Systematic Surge Protection for Worst-Case Transient Loadings in Water Distribution Systems

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Abstract: Estimating appropriate water demands for the design of a distribution system is itself difficult, but the continuously fluctuating nature of these demands has the added potential of creating water hammer problems that might result in catastrophic pipeline or system failure. To first identify and then avoid these eventualities, this paper searches a predefined set of possible water hammer events in water distribution systems to identify the most severe transient loadings and then conducts a search for suitable surge protection strategies. Genetic algorithms and particle swarm optimization are combined with transient analysis first to identify a set of worst-case loads and then to seek an optimal protection strategy to cope with them. Case studies show that the worst case is not always obvious and cannot always be assumed a priori to correspond with high or low demand scenarios. Both the search for the worst-case loading and its associated optimal protection strategies are strongly sensitive to the characteristics of both the pipe system and the candidate transient events.

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Introduction

A water distribution system (WDS) is designed and operated to deliver water in sufficient quantity, of acceptable quality, at appropriate pressure, and as economically and reliably as possible. Traditionally, a few representative loading conditions have served as a basis for system design, with widely applied criteria such as either peak-hour or peak-day demand (with a chosen fire flow) being typical design loads for steady state operation, and pump stoppage due to power failure being a typical design event for transient studies. Once base loadings have been determined, optimization is sometimes used to select an economical set of pipe sizes and classes to ensure acceptable network performance. By selecting the smallest acceptable diameters and lowest feasible pipe classes to minimize cost, steady pressures will be ensured to be at least marginally above acceptable levels, whereas the most severe transient pressures will be at least marginally below the pipe's pressure rating.

Yet, determining design loads for this kind of analysis is not as straightforward as it is sometimes assumed. Uncertainty arises for many reasons including the randomness of fire flow, the variations in local climate, the inexact determination of system strength, capacity, and response, and the partially random nature of population growth, all of which create demand variations on an annual, seasonal, daily, hourly, and momentary basis.

Over the years, numerous hydraulic transient approaches have been articulated to identify system weak points, to predict the potentially destructive effects of hydraulic transients under various worst-case scenarios, and to evaluate how they may possibly be eliminated or controlled (e.g., Wylie and Streeter 1993; Chaudhry 1987; Thorley 2004; Boulos et al. 2005; Wood et al. 2005; Ghidaoui et al. 2005; Jung et al. 2007). In particular, Boulos et al. (2005) provide a detailed transient analysis flowchart for the selection of components for surge control and suppression in water distribution systems, concluding that a transient analysis should always be carried out to determine the impact of each proposed strategy on the resulting system performance. Wood et al. (2005) compare the accuracy and computational time requirements for both the method of characteristics and the wave characteristic method for solving hydraulic transient problems. Ghidaoui et al. (2005) provide a historical and physical overview of water hammer phenomena, offering a general compendium of key developments and reflecting on the state of the art from both a theoretical and a practical perspective. Jung et al. (2007) argued that only systematic transient analysis can be expected to resolve complex transient characterizations and adequately protect distribution system.

In addition, issues related to system integrity, safety, and performance have also been considered previously. Laine and Karney (1997) applied optimization to a simple pipeline connecting a pump and a storage reservoir. A complete enumeration scheme as well as a probabilistic selection procedure were incorporated into both transient and steady state analysis. Lingireddy et al. (2000) showed that a surge tank design model obtains an optimal set of decision variables when satisfying a specified set of pressure constraints. This model was developed based on a bilevel optimization framework, minimizing a nonlinear objective function using a genetic algorithm (GA). Jung and Karney (2004) considered the impact of transients on the choice of optimal diameter in a network considering both steady and transient criteria. Jung and Karney (2006) presented the optimum selection of hydraulic devices for water hammer control in a water distribution system. GA and particle swarm optimization (PSO) were used to optimize the preliminary selection, sizing, and placement of surge protection devices.

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Despite their obvious sophistication, previous transient approaches have almost invariably adopted a definition of design event that is assumed a priori to result in a worst-case transient loading. Yet, as a system's response is complex and nonlinear, and as the timing and magnitude of the events it experiences are uncertain, the hydraulic analyses and associated protection measures may not be sufficiently conservative to fully protect the pipe system. For example, the selected pipe diameters in Jung and Karney (2004) and the hydraulic devices in Jung and Karney (2006) were only optimal for the given surge events; they could well be suboptimal, or even seriously inadequate, for other design events. In reality, selecting appropriate design water demands from their continuously fluctuating range of values is difficult; further, the search for the worst case considering the dynamic behavior in a WDS is itself a challenging task due to the complicated nonlinear interactions among system components and variables. Certainly the work of Filion and Karney (2002) indicated that the worst case in a network is not always obvious and seldom can be assumed to simply correspond to high or low demand scenarios.

To directly address this issue, this paper first identifies and then avoids these worst cases by searching a predefined set of possible water hammer events and protection strategies. Thus, the most severe transient loading conditions are identified, suitable surge protection strategies are found, and then the process is repeated as the protection strategy itself changes the system response and possibly the definition of the worst-case event. GA and PSO approaches are combined with transient analysis first to identify a set of worst-case loads and then to seek an optimal protection strategy to cope with them. Case studies demonstrate how the overall quest for an optimal surge protection strategy is realized in a particular example system.

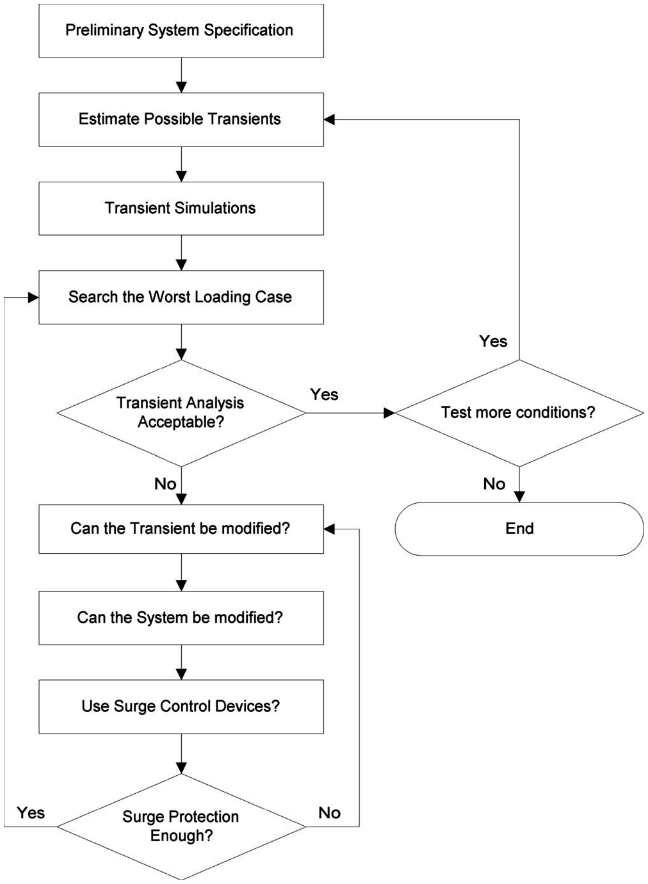

Fig. 1. Flowchart for systematic surge protection

Systematic Surge Protection for Worst Conditions

The flowchart for systematic surge protection offered in Fig. 1 summarizes a comprehensive procedure for identifying the worse loading case and for suggesting the appropriate transient protection. The procedure begins with a preliminary specification of system configuration. A set of possible water hammer loadings is first simulated and then searched in order to identify the worst-case loading. Once this preliminary design condition is determined, it is compared against some performance criterion; for example, that the pipeline system should not experience any pressures in excess of some specified peak threshold, and that it should experience no negative pressures. If the worst-case transient response is deemed acceptable, one then assesses whether other transient initiation events (or perhaps system configurations) ought to be considered.

If the worst transient response is unacceptable, a modification of either the transient itself or the system response is necessary. Although the complexities of transient analysis render systematic approaches difficult, many strategies ranging from system modification and operational considerations to using surge control devices are possible (Boulos et al., 2005). First, the direct action approaches—the modifications of the transient—aim to influence the root causes of flow changes, such as adjusting valve or pump operations. Second, system modifications can be considered, such as pipe reinforcement (i.e., increasing a pipe's pressure rating), rerouting conduits, using larger diameter pipes, changing the pipe material, or strategic changes in system topology; such adjustments alter both the system and its transient response. This strategy is explored by Jung and Karney (2004) by considering the impact of transient conditions on the question of diameter selection. The final (yet likely most common) protection strategy involves diversionary tactics that employ various surge protection devices by which fluid is drawn into, or expelled from, the piping system in order to reduce the severity of the flow changes. This approach of specifying hydraulic devices for transient control is applied by Jung and Karney (2006).

The procedure is necessarily iterative as each pass through the loop adjusts the system response, and thus could modify those conditions that create the worst-case loadings.

Mathematical Formulation

Searching for the worse-case loading in WDS can be accomplished using optimization methods and hydraulic models. Given a network, the worse-case loading is defined here by the set of baseline demands (B_D), time-varying demands (V_D), operation times of time-varying demands (V_T), time-varying tank levels (T_L), and operation times of time-varying tank levels (T_T) which result in extreme pressures. The overall optimization problem can be stated mathematically as follows; either

$$\text{minimize } H_{\min}(B_D, V_D, V_T, T_L, T_T) \tag{1}$$

or

$$\text{maximize } H_{\max}(B_D, V_D, V_T, T_L, T_T) \tag{2}$$

subject to the governing momentum and continuity equations for transient flow (Wylie and Streeter 1993). The objective criteria can be applied to the whole system (without regard to where the

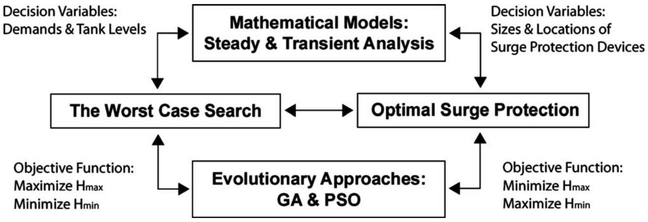

Fig. 2. Optimization of the worst-case search and its protection

minimum or maximum heads occur) or to particular locations.

Once the worst-case loading is determined, various surge protection strategies are invoked. The optimal design of surge protection devices is simplified here by the set of locations (D_L) and sizes (D_S) of devices which results in either maximizing the minimum head or minimizing the maximum head. A more global and comprehensive optimization of surge protection devices is presented in Jung and Karney (2006). The overall optimization problem is specified as follows:

$$\text{minimize } H'_{\max}(D_L, D_S) \tag{3}$$

$$\text{maximize } H'_{\min}(D_L, D_S) \tag{4}$$

subject to the governing transient equations and a pressure head constraint:

$$H^*_{\min} \leqslant H' \leqslant H^*_{\max} \tag{5}$$

where H'=piezometric head of the worst-case loading and $H^*_{\max}$ and $H^*_{\min}$=maximum maximum permissible heads (e.g., representing pipe ratings or health concerns for negative pressures). The objection function (3) is applied to the case of the worst maximum head of Eq. (2); the function (4) is used for the worst minimum head of Eq. (1). Alternatively, the goal could be to minimize the difference between the maximum head and minimum head as in Jung and Karney (2006).

Fig. 2 presents a schematic layout for optimizing the selection of worse-case load and the corresponding protection measures. A suitable optimization method like GA or PSO is invoked by initializing the decision variables including both baseline and time-varying demands as well as the tank levels, and their operational times. With initial decision variables selected, the governing transient equations are solved to calculate the maximum and minimum heads. Objective values ($H_{\max}$ or $H_{\min}$) are used to evaluate the fitness of the individual solutions and a new population of trial solutions is created. Once converged, GA and PSO are again used to obtain the optimal system performance in a similar manner; however, the objective functions are now oriented to the selection of protection measures. In the following examples provided here, for simplicity only pressure relief valves are considered; their sizes and locations are selected as decision variables in the GA and PSO programs. A detailed description and the computer implementation of GA and PSO applied in this paper are presented in Jung et al. (2006). Due to the stochastic characteristics of both optimizations, five simulations are performed using varying random seeds. They produce slightly different results so the "best" (most severe or limiting transient) of the group is selected.

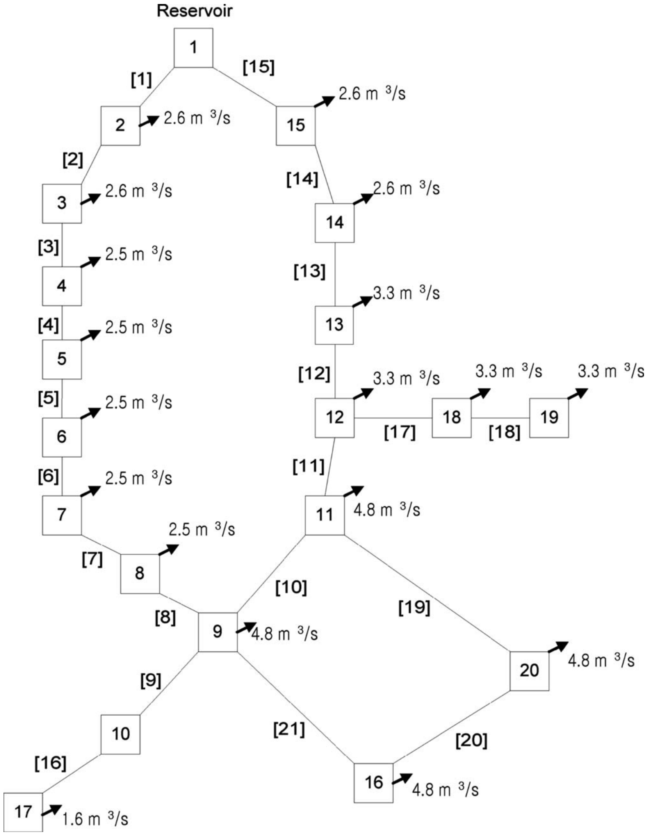

Fig. 3. New York City Water Supply Tunnels

Case Study

The case study is based on the well-known New York City Water Supply Tunnels. The case study network shown in Fig. 3 has been extensively studied for WDS optimization (e.g., Dandy et al. 1996; Eusuff and Lansey 2003; Maier et al. 2003; Jung and Karney 2004). The profile comprises 20 nodes, 21 pipes, 1 source, and 19 demand nodes. Pipe length and diameter information is given in Dandy et al. (1996).

Case 1: Search for Worst Transient Loading

This case study seeks to find the set of worse-case loadings which result in either the largest maximum head or the smallest minimum head. The baseline demands of the system are assumed to be accurately known as indicated in Fig. 3. Time-dependent demands for all nodes are set to $\pm 10\%$ of the baseline demands. The initial level of the reservoir at Node 1 is set as 120 m with a variation of ± 10 m. The water level variation of the reservoir also can be used for a pump operation change (e.g., stop and startup). For simplicity, the operation times of the time-varying parameters are fixed at 1 s as the shortest operation times create the most severe transient. In a more thorough study, one might test combinations of criteria such as allowing one demand to change quickly, two to change more slowly, etc., or to use a probabilistic set of loads. All the transient, modeling results presented here were obtained using the method of characteristics (Wylie and Streeter 1993). Further details of this numerical procedure are presented in Jung and Karney (2004).

The two optimization methods, GA and PSO, are considered to satisfy Eqs. (1) and (2) using a population size of 200 and 100

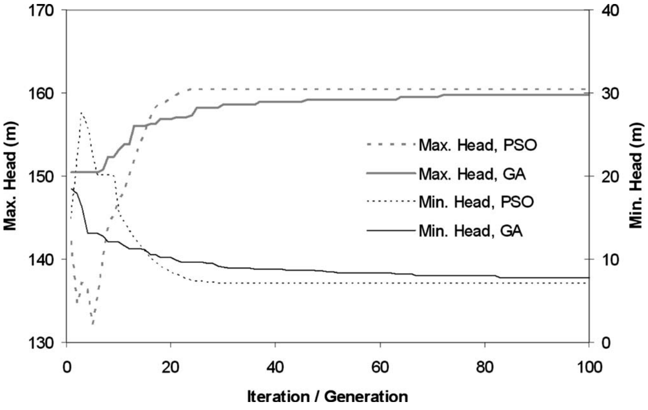

Fig. 4. Evolutionary procedures for searching the worst loading conditions

generations. The length of each chromosome in GA is 8 so the corresponding discrete search step is 0.078 (=20/2^8). The maximum velocity (allowable maximum position change per generation) for the PSO approach is set as 2. Fig. 4 follows the evolution of the GA and PSO procedures to find the worst sets of the variation of tank level and demands that maximize the maximum head or minimize the minimum head. Both procedures exhibit similar rapid convergence over the first 20 generations but slow considerably thereafter. Table 1 presents the optimization results of GA and PSO searching for the worst cases. The intuitively expected worst case involving the highest reservoir level increase (10 m) and maximum decrease (−10%) of all demands produce a maximum head [159.7 m at Node 17, shown in Fig. 5(a)], that significantly turns out to be slightly less severe than the worst maximum heads (160.5 m by PSO and 159.8 m by GA) by the more systematic search. Node 20 is notable as its variation is opposite the others. The search for the worst minimum head is even more unexpected. Table 1 presents Nodes 2–13, 16, 17, and 20 exhibit a contrary pattern relative to the intuitively expected outcome. The highest reservoir level decrease (−10 m) and maximum increase (10%) of all demands produce the minimum head of 10.3 m at Node 19 [shown in Fig. 5(b)], which is less severe than the worst minimum heads of 7.0 and 7.8 m obtained by PSO and GA, respectively. In this case, although both find the similar solution sets, the PSO provides slightly better results, especially in the case of the worst minimum head.

Table 1. Representative Optimization Results of GA and PSO: 10% Range

	Maximize $H_{\max}$		Minimize $H_{\min}$	
Node	PSO	GA	PSO	GA
1[a]	10	10	−10	−10
2	−10	−8.43	−10	5.45
3	−10	−9.84	−10	−6.63
4	−10	−9.76	−10	−7.18
5	−10	−9.69	−10	−6
6	−10	−9.06	−10	−8.35
7	−10	−9.61	−10	−9.84
8	−10	−8.27	−10	−9.53
9	−10	−9.45	−10	−9.61
11	−10	−9.37	−10	−9.84
12	−10	−9.69	−10	−6.47
13	−10	−9.92	−10	−8.43
14	−10	−9.53	10	3.49
15	−10	−8.98	10	7.33
16	−10	−9.76	−10	−9.84
17	−10	−10	−10	−9.76
18	−10	−9.84	10	10
19	−10	−9.69	10	10
20	10	9.92	−10	−10
$H_{\max}/H_{\min}$ (m)	160.5	159.8	7.0	7.8
Occurring time (s)	45.6	45.6	70.1	82.3
Occurring node	17	17	19	19

[a] Reservoir level change is in meters for Node 1; demand change is in % for all other nodes.

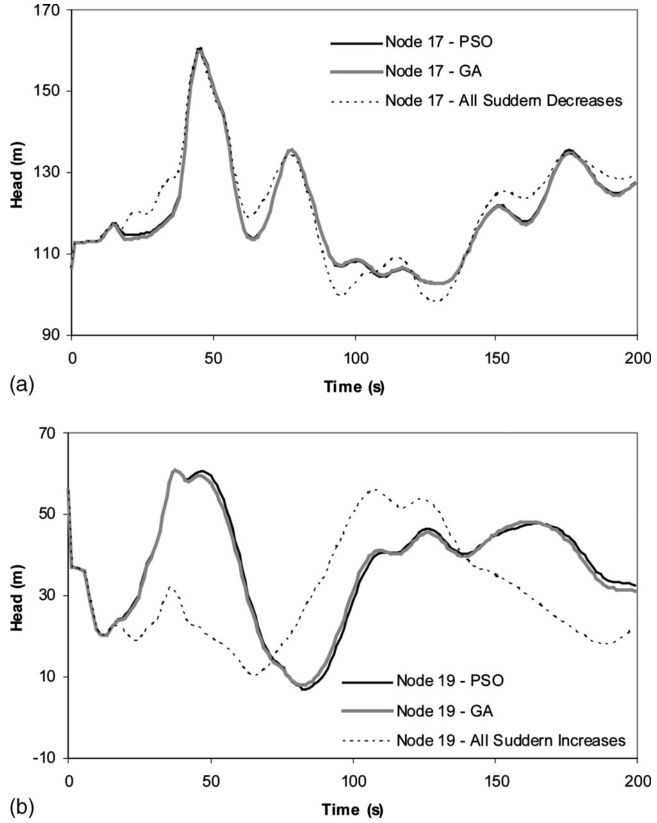

Fig. 5. Head traces of the worse loading conditions

This case study shows the highest decreases of all demands, even without considering liquid column separation, do not necessarily produce the worst maximum head in the system. Similarly, the highest increases of all demands do not necessarily produce the worst minimum head in the system. Interestingly, some demand nodes again exhibit a counterintuitive pattern. In fact, any discontinuity of pipe property (whether diameter material, thickness, or even friction), creates complex wave interactions, which can either magnify or attenuate the transient pressure wave. It is almost impossible to anticipate whether such wave affects will be beneficial or detrimental, and this often accounts for the counterintuitive system response. Overall, worse-case loadings are strongly dependent upon system characteristics and often have only weak associations with high or low demand scenarios.

Case 2: Sensitivity Analysis of Worst-Case Loading

Both optimization procedures in Case 1 found similar sets of the worst-case loadings; however, the search was based on the as-

Table 2. Sensitivity Results: 5 and 15% Ranges

	Maximize $H_{\max}$				Minimize $H_{\min}$			
	5%		15%		5%		15%	
Node	PSO	GA	PSO	GA	PSO	GA	PSO	GA
1[a]	10	10	10	10	−10	−10	−10	−9.9
2	−5	−3.8	−15	−14.1	5	2.5	15	4.2
3	−5	−4.9	−15	−14.7	5	4.8	15	−11.4
4	−5	−4.7	−15	−14.8	5	4.3	15	−6.5
5	−5	−4.0	−15	−13.1	5	4.7	15	−14.4
6	−5	−3.9	−15	−15	5	4.4	15	−14.7
7	−5	−3.9	−15	−14.7	5	4.9	15	−13.2
8	−5	−4.9	−15	−9.8	5	4.9	15	−14.9
9	−5	−4.9	−15	−14.9	5	3.3	15	−13.5
11	−5	−5	−15	−14.1	−5	−4.8	15	−15.0
12	−5	−4.1	−15	−15	−5	−4.9	15	−13.6
13	−5	−4.3	−15	−14.1	−5	−5	15	−11.2
14	−5	−4.9	−15	−14.5	−5	−4.6	15	−11.8
15	−5	−4.9	−15	−14.5	−5	−3.5	4.8	14.1
16	−5	−5.0	−15	−14.3	5	4.6	15	−14.9
17	−5	−4.9	−15	−15	5	4.7	15	−14.4
18	−5	−4.9	−15	−14.2	5	5	−15	15
19	−5	−5	−15	−14.9	5	5	−15	15
20	5	4.4	15	10.7	−5	−4.9	15	−12.9
$H_{\max}/H_{\min}$ (m)	150.9	150.6	170.3	169.2	19.2	19.5	−3.3	−4.9
Occurring node	17	17	17	17	19	19	19	19

[a] Reservoir level change is in meters for Node 1; demand change is in % for all other nodes.

sumed range of ±10% for time-varying demands. As indicated previously, estimating the variation of demand is an uncertain task giving rise to the obvious question of how the sets of worst cases are changed for different assumed ranges.

Keeping the other conditions the same as for Case 1, two different ranges (5 and 15%) of time-varying demands are investigated. Table 2 presents the sensitivity results for these ranges. Interestingly, the results for maximizing $H_{\max}$ in the ranges of 5 and 15% follow the same pattern as for 10%; that is, all nodes except Node 20 show a positive surge for valve closure. However, cases of minimizing $H_{\min}$ in the ranges of 5 and 15% are startlingly different from those arising from a 10% change. For the case of the 5% range, both PSO and GA present that Nodes 11–15 and 20 not only show a contrary pattern relative to the intuitively expected outcome but a quite different trend than that of 10%. In addition, the results of the 15% range by PSO and GA are different from those of 5% as well as 10%. Interestingly, the GA, in contrast with the previous cases, now provides a better search (−4.9 m) than the PSO (−3.3 m). This result shows the search of the worst loading case is sensitive to the assumed range for time-varying demands as well as the specific objective (i.e., worst maximum or worst minimum head).

Regardless of the different range for time-varying demands and optimization methods, Cases 1 and 2 show that the nodes at which the worst maximum and minimum head occur are dead ends (Nodes 17 and 19). As a dead end reflects a pressure wave positively and tends to double the surge pressure, it often constitutes one of the most vulnerable locations for objectionable pressures. Although dead end mains do not play important roles in steady state studies (indeed, they are often explicitly eliminated by typical skeletonization procedures), dead ends usually need special care in surge studies.

Case 3: Optimal Protection for Worst Case

If the worst transient response is unacceptable, one then needs to consider modifications of the transient and/or system. Various strategies can be applied to control the transient response as shown in Fig. 1; in the current study, two pressure relief valves (PRVs) with variable valve sizes are considered to relieve transient high pressures. Although no specific approach can be broadly representative, the current choice serves the basic goal of illustrating key relationships between system response and device behavior.

Four possible PRV sizes are considered (0.005, 0.01, 0.015, and 0.02 m^2). The PRV operation or activation head is set at 110 m, and the opening and closing times are 2 and 30 s, respectively. The decision variables of the GA and PSO procedures are the locations and sizes of two PRVs. The population size and the number of iterations for both GA and PSO are fixed at 20 and 50. The objective function of GA and PSO is to minimize the maximum head in the system; the resulting minimized maximum head in both the GA and PSO approaches is 144.5 m, an improved outcome compared to the unprotected worst maximum head in Case 1 (160.5 m for GA and 159.8 for PSO). Both the GA and PSO approaches achieve the same solution, locating the PRVs at 10 and 17 with the same valve area of 0.02 m^2.

Once the effect of surge protection devices has been investigated under the identified worst transient response, the worst loading case is again searched under the suggested surge protection strategies. Due to the introduction of the two PRVs to the system, the worst transient loading condition is modified to the new system characteristics; the resulting worst maximum heads are 145.4 m (GA) and 145.0 m (PSO). The values are very slightly higher than the maximum head of 144.5 m obtained before researching the worst loading case, but they still represent much improved control with respect to the unprotected worst maximum head at Case 1. The worst-case search and its corresponding best surge protection need to be solved iteratively until the worst case converges to an acceptable response. For example, if the adjusted worst transient loading condition, say in Case 3, is unacceptable, further modification of the system (e.g., additional surge protection devices) could be considered.

Conclusion

Estimating the appropriate water demands and their continuously fluctuating nature in a distribution system is inevitably challenging; further, determining what combination of demands, pumps, and reservoir levels will produce the most severe transient response is even more difficult due to the complicated interactions among system components and variables. In this paper, transient analysis is applied to simulate a variety of loadings in the quest to identify worst-case scenarios during distribution system design. Genetic algorithms and particle swarm optimization are combined with transient analysis to identify the worst-case loadings in example systems, and to develop the optimal surge protection strategies for the corresponding worst conditions. In practice, considerable judgment is required to select a realistic and suitable set of loading conditions to test, and what economical surge protection strategies to explore. Indeed, without dramatically limiting the search space, even modern computer systems cannot cope with the computational challenges of a rigorous and systematic search for the optimal system protection in most realistic field applications.

Even the current simplified case studies have shown that both the search of the worst-case loading and the optimal design of surge protection devices are strongly sensitive to the system characteristics (e.g., topography, pipe size, material, and thickness) as well as the transient characteristics (e.g., the range for time-varying demands). These attributes are highly interrelated so the careful selection of surge protection devices is crucial for preventing and mitigating transients. Also, the case studies confirm that dead ends constitute a highly vulnerable location and need careful consideration for surge protection. Therefore, the systematic surge protection using both the worst-case loadings and the optimal protection strategies is crucially important for water hammer control. This approach helps to train operators and designers as to how to circumvent undesirable circumstances and so, ultimately, creates significant advantages for the greater operational efficiency and emergency preparedness, better planning and more informed decision making, and increased infrastructure protection and reliability.

Notation

The following symbols are used in this paper:

B_D = baseline demands;
D_L = set of locations of surge protection devices;
D_S = set of sizes of surge protection devices;
H' = piezometric head of the worst-case loading;
$H_{\max}$ = maximum predicted heads;
$H_{\min}$ = minimum predicted heads;
$H^*_{\max}$ = maximum permissible head;
$H^*_{\min}$ = minimum permissible head;
T_L = time-varying tank levels;
T_T = operation times of time-varying tank levels;
V_D = time-varying demands; and
V_T = operation times of time-varying demands.

References

Boulos, P. F., Karney, B. W., Wood, D. J., and Lingireddy, S. (2005). "Hydraulic transient guidelines for protecting water distribution systems." *J. Am. Water Works Assoc.*, 97(5), 111–124.

Chaudhry, M. H. (1987). *Applied hydraulic transients*, 2nd Ed., Van Nostrand Reinhold, New York.

Dandy, G. C., Simpson, A. R., and Murphy, L. J. (1996). "An improved genetic algorithm for pipe network optimization." *Water Resour. Res.*, 32(2), 449–458.

Eusuff, M. M., and Lansey, K. E. (2003). "Optimization of water distribution network design using the shuffled frog leaping algorithm." *J. Water Resour. Plann. Manage.*, 129(3), 210–225.

Filion, Y. R., and Karney, B. W. (2002). "Extended-period analysis with a transient model." *J. Hydraul. Eng.*, 128(6), 616–624.

Ghidaoui, M. S., Zhao, M., McInnis, D. A., and Axworthy, D. H. (2005). "A review of water hammer theory and practice." *Appl. Mech. Rev.*, 58, 49–76.

Jung, B. S., and Karney, B. W. (2004). "Fluid transients and pipeline optimization using GA and PSO: The diameter connection." *Urban Water*, 1(2), 167–176.

Jung, B. S., and Karney, B. W. (2006). "Optimization of transient protection devices using GA and PSO approaches." *J. Water Resour. Plann. Manage.*, 132(1), 44–52.

Jung, B. S., Karney, B. W., Boulos, P. F., and Wood, D. J. (2007). "The need for comprehensive transient analysis of distribution systems." *J. Am. Water Works Assoc.*, 99(1), 112–123.

Jung, B. S., Karney, B. W., and Lambert, M. F. (2006). "Benchmark tests of evolutionary algorithms: Mathematics evaluation and application to water distribution systems." *J. Environ. Informatics*, 7(1), 26–37.

Laine, D. A., and Karney, B. W. (1997). "Transient analysis and optimization in pipeline—A numerical exploration." *3rd Int. Conf. on Water Pipeline Systems*, 281–296.

Lingireddy, S., Funk, J. E., and Wang, H. (2000). "Genetic algorithms in optimizing transient suppression devices." *Proc., ASCE 2000 Joint Conf. on Water Resources Engineering and Water Resources Planning and Management*, Reston, Va.

Maier, H. R., Simpson, A. R., Zecchin, A. C., Foong, W. K., Phang, K. Y., Seah, H. Y., and Tan, C. L. (2003). "Ant colony optimization for design of water distribution systems." *J. Water Resour. Plann. Manage.*, 129(3), 200–209.

Thorley, A. R. D. (2004). *Fluid transients in pipeline systems*, 2nd Ed., D&L George, Herts, U.K.

Wood, D. J., Lingireddy, S., Boulos, P. F., Karney, B. W., and McPherson, D. L. (2005). "Numerical methods for modeling transient flow in distribution systems." *J. Am. Water Works Assoc.*, 97(7), 104–115.

Wylie, E. B., and Streeter, V. L. (1993). *Fluid transients in systems*, Prentice-Hall, Englewood Cliffs, N.J.