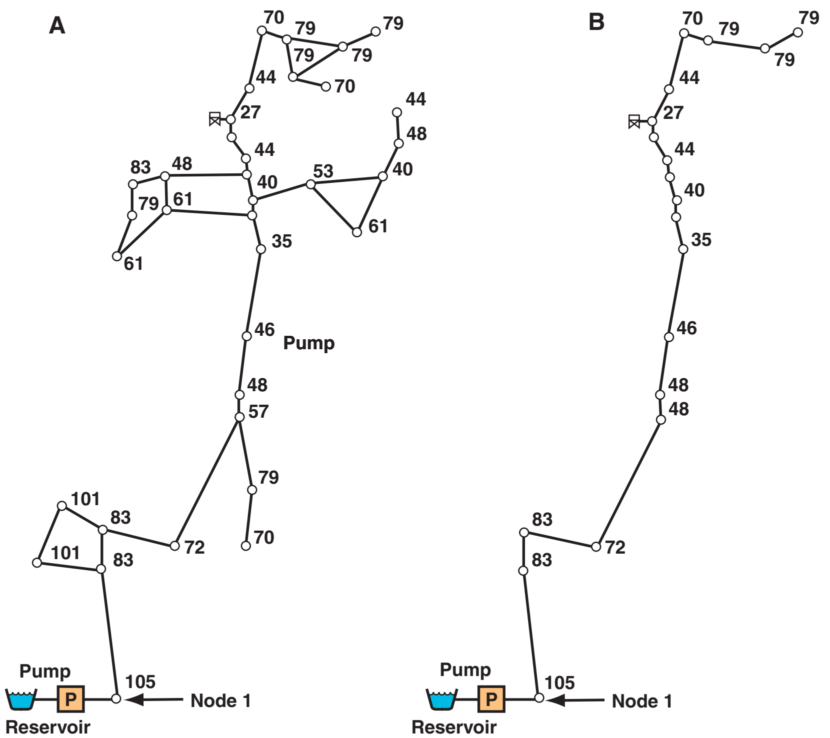


FIGURE 6 Steady-state analysis before (A) and after (B) skeletonization



Numbers represent the node pressure in psi.

areas. The design of flushing programs (e.g., unidirectional flushing) to clean water mains and restore hydraulic capacity requires comprehensive all-pipe models. Generally, more detailed models result in more accurate results and can be used in a wider variety of applications (Grayman & Rhee, 2000).

Although there is no national standard for skeletonization, the US Environmental Protection Agency (USEPA) has issued draft guidance for modeling to support the initial distribution system evaluation (IDSE) under the Stage 2 Disinfectants/Disinfection Byproduct Rule (USEPA, 2006). The guidance suggests inclusion of

- at least 50% of total pipe length in the distribution system;
- at least 75% of the pipe volume in the distribution system;
- all pipes 12 in. in diameter and larger;
- all 8-in. and larger pipes that connect pressure zones, influence zones from different sources, storage facilities, major demand areas, pumps, and control valves or are known or expected to be significant conveyors of water;
- all 6-in. and larger pipes that connect remote areas of a distribution system to the main portion of the system;
- all storage facilities with controls or settings applied to govern the open/closed status of the facility that reflect standard operations;
- all active pump stations with realistic controls or settings applied to govern their on/off status that reflect standard operations; and
- all active control valves or other system features that could significantly affect the flow of water through the distribution system (e.g., interconnections with other systems, valving between pressure zones).

Modeling of real systems always entails an unresolved tension between two elements: how simply the model can be constructed and how accurately the model represents reality. The best models incorporate the best resolution between these elements. The modeler must decide on the desired level of skeletonization for a representative model to produce accurate results for a particular application.

Primary processes of skeletonization. Skeletonization is the process of representing only selected pipes in the network model while preserving the operational performance and integrity of the larger original system. It consists primarily of three distinct operations: reduction, hydraulic equivalency, and trimming.

Reduction is the process of removing excessive pipe segmentation (caused by valves, fire hydrant, or other data-capture processes) by dissolving interior nodes on pipe reaches and combining the associated pipe segments into single pipes. For example, the reduction process might merge all series pipes of similar characteristics, e.g., diameter, material, and age. The merging of series pipes of similar characteristics is an iterative process because many consecutive merging levels may exist.

Hydraulic equivalency consists of defining an equivalent pipe to replace two or more pipes in parallel or in series while preserving their carrying capacity. The equivalent replacement pipe must produce the same head loss as the original pipes. For series pipes, the same flow must pass through each pipe in series, and the equivalent pipe is determined as the pipe with the combined length that will carry this flow rate and produces the same head loss as the original pipes (sum of all individual head losses). For parallel pipes, the head loss in each parallel pipe must be equal and is replaced by an equivalent pipe that will transport the same total flow rate for the same head difference as the original pipes.

Branch trimming consists of removing dead-end mains and hydrant leads. Branch trimming is an iterative process because many consecutive removal levels may exist. When a pipe segment with a downstream dead-end node (i.e., branch line) is trimmed, the demand at that node must be shifted to the upstream node of that pipe to preserve the total demand in the system. The resulting reduced network is hydraulically equivalent to the larger original model. A comprehensive description of the various model skeletonization operations is provided elsewhere (Boulos et al, 2006).

Skeletonization is the process of representing only selected pipes in the network model while preserving the operational performance and integrity of the larger original system.

PITFALLS OF MODEL SKELETONIZATION FOR SURGE ANALYSIS

Skeletonizing water distribution models offers considerable benefits in terms of computational performance such as a reduction in model complexity, faster model development, and shorter run times. However, such a model reduction process is applicable only under limited conditions because network hydraulic equivalency basis is derived solely from steady-state network equilibrium theory. When applied to steady-state network analysis, the skeletonized model is able to generate accurate results for flows and pressures. This theory does not hold for surge analysis and should be limited to steady-state modeling applications. Network model skeletonization for surge analysis can lead to ineffective design recommendations, leaving the system poorly protected and vulnerable to catastrophic failures and contamination from the external surrounding environment.

The following discussion highlights some of the difficulties inherent in the skeletonization rules outlined previously by identifying where these rules might be misleading and how they could lead to a poor basis of design.

Reduction. Merging series pipes (and dissolving interior nodes) may be acceptable in a steady-state analysis, depending on the level of similarity of the pipe characteristics. However, reduction for surge analysis must be more carefully assessed. Any differences in the pipe size, material, and thickness as well as valves, orifices, accumulators, and other system elements result in unique transient characteristics. The influences of these discontinuities in pipelines create pressure-wave reflections and refractions and significantly influence both the magnitude and the phase of a rapid pressure pulse during transient conditions. For example, pipe material doesn't play any role in steady-state analysis; it affects only the pipe roughness coefficient. However, the material elasticity directly affects the wave speed and significantly influences the magnitude of a surge and the phase of its wave. In addition, the approach of reallocating nodal demands (when dissolving interior nodes) during a network reduction application needs to be carefully considered in surge analysis. It eventually changes the amount and location of demands, which can affect the reflection and dissipation of a pressure wave.

FIGURE 7 Pump trip transient pressure results at node 1 before and after skeletonization

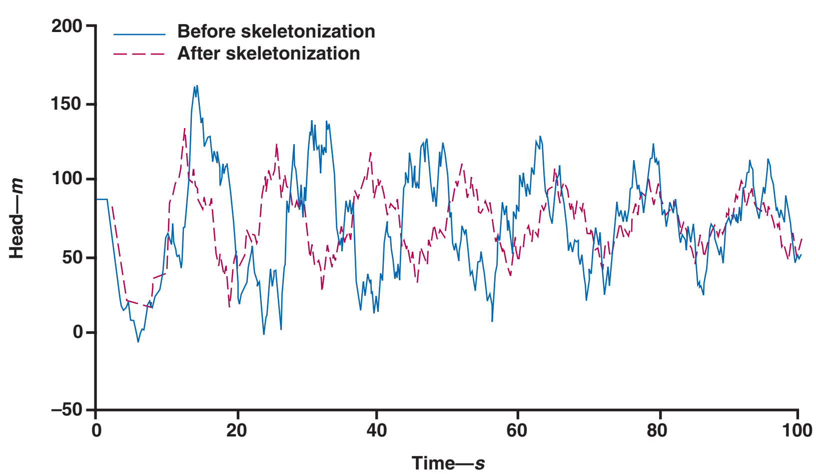


FIGURE 8 A network system before skeletonization

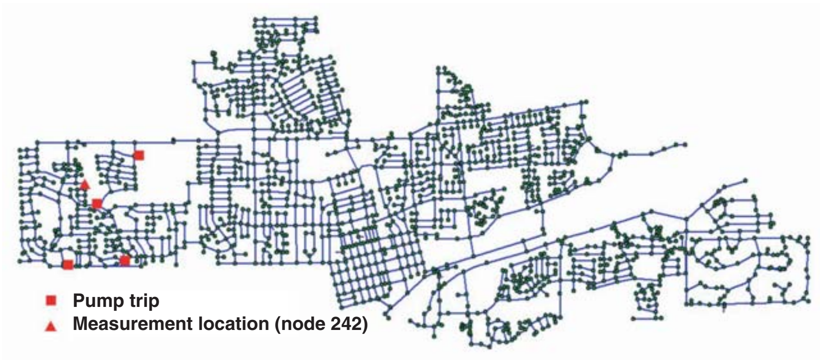
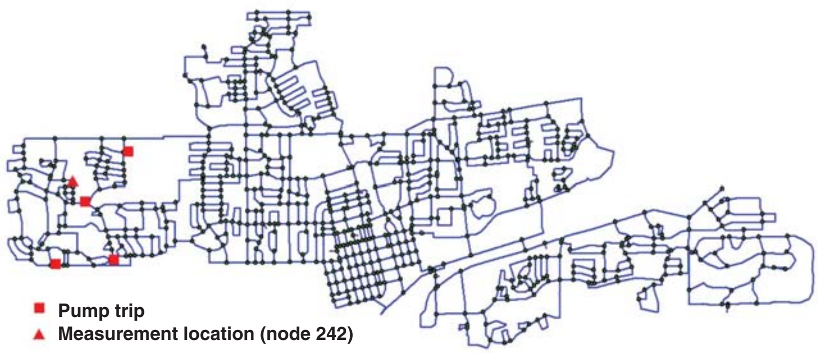


FIGURE 9 A network system after skeletonization



Series and parallel pipes. To minimize the number of pipes in the model, pipes in series and parallel pipes commonly are replaced by a single hydraulically equivalent pipe with the same carrying capacity of the original pipes. This approach holds true for steady-state analysis with virtually no effect on results. However, the hydraulically equivalent pipe omits the interaction of wave reflections and transmissions in the series and parallel pipes and often attenuates or magnifies the original surge response. For example, series pipes with area reduction can significantly increase the magnitude of the surge pressure (Wylie & Streeter, 1993), but the hydraulically equivalent pipe cannot represent the increase in surge pressure. Similarly, it is not conservative to use the equivalent pipe with the assumption that the parallel pipe configuration can alleviate water hammer. Other researchers have shown that surge response can be more severe in a looped system than in a single pipeline (Karney & McInnis, 1990). Depending on system characteristics, the looped system may not attenuate a surge pressure and in fact can often make the surge response worse.

Trimming. Branch trimming is widely applied to skeletonize a large system on the theory that a dead-end main does not play an important role in steady-state analysis, and the demand is shifted to the last remaining node to preserve the total system demand. Although branch trimming has no effect on steady-state flows and pressures, it can significantly affect surge analysis. First, the elastic behavior of a dead end will be omitted in the trimming process, and the corresponding wave reflection cannot be represented. Second, in contrast to open ends or connections to reservoirs where a pressure is negatively reflected, a dead end reflects a pressure wave positively, which means that it will experience the doubling of a surge pressure. For example, when a surge wave of 100 m reaches a dead end, that dead end will cause a positive pressure wave reflection of 100 m. Because the incoming and outgoing waves are additive, the dead end then experiences the doubling of the surge pressure, i.e., 200 m. Therefore, dead ends constitute some of the most vulnerable locations for objectionable pressures and should be carefully considered in a surge analysis. Additionally, trimming a dead end overlooks the effect of its ground elevation, which, if sufficiently high, may cause cavitation during a transient episode.

In summary, the traditional rules of steady-state model skeletonization ignore the complex interaction of transient pressure waves in the different pipe properties and characteristics of a water distribution system. The hydraulic equivalency theory used in model skeletonization and derived from steady-state network equilibrium is not applicable to surge analysis. At pipe junctions and dead ends, wave reflections and transmissions occur, which often magnify or attenuate the surge waves. Conducting a surge analysis with a skeletonized model may not be conservative and may be unsuitable for estimating transient pressure extremes in a distribution network system.

CASE STUDIES

The case studies cited here provide an opportunity to examine the rules of skeletonization and compare surge analysis results for original and skeletonized models. In particular, these studies illustrate the pitfalls of steady-state model skeletonization for surge analysis. All transient modeling results presented here can be obtained using the eigenvalue approach (Jung & Karney, 2004a), the method of characteristics (Wylie & Streeter, 1993), or the wave characteristic method (Boulos et al, 2006; Wood et al, 2005a) and can be reproduced using available commercial or in-house water hammer codes.

Case 1: A small water pipeline system. The first case study uses the small water pipeline system shown in Figure 1. This system consists of a 200-m (656.2-ft) head reservoir feeding a network of five pipe sections and four junctions. Each pipe has a diameter of 1 m (3.3 ft), length of 1,000 m (3,280.8 ft), Hazen-Williams roughness coefficient of 100, and wave speed of 1,000 m/s (3,280.8 fps). The elevation of each junction is assumed to be 0 m. Junction J4 designates a dead end with no external demand. Terminal junction J1 has a demand of 1 m^3/s (35.3 cfs). A rapid demand decrease over a 1-s time period is initiated to introduce a transient condition.

In this case study, three levels of skeletonization are demonstrated. For the first level, parallel pipes P1 and P2 are replaced with a hydraulically equivalent pipe (P12) that has the same length and roughness coefficient of the original pipes but an equivalent diameter of 1.302 m (4.272 ft). Second, the series pipes P3 and P12 are replaced with an equivalent pipe that has the same roughness coefficient of the original pipes but its equivalent diameter and length are 1.096 m (3.596 ft) and 2,000 m (6,561.7 ft), respectively. For the final skeletonization level, the dead-end junction J4 and pipe (branch) P5 are removed. According to the hydraulic equivalency theory, each of the three distinct skeletonized models produces the same steady-state hydraulic results as the original system. The resulting skeletonized system consists of one reservoir feeding two pipes in series.

A comprehensive surge analysis should be performed on a representative network model of the distribution system to properly locate and size the most effective combination of surge-protection devices.

Figure 2 shows the transient head profiles at junction J1 for the three levels of skeletonization. Because the skeletonized models cannot represent the reflections and transmissions of the pressure waves at the original discontinuities, as the degree of skeletonization increases, the transient response becomes more severe, compared with the original system. The figure also shows that the phase of the original surge wave and its magnitude has become deformed and thus can mislead the preset schedule of a surge protection device (e.g., surge anticipation valve) in the skeletonized model.

Figure 3 shows the maximum and minimum heads and their corresponding locations according to the different degrees of skeletonization. After the skeletonization of the parallel and series pipes (first and second skeletonization levels), the surge response becomes worse than in the original system because the maximum heads of the skeletonized models are higher and the minimum heads are lower. The skeletonization of the dead end provides less severe transient response than the second level skeletonization. For this case study, the parallel and series pipes attenuated the transient wave, but the dead end magnified it. So the reflective question would be "Does skeletonization make transient responses appear to be more or less dangerous?"

Case 2: Cavitation in a dead end. Another possible pitfall of model skeletonization is the elimination of the unique characteristics of the system components. Although a dead end located at high elevation can be easily removed in the skeletonization process, this removal can lead to a possible cavitation problem during transient conditions. If a negative surge is propagated to the dead end and its local pressure is lowered to the vapor pressure, all gas within the water is gradually released, and the water starts to evaporate. When the pressure recovers, water enters the cavity and collides with the gases, resulting in a large pressure-surge spike.

The second case study uses the small water pipeline system shown in Figure 4. This system consists of a 130-m (426.5-ft) head reservoir feeding a network of three pipe sections and three junctions. The properties of each pipe section are identical to those used in case 1, but a dead-end pipe is installed vertically 20 m (65.6 ft) from the main pipeline. The terminal junction J1 has a steady demand of 0.1 m^3/s (3.53 cfs) and a fire-flow demand of 1 m^3/s (35.3 cfs). It is assumed that the fire flow is initiated in 0.1 s. In the skeletonization process, the dead-end pipe is removed from the main pipeline. This case study illustrates the role of a dead end in surge analysis during a fire flow startup.

Figure 5 shows the transient head profiles at the hydrant (J1) with and without the dead end. In the original system, the local transient pressure at the dead end is lower than the vapor pressure, thus causing cavitation. The transient head profile after skeletonization (removal of the dead end) shows less severe transients without any cavitation. The cavitation in the original system makes the transient response worse; the maximum heads before and after skeletonization are 434.5 m (1,425.5 ft) and 245.9 m (806.8 ft), respectively. A similar case may result from the parallel- and series-pipes skeletonization process. By combining the parallel and series pipes into an equivalent pipe, the high elevation areas in the original system could be eliminated, and the presence of potential cavitation could be overlooked.

Although case 2 illustrates a single dead end, the study can easily be extended to a separate subnetwork connected to the main distribution system. The subnetwork may potentially be eliminated in the skeletonization process by shifting all node demands in the subnetwork to their associated upstream nodes; however, this skeletonization would ignore the potential for cavitation in the subnetwork. Additionally, dead ends lock pressure waves into the system in a cumulative fashion and will double a surge pressure, making the system even more vulnerable to cavitation.

Case 3: A network system. In order to show some of the shortcomings of skeletonization for surge analysis in a larger, more complex system, the rules of model skeletonization were applied to a water distribution network studied by other researchers (Rossman, 2000). This network is shown in Figure 6, part A, along with its steady-state hydraulic results. Figure 6, part B, shows the skeletonized model and its steady-state results after trimming dead-end pipes and replacing series and parallel pipes with hydraulically equivalent pipes. For this example, a transient is introduced from a pump trip initiated 2 s after steady-state equilibrium.

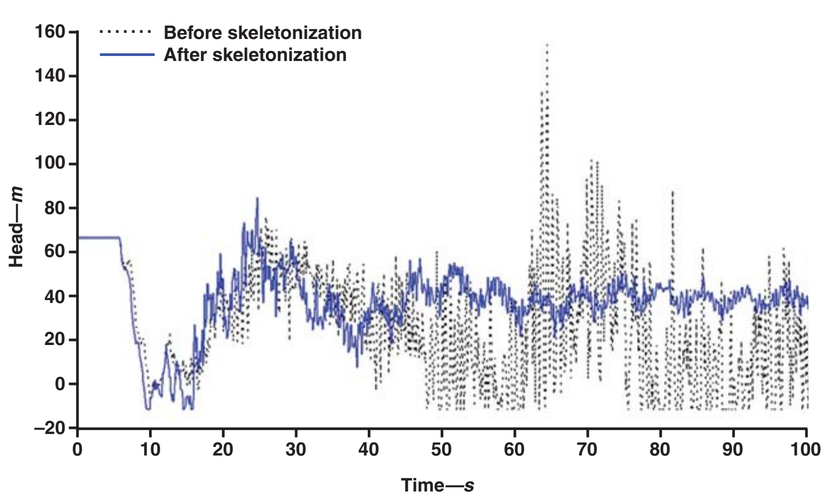
Figure 7 shows the transient head profiles at node 1 before and after skeletonization. In contrast to case 1, the transient results for the skeletonized model are less severe than those of the original system. The maximum surge heads before and after skeletonization are 161 m (528 ft) and 131 m (430 ft), respectively. Thus, the maximum surge head of the original model is 23% higher than that of the skeletonized model.

Case 4: An actual network system. To highlight some of the pitfalls of skeletonization for surge analysis on a larger, more complex system, the rules of model skeletonization were applied to an actual water distribution network (Figure 8). This system comprises 1,639 junctions, 2,088 pipes, 23 wells, 23 pumps, and one storage tank. The identity of the corresponding water utility is withheld because of security concerns.

Figure 9 shows the skeletonized model after trimming dead-end pipes and replacing series pipes with hydraulically equivalent pipes while conserving total system demand. The skeletonized network, now reduced to 1,134 pipes and 685 junctions, meets the USEPA IDSE network model guidelines (USEPA, 2006). For this example, a transient condition is triggered by pump trips initiated at 5 s. Figure 10 shows the transient head profiles at junction 242 before and after skeletonization. As shown in the figure, the transient results for the skeletonized model are much less severe than those for the original system. Satisfying the hydraulic equivalency principle, both the original and skeletonized models produce the same steady hydraulic equilibrium condition (66.6 m or 218 ft) for the initial 5-s period. However, the maximum surge heads before and after skeletonization are 153.1 m (502.3 ft) and 84.7 m (277.9 ft), respectively. Thus the maximum surge head of the original model is 81% higher that that of the skeletonized model. This exercise demonstrates some limitations of the IDSE hydraulic model guidelines for transient analysis. For example, the IDSE guidelines do not consider the importance of dead ends and high elevation points in the distribution system, both of which may significantly affect pressure surges.

Overdesign versus underdesign. The transient response of a skeletonized model can be more or less severe than that of the original model, but it is difficult to accurately predict if the transient results of a skeletonized model will be more or less conservative. Transient results are strongly dependent on the system charac-

FIGURE 10 Pump trip transient results at node 242



teristics as well as the level of skeletonization. The more conservative case may result in overdesign of surge suppression and protection devices, yet overdesign doesn't necessarily indicate a higher degree of safety unless all hydraulic transient conditions have been properly analyzed. An overdesigned system may sometimes be worse than an underdesigned one because the overdesigned hydraulic devices themselves could deteriorate the system's surge response (Jung & Karney, 2006; Karney & McInnis, 1990). On the other hand, the less-conservative results may lead to underdesign of surge suppression and protection devices, leaving the system vulnerable during surge conditions. Both overdesigns and underdesigns can place the distribution system at risk. Engineers must carefully consider all potential dangers for their system designs and estimate and eliminate the weak spots. They should then embark on a detailed transient analysis in order to make informed decisions on how to best strengthen their systems and ensure safe, reliable, and economical operations.

Transient results are strongly dependent on the system characteristics as well as the level of skeletonization.

CONCLUSIONS

Recent concerns about protecting water distribution systems from potential intrusion of contaminants attributable to low- or negative-pressure conditions have underscored the importance of surge modeling to control objectionable hydraulic transient pressures. Traditionally, surge modeling has focused on analyzing large-diameter transmission mains with few or no branches and loops. Skeletonization techniques derived from hydraulic equivalency theory have been used to reduce the size and complexity of these systems and generate smaller skeletonized models. Because of branches and loops, however, distribution systems respond differently than transmission lines, and excessive pressure surges can be present in distribution piping. The rules of skeletonization ignore the inherent problem of interaction of the surge waves in different components and the pipe properties of a water distribution system. At pipe junctions and dead-end branches, wave reflections and transmissions occur, which often magnify or attenuate the impinging surge waves. Furthermore, wave speed is a function of pipe material, diameter, and thickness. A surge analysis can be used to accurately determine the extent of transient pressure extremes but only if detailed representative models are used.

Proper system design, operation, and maintenance can help water utilities achieve a high degree of hydraulic integrity and reliability and extend the life of their water distribution systems. This requires an accurate prediction of the system's worst-case performance under all hydraulic transient conditions. Transient response is highly sensitive to the system-specific characteristics, and a skeletonized model can yield incorrect results, which in turn can lead to poor design and insufficient surge protection. Surge analysis on detailed models is becoming common practice, thanks to the rapid development of fast computers and numerical solution schemes that are both powerful and highly efficient. Properly defined models can be used to effectively estimate intrusion potential, identify susceptible regions in the distribution system that are of greatest concern for vulnerability to objectionable (low or negative) pressure surges, and evaluate how they can be avoided and/or controlled (Boulos et al, 2006; 2005).

Effective management strategy may dictate the installation of surge tanks at pump stations (to dampen negative pressure waves) and other surge-control devices at vulnerable system locations such as high points. These surge-control devices may be cost-prohibitive, but they offer the only practical opportunity to protect the public from potential intrusion of contaminants via low- or negative-pressure developments. No two water distribution systems are hydraulically identical, however, and therefore no general rules or guidelines are universally applicable for eliminating transient pressures in water distribution systems. Any surge-protection devices and/or operating strategies must be chosen accordingly.

The final choice 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 measures themselves. A combination of devices may prove to be the most effective and most economical. A comprehensive surge analysis should be performed on a detailed representative network model of the water distribution system in order to determine, locate, and size the most effective combination of surge protection devices and thus ensure safe and economical operation and protect public health.

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