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Water Distribution System Optimization Accounting for Worst-Case Transient Loadings

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ABSTRACT. This paper presents optimal transient design as a two-step optimization problem — identification and mitigation of the worst-case in a water distribution system. In the first step, particle swarm optimization was used to identify the set of critical nodes that result in the worst-case transient loading condition. In the second step, dual-objective optimization was used to determine the optimal pipe sizes that simultaneously minimize cost and the likelihood of damaging transient events, measured by a parameter named surge damage potential factor. Nondominated sorting genetic algorithms were combined with transient analysis to produce a set of Pareto-optimal solutions in the search space of pipe cost and surge damage potential factor. The New York tunnel system was tested as a case and results show that the worst-case was not always obvious and cannot always be assumed a priori. Therefore, a comprehensive and systematic optimization is required to identify the worst-case in a network. It also confirmed that transient consideration in a design phase, in conjunction with conventional least-cost pipe size optimization, will help water utilities yield tangible cost savings along with improvement in system performance.

Keywords: optimization, surge control, transient, water distribution system, worst-case scenario

1. Introduction

Water is not only important for human beings directly for drinking, bathing, and cooking, but indirectly for agriculture, industry, and electricity. As water is located locally, transporting water from sources (e.g., river and lake) to consumers is also equally important. Water distribution system (WDS) is, therefore, a vital infrastructure for the transmission, storage, and distribution of water for homes, commercial establishments, industry, and irrigation, as well as for a public need like firefighting. The goal of WDS is to meet a variety of competing requirements under a broad range of operations, evaluated by performance measures ranging from cost to reliability, robustness, and resilience, in addition to constraining regulatory stipulations. The hydraulic conditions to which the system is subject include a variety of demand scenarios — generally high demands, or low demands, with or without fires, to possibly considering complex mixes of these conditions. The WDS can be in a variety of states of operation and repair, with various pumps operating, reservoirs at various levels, and with both pipes and valves having various states of integrity and serviceability. Whenever adjusting an operating condition from one state to another, hydraulic transient arises and initiates a sequence of propagating pressure and velocity waves that transmit information about the change throughout hydraulic system. If the conditions change sufficiently slowly, the resulting pressure changes are small and do not threaten the integrity of the hydraulic system. However, by contrast, if the conditions change rapidly, large, and destructive pressure can be generated, sometimes of sufficient magnitude to burst pipes or otherwise damage equipment. Rathnayaka et al. (2016) monitored pressure transients that were generated during normal operation for one month and argued they could lead to pipe failures. Leishear (2020) found water hammer directly caused 69.5% of water main breaks, or cracks, in U.S. and Canadian piping. Leishear also found water hammer caused an additional 28.3% of water main failures in U.S. and Canadian piping, where corrosion accelerated piping failures were initially caused by cracks due to water hammer.

There have been many transient optimization studies applied to identify system weak points, to predict the potentially damaging effects of hydraulic transients under various worst-case scenarios, and to evaluate how they may possibly be eliminated or controlled. An early surge protection study that integrated numerical optimizations was performed by Laine and Karney (1997). This approach incorporated a complete enumeration scheme and a probabilistic selection procedure using both transient and steady state analysis for the optimal design of a simple pipeline connecting a pump and a storage reservoir. Lingireddy et al. (2000) showed that a specific surge tank design model obtains an optimal set of decision variables, while satisfying a given set of pressure constraints. Boulos et al. (2005) provided a detailed transient analysis flow chart for the selection of components for surge control and suppression in WDSs

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and concluded that a transient analysis should always be carried out to determine the impact of each proposed strategy on the resulting system performance. Jung and Karney (2009) identified the most severe transient loading conditions and then presented the optimal design of pressure relief valve (PRV) for the identified worst-case. El-Ghandour and Elansary (2019) developed an optimal control of pressure surges in WDS using PRV as a protection strategy. They used a genetic algorithm (GA) model to minimize the difference between maximum and minimum pressures by optimizing PRV number, and their best locations, sizes, set pressure points, opening time and closing time of each valve. Similarly, Kim and Kim (2020) considered an optimal PRV design with single-objective and multi-objective optimizations. Huang et al. (2020) developed a multi-objective optimization framework for WDS design by accounting for transient impacts as well as the least-cost design problem. They found upsizing pipes could be effective to mitigate transient impact but at the expense of more cost. Al-Khomairi et al. (2020) provided a lifecycle cost optimization for WDS considering steady and unsteady flow conditions. They applied the proposed method in a real WDS considering the decision variables with pipe diameter, pipe material, surge tank size, and operation and maintenance cost throughout project service life. El-Ghandour et al. (2021) presented a methodology of finding the optimal rehabilitation of WDS under both steady-state and transient conditions. They also investigated the stability and reliability of the obtained optimal solution with the uncertainties of pipe roughness. Despite various transient optimization studies, there has been, within author’s understanding, no systematic approach of combining an optimization of WDS design (including transient protection and minimization as well as the least-cost design problem) with the worst-case transient loading condition. As found in Filion and Karney (2002) and Telci et al. (2018), the worst-case in a network is not always obvious and seldom can be assumed to simply correspond to high or low demand scenario.

To address this issue directly, this paper proposes to formulate optimal design as a two-step optimization problem, i.e., identification and mitigation of the worst-case in a network. In the first step, numerical optimization is used to identify the set of critical nodes whose failure will result in the worst-case transient loading condition. In the second step, dual-objective optimization is used to determine the optimal pipe sizes that simultaneously minimize cost and the likelihood of damaging transient events, measured by a parameter named surge damage potential factor. Nondominated sorting genetic algorithms are combined with transient analysis to produce a set of Pareto-optimal solutions in the search space of pipe cost and surge damage potential factor. As a case study, the New York tunnel system is considered to search the most severe transients under multiple loading conditions and then to find the least-cost optimization with the selection of pipe diameters while simultaneously minimizing the likelihood of damaging transient events. This paper first explores pressure surge control strategies, followed by the mathematical formulations of the two-step optimization and the case study.

2. Pressure Surge Control Strategies

Pressure surge control starts with a preliminary specification of system configuration. A set of possible pressure surge loadings are first selected to represent a realistic range of operational scenarios. These are then simulated, and worst-case loadings are identified and compared against some performance criterion; for example, that pipeline system should not experience any pressures in excess of some specified peak threshold and that it should effectively eliminate negative pressures. If the worst transient response is unacceptable, appropriate surge controls need to be considered. The flowchart for pressure surge control in Figure 1 (Jung and Karney, 2020) summarizes the set of considerations with five key protection strategies, often useful in practice when developing a transient or pressure surge control strategy.

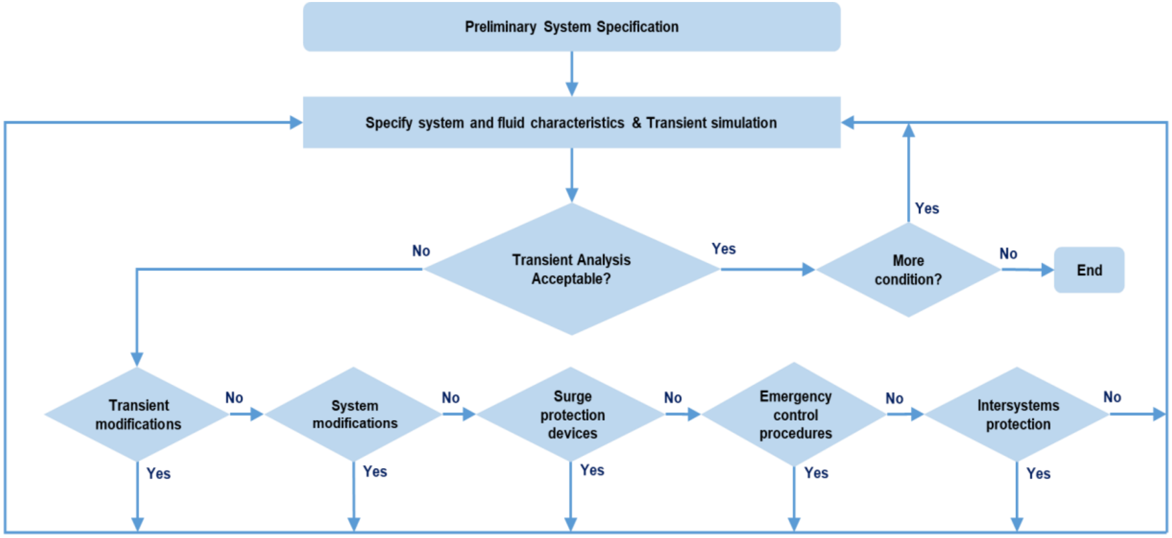

Figure 1. Flowchart for pressure surge control (Jung and Karney, 2020).

First, transient modification is considered with the goal of influencing the root causes of flow changes, such as adjusting the way valves or pumps are operated. For example, extending the effective time to open or close a valve (i.e., multi-stage valve opening/closure or a prolonged actuation) to longer than the characteristic length of a system can be an economical option. Second, system modifications might be considered, such as pipe reinforcement (i.e., increasing a pipe's pressure rating), rerouting some conduits, using larger diameter pipes, changing the pipe profile or material, or other strategic changes in system topology or loading condition. Third, probably the most widely applied strategy is to employ dedicated surge protection devices. Many options (e.g., surge vessels, air valves and relief valves) have been invented to smooth the transient events. Fourth, an emergency control system can be another effective protection strategy. When an emergency event like a pump trip occurs, control systems might be configured to counteract the negative effects of the emergency event. The final protection strategy is to exploit or create inter-system connections. The idea of inter-system protections is to relieve a surge pressure by connecting a system under a transient condition (e.g., due to a pump trip) to a nearby piping system under normal operation — a bypass line with a check valve is added to allow one-way communication. Although this strategy is only rarely applied, it can be quite effective if appropriate prerequisites are met.

Overall, the choice of specific options from the above five protection strategies is inevitably iterative. Each pass through the loops in Figure 1 adjusts and refines the system response with the goal that the overall design gradually evolves to an acceptable level of transient protection. In this paper, the worst-case transient loading is identified using an optimization method and a hydraulic transient model. Both optimization method and hydraulic transient model are used again to mitigate the identified worst-case transient loading condition. This paper specially considers the interaction of system characteristics with surge control choices while simultaneously finding the least-cost optimization with the selection of pipe diameters.

3. Model Formulation: Worst-Case Scenario Search

A worst-case scenario may be performed by analyzing a transient event repeatedly with a transient simulator for several different hydraulic states (the combinations of system demands, reservoir water levels, and setting of system components such as pumps and valves) and then by comparing the maximum and minimum transient pressures simulated for each system state. However, determining what combination of demands, pumps and reservoir levels produces the most severe transient response is difficult due to the complex interactions among system components and variables (Jung and Karney, 2009). Telci et al. (2018) also investigated the emergency shutdown protocols of a liquefied natural gas ship-loading system and found that the common surge mitigation intuition (e.g., slower valve closure will have milder surge effects) can sometimes be misleading. This is because system characteristics including any discontinuity of pipe property (whether diameter, material, thickness or even friction) creates complex wave interactions, which can either magnify or attenuate transient pressures. It is almost impossible to anticipate whether such wave effects will be beneficial or detrimental, and this often accounts for the counter-intuitive system response.

In this study, the search for the worst-case loading in WDS is accomplished using an optimization method and a hydraulic transient model. The damage sustained in surge pressure, which sometimes is not noticed at the time but may result in intensified corrosion or fatigue combined with repeated transients, could cause future pipeline failures. Therefore, the likelihood of a damaging transient event is measured by a parameter named surge damage potential factor (SDPF), defined as the integral of the transient pressures that are lower than the minimum required level (e.g., datum) or higher than the maximum allowable transient pressure level (e.g., pipe ratings). Given a network system, the worst-case loading is defined here by the set of baseline demands (D_B), time-varying demands (D_T), and operation times of time-varying demands (T_O), which result in maximizing the SDPF. The overall optimization problem can be stated mathematically as follows:

$$\begin{aligned}&\mathit{Maximize\ SDPF} =\\ &\sum_{i \in N_{node}} \int \left| H_i(D_B,\ D_T,\ T_O) \right| dt,\ H < H^*_{\min}\ \mathit{or}\ H > H^*_{\max}\end{aligned} \tag{1}$$

subject to the governing transient equations (Wylie and Streeter 1993):

$$\frac{1}{gA_p}\frac{\partial Q}{\partial t} + \frac{\partial H}{\partial x} + \frac{R}{\Delta x} Q\left|Q\right|^{n-1} = 0 \tag{2}$$

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA_p}\frac{\partial Q}{\partial x} = 0 \tag{3}$$

$$H_i(t,\ D_B) = C_1,\ Q_i(t,\ D_B) = C_2,\ t = 0,\ \forall i \in N_{node} \tag{4}$$

$$f\,(H_i(t),\ Q_i(t)) = C_3,\ t > 0,\ i = \mathit{boundary\ nodes} \tag{5}$$

where $H^*_{\max}$ and $H^*_{\min}$ = maximum and minimum allowable pressures, respectively; x = distance; t = time; H = piezometric head; Q = fluid discharge; a = shock wave celerity; A_p = cross-sectional area of pipe; and g = gravitational acceleration. Equations (2) and (3) represent the momentum equation and mass conservation for transient flow in closed conduits. The friction term in the momentum equation assumes steady friction here and represented as:

$$\mathit{Darcy-Weisbach}: R = f_p \Delta x / 2gD_p A_p^2,\ n = 2 \tag{6}$$

$$\mathit{Hazen-Williams}: R = \Delta x / (0.278 C D_p^{\ 2.63})^{1/0.54},\ n = 1/0.54 \tag{7}$$

where f_p = Darcy-Weisbach friction factor; C = Hazen-William's roughness coefficient. Two hyperbolic partial differential Equations (2) and (3) are subject to initial conditions in Equation (4) and boundary conditions in Equation (5), where C_1, C_2 and C_3 are the vectors of constants. Initial conditions are typically taken as steady. Simple boundary conditions are constant reservoir level and fixed demand, but combined relationships between H and Q are typical for most boundaries.

Hydraulic transient model is described by the two hyperbolic partial differential Equations (2) and (3). A general analytical solution of these equations is impossible due to the nonlinearity of the momentum equation and the complexity of the associated boundary conditions. Various methods have been developed for analyzing transient flow in pressurized conduits. Simple analyses are conducted with the arithmetic method by neglecting friction and using the basic equation of water hammer and the graphical model neglecting friction but taking it into account by a correction (Wylie and Streeter, 1993). More complicated but more accurate forms of analyses are the implicit method using a finite difference procedure which is particularly applicable in situations where inertial forces are not as important as the storage or capacitance effect; linear analysis methods that linearize the friction term and drop other nonlinear terms in the two governing equations and then produce an analytical solution to the equations using sine-wave oscillations; the method of characteristics (MOC) which transforms the partial differential equations of motion and continuity into ordinary differential equation and then integrates the equations to obtain a finite difference representation of the variables; and waver characteristic method (WCM) that tracks the movement and transformation of pressure waves as they propagate with time throughout WDS in an event-oriented environment (Wylie and Streeter, 1993; Boulos et al., 2005; Ghidaoui et al., 2005). Because the MOC computes solutions at interior nodes, it features higher spatial resolution, whereas the WCM makes simplifications that yield more efficient computations. Jung and Karney (2004) introduced an eigenvalue method of transforming the hyperbolic partial differential equations of transient model into a characteristic form which is eventually the same form as the MOC. Nault et al. (2018), considering the advantages of both MOC and WCM, developed a generalized characteristic method by combining a flexible friction approximation with a variable reach scheme. Typically, both characteristic solution methods, MOC and WCM, are widely used for simulating transient pipe network flows in practice.

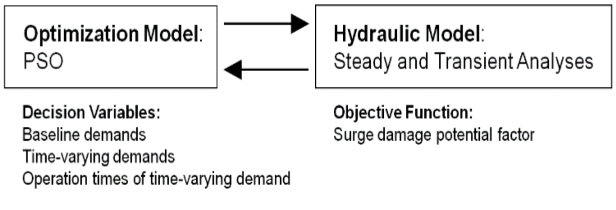

Figure 2. Flowchart of the worst-case search.

Figure 2 presents a schematic layout for searching the selection of worst-case loading. Particle swarm optimization (PSO) (Jung et al., 2006) is invoked by initializing the decision variables of baseline demands, time-varying demands and operation times of time-varying demands. With initial decision variables selected, the governing transient equations are solved to calculate the SDPF. Objective values, SDPFs, are used to evaluate the fitness of the individual solutions and a new population of trial solutions is created. Due to the stochastic characteristics of PSO, a number of simulations are performed using varying random seeds. Since they produce slightly different results, the "best" (most severe transient) of each group is selected.

4. Model Formulation: Optimal Design for the Worst-Case

Once the worst-case loading is determined, various surge protection strategies could be introduced to relieve water hammer effects. This article specially considers the interaction of system characteristics with surge control choices while simultaneously finding the least-cost optimization with the selection of pipe diameters. System modifications, such as increasing pipe's pressure rating, rerouting to better profiles, using larger diameter pipes, changing the pipe material, or strategic changes in system topology, can alter both the system and its transient response. While increasing pipe size improves the transient response, minimizing pipe size (so minimizing cost) has been the goal of conventional optimization problems for a given set of demand loading and operating conditions (Lansey and Mays, 1989; Simpson et al., 1994; Dandy et al., 1996). Clearly, even in this trivial example, optimization of the two objectives (maximization of surge protection and minimization of pipe costs) cannot be achieved simultaneously.

In this study, the optimal design of WDS is therefore formulated as a two-objective optimization problem. The first objective is formulated in Equation (8) as a least-cost optimization problem with the selection of pipe diameters as decision variables. The second objective is to minimize the likelihood of a damaging transient event and formulated in Equation (9) to minimize the SDPF. Both objectives can be stated mathematically as:

$$Minimize\ pipe\ \cos t = \sum_{k \in N_{pipe}} C_k(D_k,\ L_k) \tag{8}$$

$$Minimize\ SDPF = \sum_{i \in N_{node}} \int \left| H_i(t) \right| dt,\ H < H^*_{\min}\ or\ H > H^*_{\max} \tag{9}$$

subject to the governing transient Equations (2) to (5) and a set of algebraic constraints:

$$H_i(t) \ge H_{\min i},\ t = 0,\ \forall i \in N_{node} \tag{10}$$

$$D_k \in \{D\},\ \forall k \in N_{node} \tag{11}$$

where D_k = discrete pipe diameters selected from a set of available pipe sizes $\{D\}$; N_{pipe} = total number of pipes; $C_k(D_k, L_k)$ = cost of pipe k with diameter D_k and length L_k. Equation (10) requires that the nodal pressure H for any node i (where total number of nodes is N_{node}) is equal to or greater than a specified minimum pressure $H_{\min}$ for steady state condition.

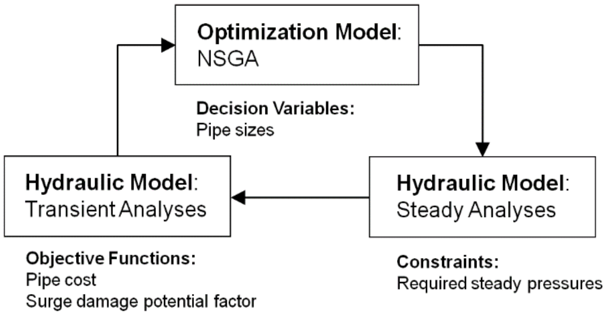

Figure 3. Flowchart of pipeline system optimization for dual-objective problem.

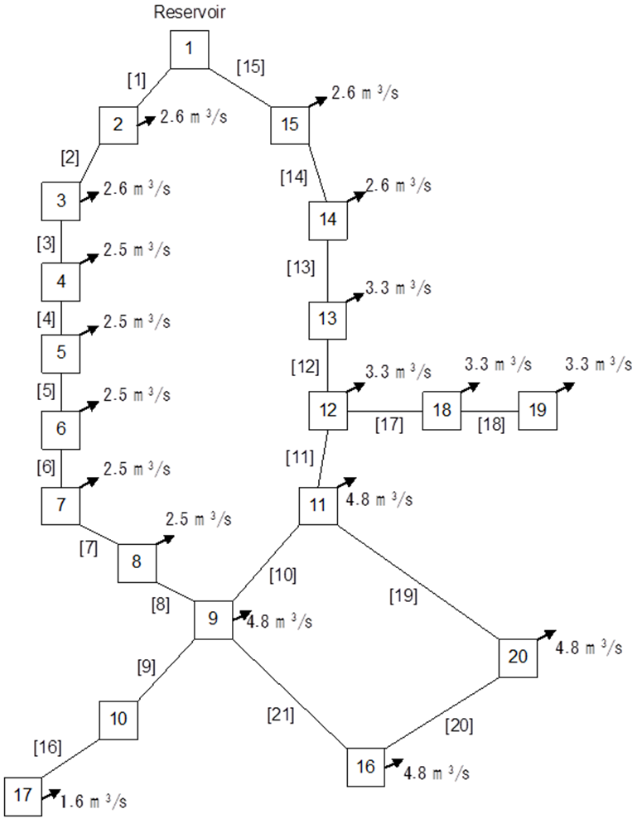

Figure 4. New York tunnel system schematic.

Given the dual-objective (pipe cost and surge damage potential factor) problem, nondominated sorting genetic algorithms (NSGAs), developed by Srinivas and Deb (1994), are used to circumvent subjective decision making and to generate Pareto-optimal solutions for the multi-objective optimization problem. Figure 3 depicts a flowchart of the framework for optimizing the pipeline system considering the dual-objective problem. First, the optimization program initializes the pipe sizes as decision variables, and the pipe cost is calculated. The hydraulic model with steady analysis then analyzes the given system and uses the optimization program to check if the solution satisfies the required constraints given by Equations (10) and (11). The hydraulic transient model computes the second objective function shown in Equation (9) with the governing transient Equations (2) to (5). With the dual-objective function values, the optimization model then evaluates the proposed design and creates a new set of system alternatives for the next iteration. The iterations continue until an optimal or an acceptable solution is reached.

5. Case Study

The case study uses the New York tunnel system (Schaake and Lai, 1969). The network, which is shown in Figure 4, has been extensively studied for steady state conditions. It comprises 22 nodes (20 demand nodes), 21 pipes, and one source node. The system is gravity driven and draws water from the source reservoir to its downstream network. The objective of the optimization problem is to add new pipes parallel to the existing ones. The new pipe diameters need to be selected from 15 available sizes. A single demand pattern (57,130 L/s) was considered, and a minimum allowable hydraulic grade was specified for each node. The network and cost data are given in Dandy et al. (1996). Since the system was first examined in 1969 by Schaake and Lai, numerous researchers have used it to test the numerical effectiveness, efficacy, and performance of their respective techniques (Dandy et al., 1996; Wu et al., 2001; Eusuff and Lansey, 2003; Maier et al., 2003). These approaches, however, were based only on steady state hydraulic optimization. Our case study first seeks to find the set of worst-case loadings, which result in the largest likelihood of a damaging transient event. Next, we determine optimal pipe sizes to cope with the worst-case events, while minimizing the overall cost for a given set of demand loadings. The above solutions must, of course, satisfy the required hydraulic performance constraints.

5.1. Worst-Case Scenario Search

The search of the set of transient worst-case loading, maximizing the SDPF formulated in Equation (1), is first considered. WDS must sometimes deliver large flows (e.g., fire flow demands) with adequate pressure. Design procedures should, therefore, evaluate the system's ability to supply those demands at all relevant locations (e.g., fire-fighting demands). In this case study, the goal is to find the worst multiple transient flow loading that maximizes the SDPF. All junctions are set to have a sudden flow demand of 3 m^3/s and the system is assumed to have up to two simultaneous events at any two given nodes. For simplicity, the opening times of the transient flow loadings are fixed at 1 s, since the shortest operation times create the most severe transient events. The maximum permissible heads $H^*_{\max}$ and $H^*_{\min}$ in Equation (1) are assumed to be 304.8 and 54.9 m, respectively, for the whole system. All transient modeling results presented here can be obtained using the method of characteristics (Wylie and Streeter, 1993).

PSO is used to search the worst system performance maximizing the SDPF. As a decision variable, the location and number of transient flows are selected by the PSO program. The parameters used for the PSO program are based on the empirical study of PSO (Jung et al., 2006) including the population size of 20 and 100 iterations. After 5 simulations with varying random seeds, four PSO solutions show the same results that the worst transient flow locations are Nodes 18 and 19, and the maximized SDPF is 79000 m-s. It is worth noting that the locations of the two transient flows are located at the dead-end pipes. Since a dead end reflects a pressure wave positively (doubling of a surge pressure), dead ends often constitute some of the most vulnerable locations for objectionable pressures. It should be also noted that the worst-case is not always obvious and cannot always be assumed a priori. Since system characteristics including any discontinuity of pipe property such as different pipe diameter, material, thickness creates complex transient wave interactions, a comprehensive and systematic optimization is required to identify the worst-case, especially, in a complicated network.

5.2. Optimal Design for the Worst-Case

WDS designer must anticipate the unacceptable transient pressures of transient flow scenario and then consider corresponding surge protection strategies. This case study is intended to show the influence of pipe sizes on surge protection and to find the optimal set of pipe sizes to minimize the likelihood of the surge damage sustained in the worst-case transient flow scenario. The traditional optimization goal of finding optimal pipe sizes (i.e., minimizing pipe cost for a given set of steady demand loadings while satisfying minimum-required steady state pressures) is also taken into account. To solve the dual-objective problem, multi-objective optimization method is applied to produce a set of Pareto-optimal solutions in the search space of pipe cost and SDPF.

NSGA, as the multi-objective optimization method, was applied to satisfy Equations (8) to (11). In the NSGA, the probabilities of mutation and single-point crossover, the length of each chromosome, population size and generation number are set to 0.025, 0.9, 84, 400, and 100, respectively. For this problem, 16 decision variables including a "do nothing" option made up a solution space of 16^{21} or 1.93×10^{25} possible pipe combinations. NSGA initialized the population of pipe diameters, and then calculated the cost of pipelines and the SDPF of the transient network design model satisfying the given constraints, and then created a new population for the next generation.

The resulting solutions are shown in Figure 5, where the *X*-axis plots the pipe cost in Equation (8) and the *Y*-axis plots the SDPF in Equation (9). The interaction among the dual objectives give rise to a set of Pareto-optimal solutions. Each solution on the Pareto-optimal curve is not dominated by any other solution. In going from one solution to another, it is not possible to improve the first objective of minimizing the pipe cost without making worse the second objective of minimizing the SDPF. This leads to a trade-off relationship between the dual objectives, where a decision maker can choose a preferred solution.

Table 1 shows the pipe cost, SDPF and pipe diameters chosen in the Pareto-optimal solutions that correspond to 31 distinct results. When the pipe cost increases from $42.6 million to $56.7 million (M1 to M15), the 33% additional investment in pipe can achieve an 84% reduction in surge damage (2800 to 457 m-s). Similarly, when the pipe cost increases from $56.7 million to $70 million (M15 to M31), the 23% additional investment in pipe can achieve the condition of no damage with the given transient event. A decision maker can use the information in Figure 5 and Table 1 to evaluate the marginal rate of tradeoff between the pipe cost and the SDPF. Table 1 also shows that the sizes of pipes P17 and P18 are distinctly bigger than the other pipes as the SDPF increases. This is because they are located next to the surge-creating nodes N18 and N19 and the proper sizing of pipes P17 and P18 is most crucial for effectively controlling the surge pressure.

Figures 6, 7 and 8 depict the transient head profiles at five representative nodes (Nodes 9, 10, 17, 18 and 19) of the multiobjective solution M1, M15 and M31, respectively. As pipe cost increases with a bigger diameter, the resulting reduction in velocity decreases the magnitude of the pressure wave, increasing the minimum pressure. For example, the minimum pressure head at Node 17 of the solution M1 is 41.7 m, where the minimum pressure is improved to 46.6 m at M15 and 55.0 m at M31. The results indicate that the proper sizing of pipe diameters is crucial in preventing water hammer so, if the modifications of pipe size are considered in the design process, they can form a reliable and cost-effective surge control strategy.

6. Discussion and Future Studies

The methodology and case study of transient optimization identify the set of critical nodes that result in the worst-case transient loading condition and then find the optimal pipe sizes that simultaneously minimize cost and SDPF. Several specific points need to be carefully investigated and discussed:

- Determining transient loadings and their consequent responses are not straightforward as it is sometimes assumed. Estimating water demands requires two fundamental questions: (i) How much water will be used? and (ii) How will usage change as a function of time? However, the associated answers are often uncertain and complex and the number of possible combinations of loadings is almost overwhelming. Not surprisingly, the optimal transient protection design for an improper selection of transient loadings would be not comprehensive and, possibly, misleading. The search for the worst-case loading in a network is, therefore, equally important as the search for the optimal transient protection. The case study presents the worst-case is not always obvious and cannot always be assumed a priori so a comprehensive and systematic optimization is required to identify the worst-case in a network.
- Transient analysis has been often left until design and even construction process is well advanced. Many factors such as choice of pipeline route, pipe diameter, wall material and thickness, and device selection (e.g., specific pump and valve choices) have occasionally been made on the basis of steady flow analysis alone. However, the interacting choices of pipe diameter, pipe material and wall thickness, and adopted operating conditions can strongly influence

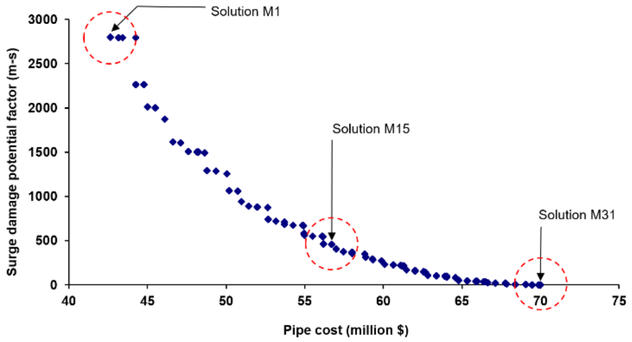

Figure 5. Pareto-optimal solutions of pipe cost and surge damage potential factor.

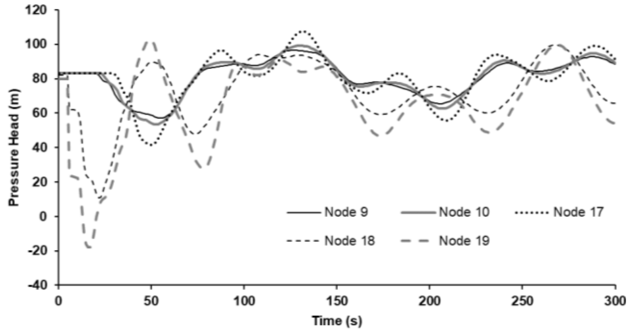

Figure 6. Transient head profiles of multi-objective solution M1.

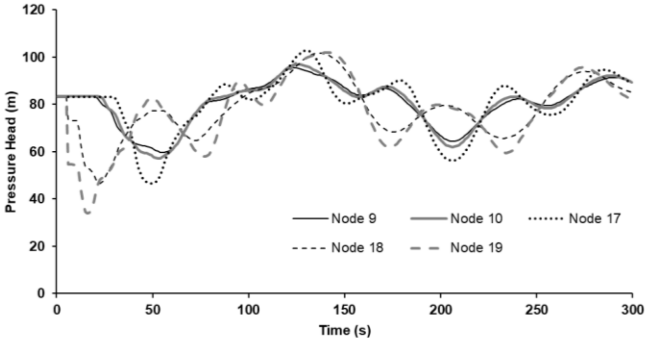

Figure 7. Transient head profiles of multi-objective solution M15.

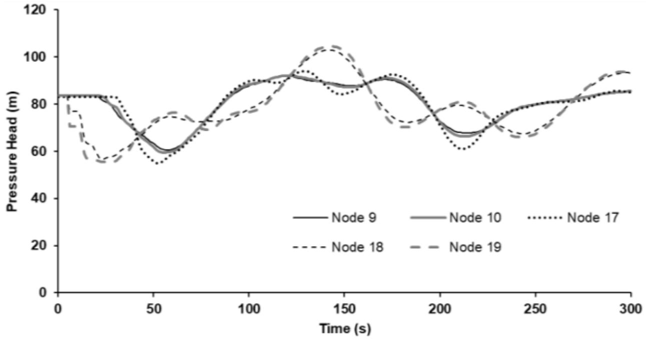

Figure 8. Transient head profiles of multi-objective solution M31.

the nature of the pipeline transient response. Therefore, transient considerations in the design phase are fundamental in determining the ultimate system performance and cost. If the understanding of hydraulic transient behavior were improved, then an initial transient analysis undertaken in parallel with considerations of steady flow behavior might yield tangible cost savings along with improvement in network behavior.

- The surge event in the case study is based on the transient flow loading of sudden flow demand but, in most WDSs, the search of worst-case scenario may need to be extended to other transients such as full pump trip or a combination of valve closures. In addition, this paper only selects pipe diameters for surge protection but there are many other design criteria like system topography, pipe material, pipe thickness, surge protection devices (e.g., air valves and surge tanks) selection and location. More global and comprehensive analyses are required for the search of worst-case scenario and transient optimization; in practice, a considerable amount of sound engineering judgement is always required to select a realistic and suitable set of economical surge protection strategies to explore.
- Surge pressure can directly cause water main breaks, but the damage is not often noticed at the time but may result in intensified corrosion or fatigue combined with repeated transients and cause pipeline failures later. Therefore, a new transient index SDPF is proposed to consider the likelihood of a damaging transient event. However, the new transient index has its own weakness which needs to be carefully assessed. The factor is the sum of the likelihood of the surge damage at the nodes considered so sensitive to the level of model discretization in a network. Nodes should be, therefore, selected properly and then incorporated during analysis. Furthermore, real systems have the transients that often decay much faster than numerical models; hence, the model results might tend to emphasize what is actually least certain.
- The optimization in the case study is based on an implicit assumption on the loading conditions, which is questionable. The loading conditions are often subject to uncertainty (e.g., the satisfaction of the minimum required pressures is not certain) as a direct result, the conventional deterministic system design could be inappropriate under unexpected and/or unusual loading conditions, either by being over-designed (easily meeting the required conditions but at too great a cost) or under-designed (failing to meet the required conditions). Researches in this probability-based reliability, robustness and resilience in WDS optimization (Gheisi, 2016; Savic et al., 2018; Shin et al., 2018; Paez, 2019) and global water resource management problems (Li et al., 2019; Nie et al., 2021; Xiao et al., 2021) have been done; however, within author's understanding, there has been no transient optimization study with the uncertainties of loading conditions. More complete and comprehensive future study may be considered with the uncertainties of loading conditions.

Table 1. Pareto-Optimal Solutions

	Pipe Cost ($ Million)	SDPF[2] (m-s)	Pipe Size (mm)							
			P1 ~ 6, 9 ~ 15, and 20	P7	P8	P16	P17	P18	P19	P21
M1[1]	42.6	2800	-[3]	3000	-	2700	3000	2100	1500	2100
M2	44.3	2270	-	3000	-	2700	3300	2100	1500	2100
M3	45.0	2010	-	3000	-	2700	3000	2700	1500	2100
M4	46.1	1870	-	3000	-	2700	3300	2400	1800	2100
M5	46.6	1620	-	3000	-	2700	3300	2700	1500	2100
M6	47.6	1510	-	3300	-	2700	3600	2400	1500	2100
M7	48.8	1290	-	3300	-	2700	3600	2700	1500	2100
M8	50.2	1060	-	4200	-	2400	3900	2700	1800	1800
M9	51.0	941	-	4200	-	2400	3600	3300	1800	1800
M10	51.4	890	-	4200	-	2400	3900	3000	1800	1800
M11	52.7	743	-	4200	-	2400	3900	3300	1800	1800
M12	53.7	709	-	4500	-	2400	4200	3000	1800	1800
M13	53.7	685	-	4200	-	2400	4200	3000	1500	2100
M14	54.9	579	-	4500	-	2400	4200	3300	1800	1800
M15	56.7	457	-	4500	-	2400	4500	3300	1800	1800
M16	57.0	404	-	4200	-	2400	4200	3900	1800	1800
M17	57.5	376	-	4200	-	2400	4500	3600	1800	1800
M18	58.9	314	-	4200	-	2400	4200	4200	1500	2100
M19	59.3	293	-	4500	-	2400	4500	3900	1800	1800
M20	60.1	231	-	4200	-	2400	4500	4200	1800	1800
M21	61.5	168	-	4200	-	2400	4500	4500	1800	1800
M22	62.8	108	-	4200	-	2400	4500	4800	1800	1800
M23	64.0	87.6	-	4200	-	2400	4500	4800	1800	2100
M24	64.8	56.1	-	4500	-	2400	4500	5100	1800	1800
M25	64.8	49.5	-	4200	-	2400	4500	5100	1500	2100
M26	65.9	39.2	-	3300	2400	2100	4500	5100	1500	2100
M27	66.6	27.2	-	4500	-	2400	4500	5100	1500	2400
M28	67.1	20.0	-	4500	-	2400	4800	5100	1500	2100
M29	67.9	7.4	-	4200	-	2400	4800	5100	1500	2400
M30	69.5	1.0	-	3600	2400	2100	4800	5100	1500	2400
M31	70.0	0.0	-	3900	2400	2100	4800	5100	1500	2400

Note: [1]The result of multi-objective solutions; [2]Surge damage potential factor shown in Equation (9); [3]Not applicable (no pipe required).

- Once optimal surge protection strategies have been investigated under the identified worst transient response, the worst-case is again sought under the suggested surge protection strategies. The worst-case search and its corresponding best surge protection need to be solved iteratively until the worst-case converges to some acceptable response.
- Finally, the ultimate design goal of WDS needs to achieve several other objectives such as minimizing operating cost and risks and maximizing reliability and water quality. Finding the best solution for a certain objective is often against achieving the other design goals. This paper presents the dual objectives of minimizing pipe cost and surge damage, but a real design tends to be more complicated with multiple objectives and design criteria. Given this, with almost every parameter having a set of measurement challenges and operational uncertainties, it would not be easy to define clearly an “optimum” system. And any such optimization is usually premised on the concept that there is available resources to be redeployed in some more beneficial way, but this is often not the case and in fact these resources are crucial for some other operational state unconsidered by the optimization framework. Thus, as in so many other areas, effective design is a question of balancing tradeoffs, seeking an effective resolution among a set of competing objectives and risks (e.g., flow and pressure control, design and system constraints, operating and capital budgets, etc.), where various alternatives need to be evaluated and compared both at initial commissioning and as the system evolves over its operational life.

7. Summary and Conclusions

Determining what combination of demands, pumps, and reservoir levels will produce the most severe transient response is difficult due to the complicated interactions among system components and variables. The search for the worst-case loading in a network is, therefore, crucially important for its associated optimal surge protection strategies. In this paper, particle swarm optimization is combined with transient analysis to identify the worst-case transient loadings. The optimal design is then formulated as a dual-objective optimization problem: the first objective is formulated as a least-cost optimization problem with the selection of pipe diameters, and the second objective is set to minimize the likelihood of damaging transient event, measured by a parameter named surge damage potential factor. Non-dominated sorting genetic algorithms are combined with transient analysis to produce a set of Pareto-optimal solutions in the search space of pipe cost and surge damage potential factor. The case study using the New York tunnel system indicates that the combination of evolutionary algorithms with transient analysis significantly helps to locate the worst-case loading and to develop the optimal surge protection strategies for the corresponding worst condition. It should be noted that the worst-case is not always obvious and cannot always be assumed a priori so a comprehensive and systematic optimization is required to identify the worst-case in a network. The study also confirms that pipe size plays a significant role in controlling transient response, so the transient consideration in the design process can form an effective and inexpensive surge control strategy, in conjunction with the traditional least-cost optimization problem with the selection of pipe diameters. The transient consideration can help water utilities yield tangible cost savings along with improvement in system performance.

The surge protection strategy in this study was limited to the optimal selection of pipe diameters, but more global analyses and future research may be considered with other transient events and surge control strategies. More comprehensive optimizations may include other design goals such as minimizing operating cost and risks and maximizing reliability and water quality. What is at stake is an effective tradeoff in design and operation and a practical balancing of risks, where the risks to the health of the system associated with various alternatives need to be evaluated and compared both at initial commissioning and as the system evolves over its operational life. This level of analysis is difficult and seldom undertaken, although the stakes associated with improper design are often high. More comprehensive and complete optimizations need to be considered in future research.

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