Transient Analysis of Water Distribution Systems

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The pressures generated by transient (water hammer) conditions in pipe systems are frequently three or more times the value of normal operating pressures. Thus, transient pressures must be known if the size and strength of the required pipe is to be rationally selected, if surge-suppression equipment is to be logically sized, and if system operating rules are to be intelligently specified. In practice, however, analysts frequently neglect transient conditions, particularly in complex systems such as distribution networks. With modern computer techniques it is possible to analyze distribution systems under a wide range of flow conditions and with relatively few restrictions. Examples are presented of the dangers of oversimplifying either the physical system or the operating conditions.

Pressure pipe systems are subject to a wide range of physical loads and operational requirements. For example, underground piping systems must withstand internal and external corrosion, various forms of bedding stresses, differential settlement, construction damage, local stresses at connections, as well as other external and internal forces. As a result of this ongoing chemical and physical attack, both the hydraulic and structural capacities of the pipe are reduced over time until some kind of failure occurs. The failure may be physical in nature, such as a break that causes loss of water and pressure, or it may be economic, arising from increased fluid friction with its associated reduced flow capacity, increased power costs, or both. In Canada alone, the estimated cost of repairing water main breaks exceeds Can$100 million annually.

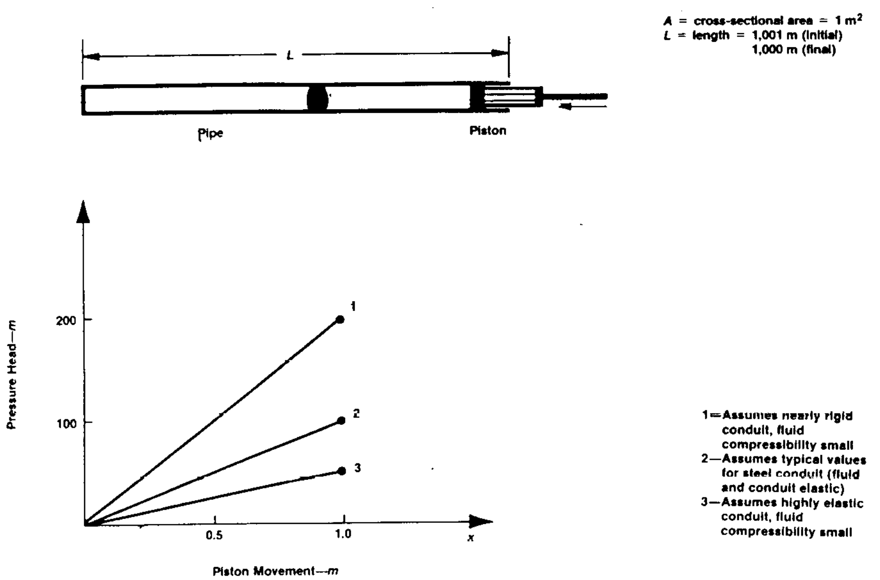

Figure 1. Relation between fluid compressibility and pressure head in a closed conduit

One source of loading that is commonly neglected in water distribution system analysis is due to water hammer or transient conditions. Although it is well known that the pressures generated during transient conditions should be an important consideration when simple pipeline systems are being designed, there is widespread belief that transient conditions are intrinsically less severe in network applications. In fact, several examples in this article demonstrate that the maximum transient pressure in some branched and looped systems may exceed the corresponding pressure rise in a simple system. Thus, if the size and strength of the required pipe are to be rationally selected, if the surge-suppression equipment is to be logically sized, and if system operating rules are to be intelligently specified, reliable transient analysis is essential.

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In the past few years, many refinements and improvements have been made in the accuracy and efficiency of transient analysis. More attention, however, has frequently been given to how the analysis is performed than to what is being modeled. Many articles have been written on the relative accuracy and computational merits of various numerical procedures; few have considered the sensitivity of transient conditions to the assumed initial state or what kind of interaction between automatic control devices can lead to the most severe transient problems. Yet such issues are central to system design and operation.

This article emphasizes that the details of how a hydraulic system is modeled or represented can have a critical impact on the predicted transient conditions. Examples illustrate the following three points: (1) in some pipeline systems, the maximum transient pressure is quite sensitive to the assumed initial steady-state velocity; (2) transient conditions may sometimes be more severe in branched or looped systems than in simple series pipelines; and (3) oversizing surge-suppression equipment such as relief valves may degrade a system's transient response. The key result is that transient phenomena in a pipeline system can be both surprising and dramatic. Because of the complexity of system response, the transient analyst must learn to think fundamentally and analyze comprehensively.

Transient analysis and design

Unfortunately, transient analysis is not easy. The governing equations describing the flow are of the nonlinear partial differential variety, the hydraulic devices are complex and data on their performance are difficult to obtain, and the pipeline systems themselves are subject to a host of operating conditions and requirements. To make matters worse, the physical character of the pulse wave propagation is frequently hard to visualize or interpret even for the analyst accustomed to transient phenomena.

The complexity of transient phenomena has, at times, induced many analysts to adopt simplified design procedures. The analysis of hydraulic systems is often facilitated in two primary ways: (1) complex components and other complications in the physical system itself may be ignored, or (2) the range of operating and loading conditions to which the system is subjected is greatly reduced. These simplifications are rationalized on the grounds of necessity (the actual physical system cannot be analyzed) and conservatism (the analyzed system performs worse than the real one). Unfortunately, the assumption that some rudimentary and conservative system can be found is questionable. It is difficult to simplify a pipeline system to ensure worst-case performance under all transient conditions, particularly if the simplifications are made before any analysis has been performed.

Traditional wisdom for identifying worst-case scenarios is based on elementary equations, rules of thumb, or common sense; in other words, simple relations that may have little or no bearing on the performance of more complex systems. Several of the most common of these ideas are presented in this article along with counterexamples

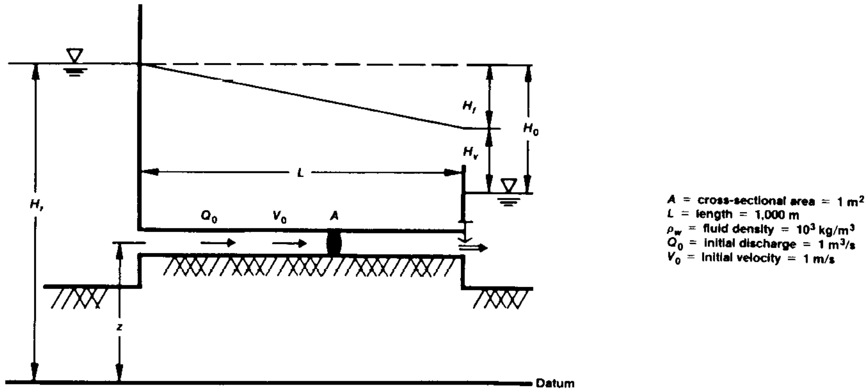

Figure 2. Fluid and pipeline properties of two constant head reservoirs joined by a series pipeline with a downstream valve

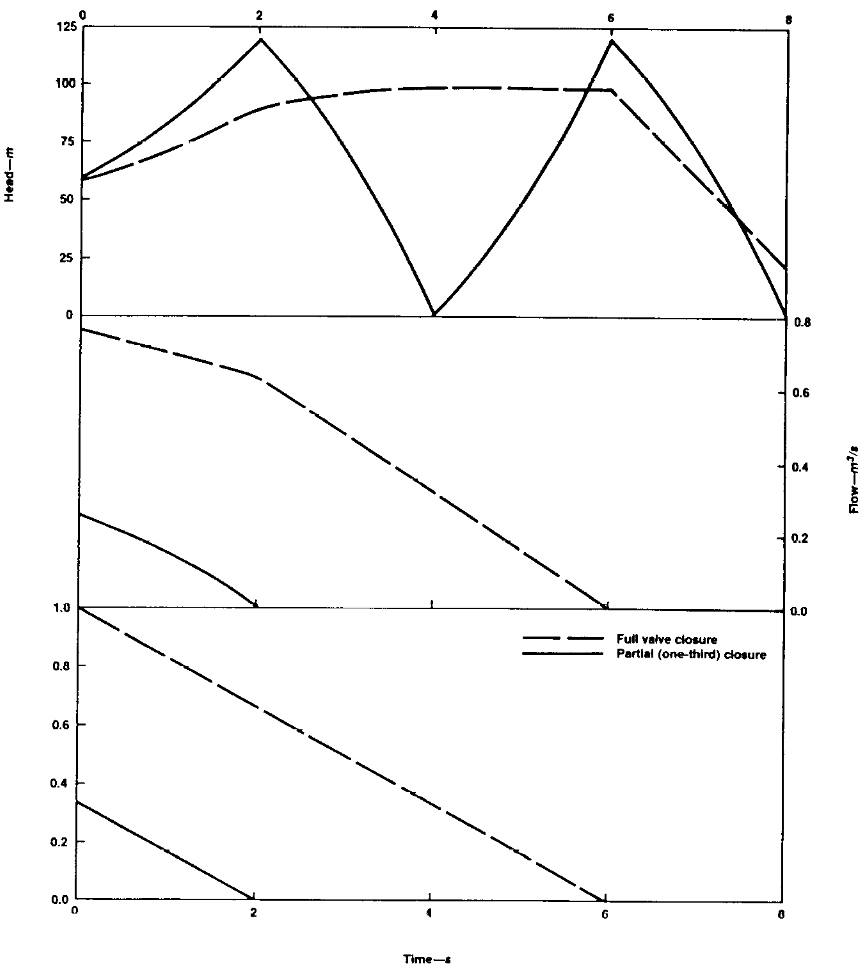

Figure 3. Valve action and transient response of a single-pipe system to valve closure from full and partial (one-third) opening (*head and discharge values are given at the valve end of the pipe;* $H_0 = 60$ *m,* $f = 0.010$)

to show how they can break down. The main point, however, is that: comprehensive transient analysis is both technically and economically possible. Only comprehensive analysis can ascertain the relevant and most critical range of loading conditions. Moreover, the analysis should be performed on a realistic representation of the physical system without making unwarranted, and possibly incorrect, assumptions about what components can safely be neglected.

Although it should be pointed out that all of the warnings and some of the examples presented in this article have been known for years, in practice there has been a tendency to rely on a priori assumptions of what constitutes good transient design. These before-the-fact assumptions may well be valid under some circumstances, but there is little reason to be presumptuous. Water supply systems are costly to build, operate, and maintain, whereas computer resources are cheap and plentiful. In many applications, comprehensive transient analysis is economically justified.

Several of the examples presented in this article are based on analysis of a water transmission and distribution system owned by the city of Calgary, Alta., Canada. The engineering department of the city of Calgary is pioneering a comprehensive investigation of transient conditions in its large and sophisticated pipe network. The purpose of this study is to rationally identify those conditions under which transient pressures are most severe and to investigate the influence of various remedial strategies. This information may have significant implications for the design, protection, and operation of water distribution systems.

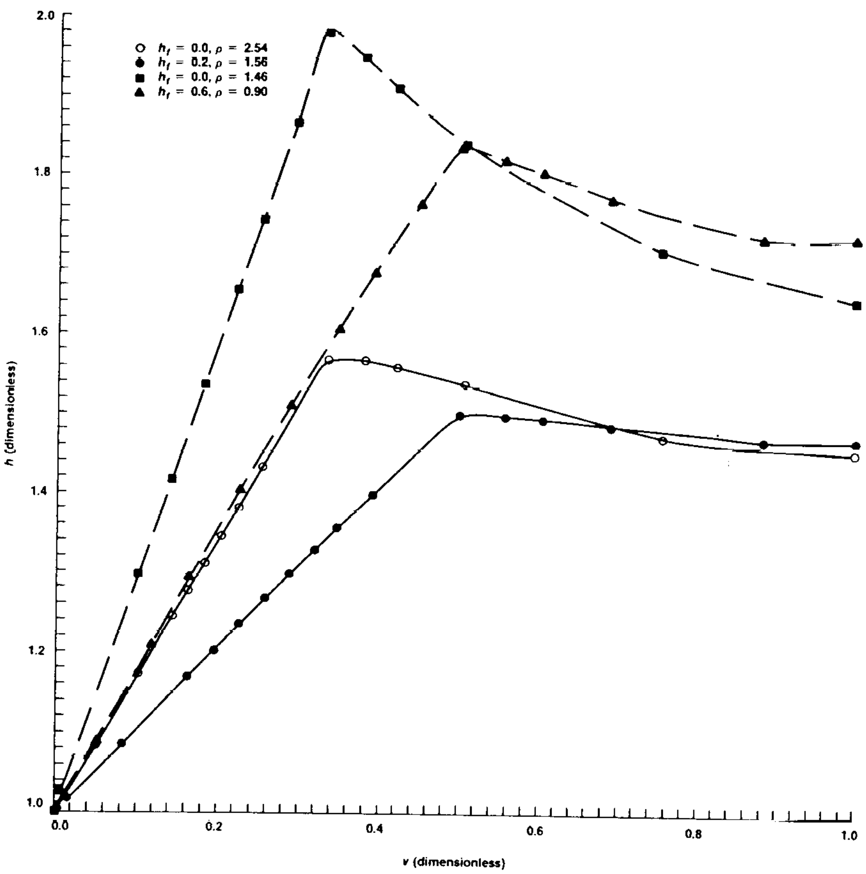

Figure 4. Effect of valve closure from partial opening on maximum head at valve end (*dimensionless friction loss* $h_f = H_f/H_r$; *pipeline constant* $\rho = aV_0/2gH_0$; $t_c = 3$)

Transient phenomena

Fluid properties. An air of mystery and confusion often surrounds the role and significance of transient phenomena in closed conduits. Because of the complexity of the governing differential equations and the dynamic nature of system response, transient analysis has frequently been relegated to a backwater of pipeline design. Like many other backwaters, this one is inhabited by a rare species—the transient specialist—who is believed to have a rather unnatural appetite for higher mathematics. At the most fundamental level, however, transient conditions arise as a direct consequence of basic fluid properties and simple conservation laws.

Two of water's properties will be obvious to almost anyone: liquid water is immensely heavy and is very difficult to compress. What is not obvious, however, is that these two properties go a long way to explain why transient pressures can be so large and under what conditions the largest pressures tend to occur.

Liquid water has a density of approximately 1,000 kg/m^3 under normal temperatures and pressures. As a result, water pipelines tend to contain vast amounts of mass, momentum, and kinetic energy. For example, a closed conduit 1,000 m long and 1 m^2 in cross section carrying water at 1 m/s contains 1,000 m^3 of water having a mass of 10^6 kg, a momentum of 10^6 kg m/s, and a kinetic energy of 500,000 J. Clearly, because such large amounts of momentum are involved, Newton's second law requires equally large forces to change the flow velocity for the entire pipe. This is particularly true if the changes in velocity take place rapidly.

But how can these large forces be generated? In open-channel flow it is possible to change the elevation of the fluid surface and produce a surge wave that will propagate in the channel. In essence, this wave uses the force of gravity to accelerate or decelerate the free-surface flow. When water flows or is contained in a closed conduit, however, no free surface is present; it is not possible to lift the fluid against gravity (unless the pipe breaks). The only location at which gravity might play a role is in devices such as reservoirs or surge tanks at the ends of the pipe. Even here, however, changes in elevation can take place only relatively slowly as a result of mass accumulation taking place over a period of time. To generate large forces rapidly, a different mechanism is required, and it is here that the compressibility of water plays such a vital role.

The role of fluid compressibility can be understood by study of Figure 1, which depicts a piston in a closed conduit and the resulting change in fluid pressure (head) as the piston is very slowly moved in the pipe. The resulting head change will be a function of the piston's travel and how elastic the pipeline is. Typical values of both parameters are shown for a pipeline with an initial length of 1,001 m and a final length of 1,000 m. Clearly, valve is shut. However, in order for the fluid mass as a whole to be stopped, a decelerating force sufficient to eliminate the substantial 10^6 kg m/s of momentum must be applied. The only way to provide the required decelerating force is to compress the fluid, thereby generating an increase in pressure large enough to arrest the fluid flow. Because water is heavy, the required force is large; but because water is only slightly compressible, the wave or disturbance will travel quickly. In a system like the one shown, a pressure wave of approximately 100 m would propagate along the pipeline at roughly 1,000 m/s.

In many ways, this system is typical. Closed-conduit systems frequently carry huge amounts of momentum and kinetic energy, and, in addition, hydraulic conditions are in an almost continual state of change. For such systems, the only available mechanism for controlling or changing the flow conditions is shock wave propagation resulting from fluid and pipeline elasticity. Only if the changes in flow rate take place gradually, such that the mass imbalance in the line is always small, is it possible to go smoothly from one steady condition to another. Under these circumstances, no large fluctuations in pressure head or velocity occur, because the pipeline is always near a state of equilibrium.*

If rapid changes occur, whether caused by standard operating procedures or accidental events, a relatively large mass imbalance may arise. The associated pressure pulses are of great magnitude and are capable of bursting or damaging pipelines. In order to model or predict these rapid transient phenomena, complete equations of motion need to be written and solved, both for the pipeline and for all the devices used to control the flow. Standard texts such as those by Wylie and Streeter[1] and Chaudhry[2] provide the details. The more complete mathematical description should not, however, detract from fundamental insights. Transient conditions arise from local disturbances to the fluid flow that create a mass imbalance. This mass imbalance then acts through the combined effects of fluid and pipeline elasticity to accelerate the flow and, ultimately, create a new steady state.

Special devices that are designed to control or eliminate transient effects should be viewed with caution. It is the physical nature of the control problem that dictates that transient conditions must occur and that frequently deter-

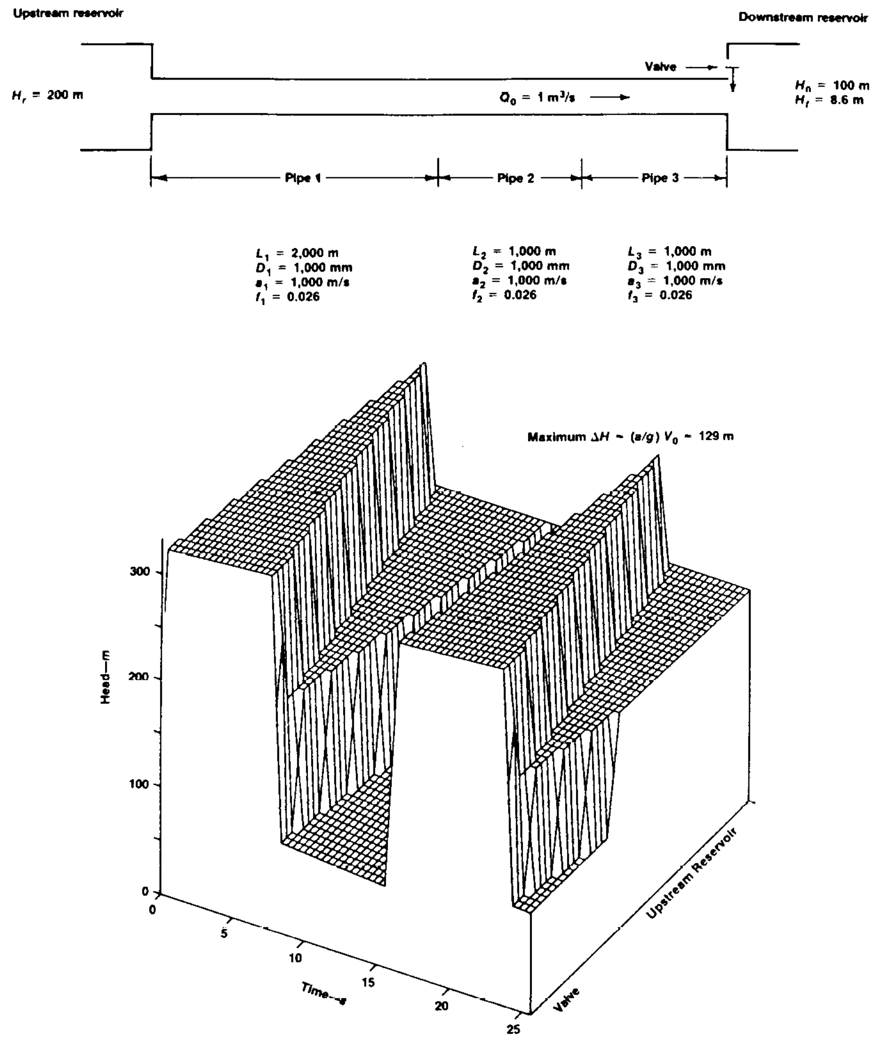

Figure 5. Plan sketch, parameter values, and three-dimensional response surface for instantaneous downstream valve closure in a simple series pipeline

any movement of the piston, no matter how slowly accomplished, will be accompanied by changes in fluid density, conduit dimension, and pressure. Even though the resulting changes in density and dimension are typically small, the changes in fluid pressure can be large and cannot be neglected.

The connections between this simple static compression test and a pipeline transporting fluid are easily made. If the actual conduit length in the static case is taken to be the final value of 1,000 m, what this pipe experiences during the compression can be thought of as a mass imbalance. That is, more fluid is forced to enter the conduit than was originally contained within it. Whenever such an imbalance occurs, compressibility effects must play a role. Thus, whenever flow conditions in a pipeline result in more fluid entering one end than is leaving the other, large pressure changes can be expected. In addition, the greater the mass imbalance, the more severe the resulting pressure changes tend to be. In anticipation of ideas to be broached subsequently, it could be suggested that mass imbalance constitutes a more natural and theoretically satisfying criterion for the severity of a system's transient response than does fluid velocity.

The origin of transient conditions. The connections between fluid properties (density and compressibility) on the one hand and the law of mass conservation on the other are fundamental to an understanding of fluid transients. Suppose, for example, an adjustment is made to a valve at the downstream end of a pipeline carrying fluid at some initial velocity (Figure 2). For simplicity, it is assumed that the valve is suddenly closed. The valve, of course, can only act locally—it specifies a relationship between flow through the valve and the head loss across the valve. In this case, the discharge and velocity of the fluid at the valve become zero the instant the

*Even in cases such as this, however, the actual mechanism for maintaining equilibrium in the pipe is still mass imbalance and compressibility effects. The only difference is that the pressure waves are much smaller in magnitude and travel quickly relative to the changes that occur at the ends of the conduit. In such applications, it is often justified to approximate transient behavior by assuming the fluid to be incompressible. Neglecting fluid compressibility leads to the so-called "rigid water column" model.

mines how dramatic transient conditions will be. Often, as in other areas of engineering, no design is superior from all points of view. Instead, there may be compromises that trade off a degree of control under some circumstances for less control under others.

Transient folklore

Much traditional "wisdom" has evolved over time on how to cope with the intricacies of transient phenomena. This wisdom often pertains to design assumptions that simplify the analyst's task by restricting the number and complexity of transient cases that need to be analyzed or specified. In light of modern computer power, however, the rationale for these assumptions needs to be questioned. Indeed, many of the a priori design assumptions are so misleading and so frequently false that they should not be regarded as rational design rules but more as outdated and discredited transient folklore.

In this article, several of these misconceptions are addressed, and, by means of counterexamples, their potential for erroneous application becomes clear.* To avoid misleading the reader, the title of each topic is stated as the converse of the often improperly understood and applied design axiom.

The three most widely revered axioms of transient folklore probably are:

- maximum steady-state velocities (flows) produce maximum transient head change,
- networks fare better (i.e., looped or branched configurations alleviate water hammer), and
- if one surge-protection device is good, then two (or more) are better.

The examples that follow were not difficult to find, nor have they been substantially altered to make the results contradict the aforementioned notions. They simply demonstrate that there are important cases for which these guidelines are either false or, at the very least, misleading.

Like much of what is called folklore in other areas, the previously stated transient rules have some basis in fact. For example, the origin of the first two rules can be traced to the famous fundamental equation of water hammer, which is also called the Joukowski relation. This relation equates changes in head (ΔH) in a pipe to the associated changes in fluid velocity (ΔV):

$$\Delta H = \pm (a/g)\, \Delta V \qquad (1)$$

in which a is the wave speed and g is the acceleration resulting from gravity. Clearly this equation implies that the

*All of the transient simulations presented here were produced using T_RA_NSAM (acronym for Transient Analysis Model), which is a proprietary software product of HydraTek Associates, Toronto, Ont., Canada.

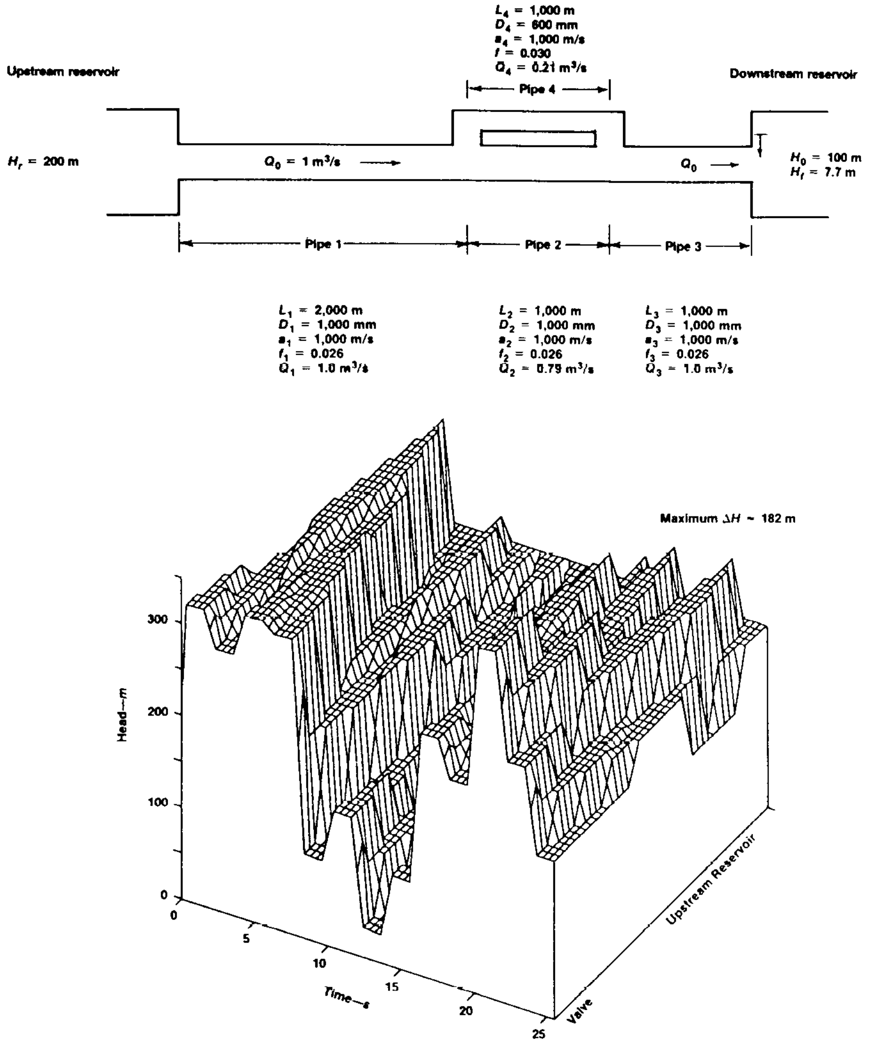

Figure 6. Plan sketch, parameter values, and three-dimensional response surface for instantaneous downstream valve closure in a looped-pipe network

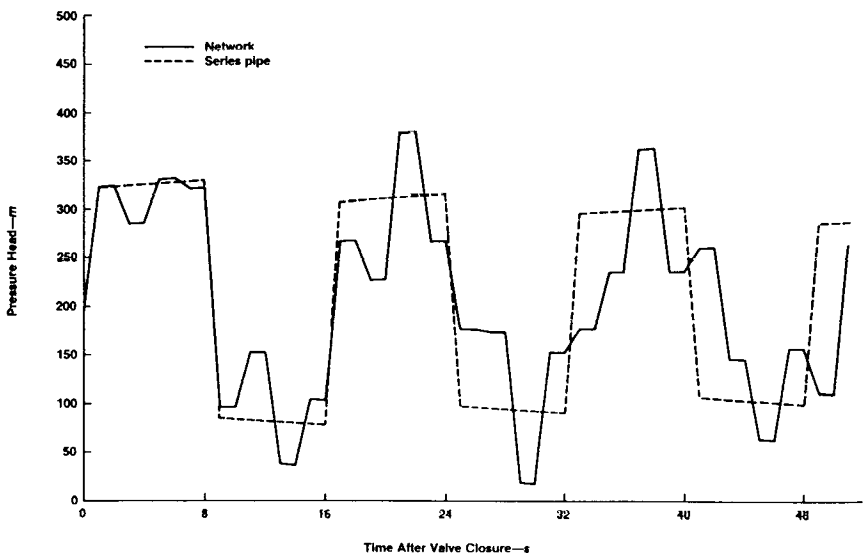

Figure 7. Variation in pressure head at the valve end for a simple series pipeline and a looped network

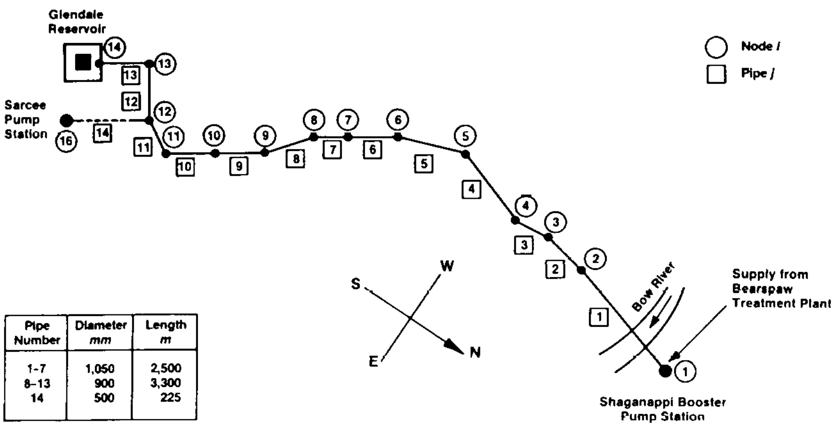

Figure 8. Plan sketch of the Glendale feeder main (*not to scale*)

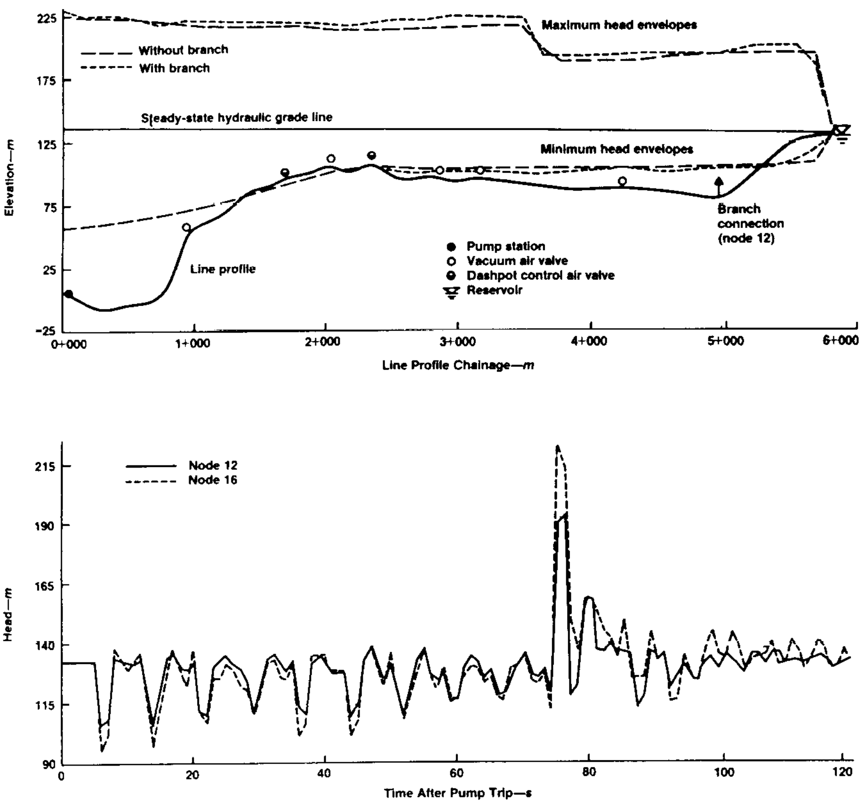

Figure 9. Profile of the Glendale feeder main (showing maximum and minimum transient head envelopes and steady-state hydraulic grade line) and pressure head traces at branch connection (node 12) and at end of branch pipe (node 16)

greater the value of ΔV, the greater the resulting change in pressure head.

Because the maximum possible change in velocity occurs when the initial velocity is greatest, it appears that the first rule must apply. In addition, networks carry flow in parallel lines, which must make it more difficult to change velocity quickly and must attenuate pressure surges by causing wave reflections at junctions. Therefore, the second rule also appears to be true. The logic leading to these two rules is faulty, however, and the conclusions are dangerous.

Most simple expressions, such as the Joukowski relation, are only applicable under restricted circumstances. When the required conditions are met, the simple relationships are often both powerful and accurate. In the case of the Joukowski relation, the two most important restrictions are that there should be no head loss resulting from friction and no wave reflections (i.e., there is no interaction between devices or boundary conditions in the system). If these conditions are not met, the Joukowski expression is no longer valid. In addition (and what is more frequently forgotten), the conclusions that are based on this rule may no longer be valid. To be specific, if the Joukowski relationship does not apply, it may be difficult to identify the set of conditions that produces worst-case response.

Maximum velocities do not necessarily mean maximum heads. A simple and convincing demonstration of the limitations of the Joukowski relation can be found in the two-reservoir, single-pipe and downstream-valve system of Figure 2. The closure behavior of the valve is given nondimensionally by its τ curve, which describes the relative valve opening as a function of time. The length of the pipe is 3,280 ft (1,000 m), its wave speed is 3,280 fps (1,000 m/s), and its diameter is 2.46 ft (0.75 m). The following four cases are simulated over a 16-second time period (H_0 is the difference between reservoir heads and f is the Darcy-Weisbach friction factor):

H_0 = 65.6 ft (20 m), and f = 0.010

H_0 = 65.6 ft (20 m), and f = 0.500

H_0 = 196.9 ft (60 m), and f = 0.010

H_0 = 196.9 ft (60 m), and f = 0.500

Under each of the four conditions, the rate of valve closure remains constant at 16.67 percent of the fully open value per second. In other words, it takes 6 seconds to close the valve completely from full opening (τ = 1). Figure 3 shows the variation over time of the valve end pressure head, the valve end discharge, and the gate opening as given by τ for (1) closure from full opening, and (2) closure from one-third open for H_0 = 197 ft (60 m) and f = 0.010. The figure indicates that