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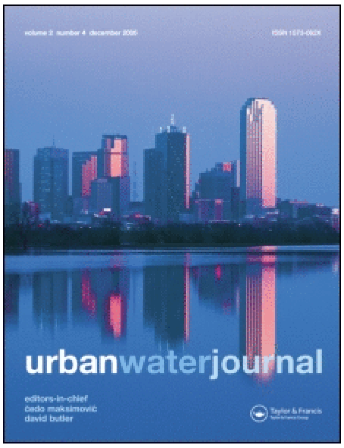

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Fluid transients and pipeline optimization using GA and PSO: the diameter connection

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Fluid transients and pipeline optimization using GA and PSO: the diameter connection

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(*Revised version received June 2004*)

This paper describes the optimal selection of pipe diameters in a network considering steady state and transient analysis in water distribution systems. Two evolutionary approaches, namely genetic algorithms (GA) and particle swarm optimization (PSO), are used as optimization methods to obtain pipe diameters. Both optimization programs, inspired by natural evolution and adaptation, show excellent performance for solving moderately complex real-world problems which are highly nonlinear and demanding. The case study shows that the integration of GA or PSO with a transient analysis technique can improve the search for effective and economical hydraulic protection strategies. This study also shows that not only is the selection of pipe diameters crucially sensitive for the surge protection strategies but also that more global systematic approaches should be involved in water distribution system design, preferably at an early stage in the design process.

Keywords: Optimization; Fluid transients; Water distribution systems

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1. Introduction

Water distribution systems (WDSs) abound throughout the world and vary tremendously in form, function, complexity and cost. The primary purpose of a WDS is to deliver water to individual consumers in the required quantity and quality with a sufficient pressure. A tremendous amount of capital has been, and will be, spent on the design of new WDSs and the rehabilitation of existing networks in both developing and developed countries. The goal of WDS optimization is to obtain the minimum cost of construction, operation, and maintenance while satisfying demands with an adequate residual pressure. Also, the flow of water in a distribution network and the nodal pressure heads must satisfy the governing laws of energy and mass conservation, in addition to prescribed boundary conditions.

Until now, numerous optimization approaches, some general and others specific, have evolved in order to achieve economy of design, construction, operation and maintenance of these systems. However, it suffices to say that most of the pipeline optimization methodology is concerned with the optimization of systems under steady or nearly steady flow conditions. Consideration of transients often takes place after assuming that the cost of controlling transients represents a small portion of the overall pipeline cost. At the same time it is generally recognized that pipe costs constitute, on average, as much as 70% of the total pipeline price, and that wall thickness is a strong determinant of these costs.

There are important feedback mechanisms between the steady and transient portion of an optimized system. The selection of pipe diameter, pipe material and pipe wall thickness strongly influences the nature of the pipeline transient response. Also, the system must deliver sometimes large and sudden fire flows at adequate pressures. While these fire flow demands occur infrequently at the various nodes in the system, they may, however, be the constraining

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factor in the design of some systems. The design procedure should consider the ability of the network to serve fire-fighting demands at all nodes. Even though the occurrence of simultaneous fires at all, or even some, nodes is improbable, there is still a wide range of fire fighting demand patterns to be considered.

Another challenging problem associated with pipeline transients is water quality risk posed by transient intrusion. It was until recently often assumed that the quality of water that entered at one end of a distribution system was essentially equivalent to that leaving at the other; even when transformations are now considered, they are still often analyzed through a steady state lens. However, since all pipeline systems leak and hydraulic transients occur routinely in most distribution systems, it is not surprising that low pressure transient waves present considerable risk of drawing untreated and possibly hazardous water into a pipeline system (Karney 2003). More recently, soil and water samples were collected near drinking water pipelines and then tested for the presence of total and faecal coliforms, *Clostridium perfringens, Bacillus subtilis*, coliphage, and enteric viruses (Karim *et al.* 2003). Indicator microorganisms and enteric viruses were detected in more than 50% of the samples analyzed. The results of this study suggest that during negative- or low-pressure events, microorganisms may directly enter the treated drinking water through pipeline leaks. Therefore, the designer should never overlook the effect of water hammer or surge pressures in the design of WDS and the determination of ultimate system cost. This means that any optimized design which fails to properly account for water hammer effects is likely to be, at best, suboptimal, and, at worst, completely inadequate. Therefore, despite its difficulties, transient analysis is essential for WDS design.

Optimal design of distribution systems has been approached from many angles and using a number of optimization tools. Traditionally, the design of water distribution networks has focused on mathematical approaches including linear, nonlinear, and dynamic programming (Anperovits and Shamir 1977, Bhave 1985, Quindry *et al.* 1981, Schaake and Lai 1969). However, these deterministic methods cannot guarantee a global optimal solution. Also, they require that the functions satisfy certain restrictive conditions (e.g. continuity, differentiability to the second order, etc.) that cannot be generally guaranteed for a WDS. Recently, genetic algorithms (GA) has been a popular optimization choice for solving problems that are difficult for traditional deterministic optimization methods (Goldberg 1989, Simpson *et al.* 1994, Dandy *et al.* 1996, Back *et al.* 1997). The main advantage of such an evolutionary algorithm is its ability to find the global optimum by using function values only. More recently, Kennedy and Eberhart (1995, 2001) developed an evolutionary optimization algorithm which is called a particle swarm optimization (PSO). In this technique, the population of potential solutions is called a "swarm" and it explores the search space rather like a flock birds searching for food. As in the GA approach, there is a global exchange of information between the individuals searching the feasible region. Also, as in GA, the PSO approach is proving to be an efficient algorithm in solving hard optimization engineering problems (Jung and Karney 2004a, 2004b).

The objective of the current paper is to obtain an optimal design of a WDS considering both steady and transient states. As an optimization method, PSO is introduced and compared to GA. A formulation using PSO and GA is developed for the optimal design of WDS and applied to the well-known New York City tunnel problem. Finally, the performance of PSO and GA are compared using a case study.

2. Optimization of pipeline systems

Whether designing a WDS using trial-and-error methods or with formal optimization tools, a broad range of concerns must be considered. Cost is likely to be the primary emphasis and includes the costs for construction, operation and maintenance. The initial capital investment for the system includes pipes, pumps, tanks, and valves. Energy consumption occurs over time as the system is operated. The main constraints are that the demands are supplied at an adequate pressure. Also, the flow of water in a distribution network and nodal pressure heads must satisfy the governing laws of conservation of mass and energy.

In this paper, water distribution network design is formulated as a least-cost optimization problem with pipe diameter selections as the decision variables. In addition to the general constraints, transient analysis is included in order to protect the system from negative transient pressure. The pipe layout, nodal demand, and minimum head requirement are assumed known. The optimization of water distribution networks can be stated mathematically as:

$$\text{minimize } f(D_1, \ldots, D_{N_{pipe}}) = \sum_{k \in N_{pipe}} C_k(D_k, L_k) \qquad (1)$$

Subject to the governing transient equations (Wylie and Streeter 1993)

$$\frac{1}{gA_p}\frac{\partial Q}{\partial t} + \frac{\partial H}{\partial x} + \frac{R}{\Delta x}Q|Q|^{n-1} = 0 \qquad (2)$$

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

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and a set of algebraic constraints:

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

$$f(H_i(t), Q_i(t)) = C_3, \text{ where } t > 0, i = \text{boundary nodes} \quad (5)$$

$$H_i(t) \geq H_{\min i}, \text{ where } t = 0, \ \forall i \in N_{node} \quad (6)$$

$$H_i(t) \geq H_{\text{datum}i}, \text{ where } t > 0, \forall i \in N_{node} \quad (7)$$

$$D_k \in \{D\}, \ \forall k \in N_{pipe} \quad (8)$$

where $D_1, \ldots, D_{Npipe}$ = discrete pipe diameters selected from the set of commercially available pipe sizes $\{D\}$[equation (8)]; $C_k(D_k\ L_k)$ = cost of pipe k with diameter D_k and the length L_k. Equations (2) and (3) represent the momentum equation and mass conservation for transient flow in closed conduits (Wylie and Streeter 1993). x is distance long the centreline of the conduit; t is time; H = piezometric head; Q = fluid discharge; D_p = inside pipe diameter; a = celerity of the shock wave; A_p = cross-sectional area of the pipe; and g = acceleration due to gravity. The friction term in the momentum equation comprises a steady portion and an unsteady portion (Zielke 1968). However, the characterization of unsteady friction is a challenging question and research is still on-going. The implicit assumption is that many fundamental conclusions arising from the study of simpler governing equations have considerable merit for an extended set involving unsteady friction or other higher order effects. Therefore, steady friction is assumed here and represented as

$$\text{Darcy} - \text{Weisbach: } R = f_p \Delta x / 2g D_p A_p^2, \quad (9)$$

$$\text{Hazen Williams: } R = \Delta x / (0.278 C D_p^{2.63})^{1/0.54}, \quad (10)$$

in which f_p = Darcy-Weisbach friction factor; and C = Hazen-Williams roughness coefficient. Two hyperbolic partial differential equations in 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 constants. Initial conditions are typically taken as steady. Simple boundary conditions of constant reservoir level and fixed demand are assumed, but combined relationships between H and Q are typical for most boundaries. Equations (6) and (7) require that the nodal pressure H for any node i (where total number of nodes is N_{node}) is equal to or greater than a pre-specified minimum pressure $H_{\min}$ for steady state and a design datum H_{datum} under transient conditions, respectively.

The remaining and challenging question is how to apply an optimization method to the problem of water distribution optimization. Gradient-based mathematical optimization methods (Anperovits and Shamir 1977, Bhave 1985, Quindry *et al.* 1981) have been widely applied and have provided efficient computation procedures for achieving a lower cost solution but the methods suffered from some disadvantages, such as: (1) being ineffective at reaching the least cost solution due to the zero-gradient optimality criteria, which easily trapped a search process at a local optimal solution: (2) lack of flexibility in handling discrete design variables and optimizing a partial network that is often required for many practical engineering designs: and (3) complexity of implementing and using the technique (Wu and Simpson 2001). Recently, GA has been integrated with hydraulic network solvers for the optimization of WDS (Simpson *et al.* 1994; Dandy *et al.* 1996, Wu and Boulos 2001). It has been shown that the GA is robust for searching optimal combinations of pipe diameters and rehabilitation actions for WDSs. More recently, Ant Colony Optimization (Maier *et al.* 2003) and Shuffled Frog Leaping Algorithm (Eusuff and Lansey 2003) have been introduced for obtaining specific optimal designs of WDSs.

Figure 1 depicts a flowchart of the procedure for optimizing the pipeline system considering both steady state and transient conditions. First, an optimization program initializes the system characteristics like pipe diameters, and then the cost of these choices is calculated. The steady state model analyzes the given system and then

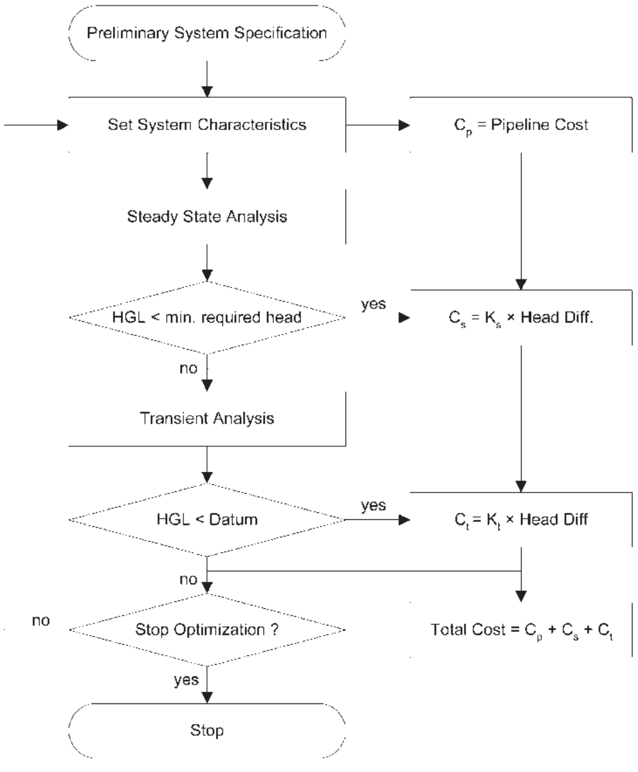

Figure 1. Flowchart of pipeline optimization.

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uses the optimization program to check if the solution satisfies the minimum allowable total head. Similarly, the transient program checks the system to consider whether or not negative pressures occur in the system. The procedure calculates the pipe cost and violation penalty cost for steady and transient head deficits. With the total cost, the optimization method evaluates the system and creates a new set of system alternatives for the next iteration.

Transient analysis is a complex topic and no attempt has been made here to be comprehensive. There are numerous techniques for controlling transients in water distribution systems. Design considerations influencing transients include strengthening the pipe (e.g. increasing its pressure rating), re-routing pipelines, using larger diameter pipes (lowering the pipeline velocity), changes in the pipe material, or strategic changes in system topology. Operational considerations like adjusting opening and closing times, increasing pump inertia (addition of a flywheel in prolonged pump run down) can modify the transients directly. Also, surge control devices can be directly employed including relief valves, check valves, bypass components, surge tanks and air chambers. Such additional protection devices permit fluid to be drawn into, or expelled from, the piping system in order to reduce the rate of flow changes. At present, selection among these kinds of approaches is difficult, thus this paper focuses on initial system design, specifically regarding the selection of pipe diameters.

3. Transient analysis in pipeline systems

The pressure fluctuations created by a flow disturbance in a closed conduit propagate as a pulse wave throughout the pipe. If the friction force is modelled by the steady state Darcy–Weisbach equation, the resulting momentum and continuity equations are presented in equations (2) and (3). They are nonlinear hyperbolic partial differential equations and a general analytical solution to them is not available; however, the governing equations can be transformed by the method of characteristics (MOC) into two pairs of ordinary differential equations. The transformed equations can be integrated to yield finite difference equations, which are conveniently handled numerically. Despite their convenience, MOC-based techniques entail a computational shortcoming that the two ordinary differential equations are valid only on the characteristics line, described by $dx/dt = \pm a$.

A pipe comprises one or more basic computational units with possibly uneven lengths Δx. A single long pipe is often viewed as a simple network with several computational units connected in series. The time step Δt is chosen as the shortest wave travel time in all of the computational units. The Courant number of the computational unit with wave speed a is $C_r = a\Delta t/\Delta x$. If either the Courant number is not unity or the wave transmission time in the two computational units is different, the resulting characteristic lines do not meet at a space-time mesh, and some interpolation between them becomes necessary. Thus, a primary disadvantage of the method of characteristics is that it requires interpolation or adjustment between points in the $x-t$ plane when the wave travel time in all computational units is not an integer multiple of the time step Δt. Since interpolation introduces errors to the solution at each calculation step, a good choice of discretization approach is crucial to a reliable transient analysis. There are various kinds of interpolations ranging from linear to higher order. Generally, higher order interpolations would be expected to yield greater accuracy in the sense that they may describe many variations better than the linear counterparts, but they require more computation time. Also, Ghidaoui and Karney (1994) have pointed out that all interpolation schemes involve a numeric alteration of the wave speed plus a diffusion of the true values and higher-order methods that involve more and more nodal points essentially increase the physical distortion of the problem. They recommend that the only way of achieving accurate, general solutions for hyperbolic equations is to keep the time step small and the Courant number as close to one as possible. In this paper, linear timeline interpolation is employed. If the characteristic is extended backward from the unknown time level $n + 1$ (node P in figure 2) to intersect a known timeline at point A, the interpolation can be done along that line between nodes (n-1, i-1) and (n, i-1) for the head value at A as

$$h_A = \frac{\tau}{\Delta t} h_{i-1}^{n-1} + \frac{\Delta t - \tau}{\Delta t} h_{i-1}^{n} \tag{11}$$

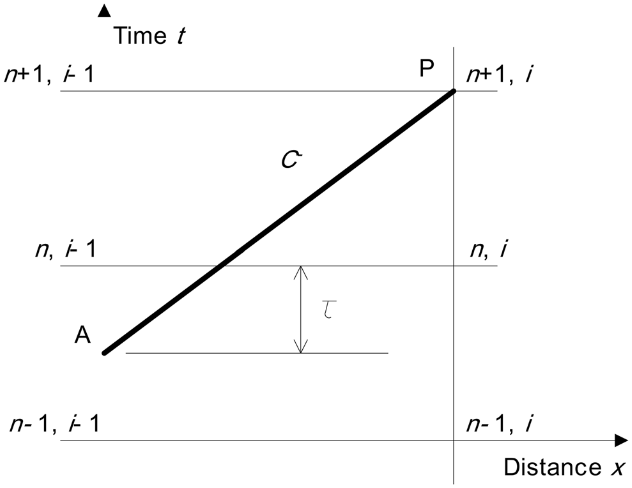

Figure 2. Characteristic line of linear timeline interpolation.

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4. Evolutionary computation

Evolutionary Computation (EC) algorithms provide solutions to many hard optimization problems that would be difficult to cope with using the traditional gradient based methods, due to the possibility of discontinuities in the search space, non-differentiable objective functions, imprecise arguments and function values (Back *et al.* 1997). The main advantage of EC algorithms is the usage of a population of potential solutions to explore the search space simultaneously, exchanging information among trial solutions and using only objective function values (and not its derivatives).

4.1 *GA approach*

The most well-known and widely applied paradigm of EC algorithms is the GA. According to GA theory, the population is binary encoded and genetic operators, inspired by biological DNA evolution procedures, are applied to the population in order to evolve it and thus explore the search space efficiently (Goldberg 1989). The GA approach does not require certain restrictive conditions (e.g. continuity, differentiability to the second order, etc.) that can seldom be guaranteed for water distribution problems, particular under transient states.

4.2 *Particle swarm approach*

Recently, a new research field, called Swarm Intelligence (SI), has arisen. SI argues that intelligent human cognition derives from the interaction of individuals in a social environment and that the main ideas of socio-cognition can be effectively applied to develop stable and efficient algorithms for optimization tasks (Kennedy and Eberhart 2001) . The particle swarm optimization (PSO) technique is an SI technique, which is mainly used for continuous optimization tasks and has been originally developed by Kennedy and Eberhart (1995). In this technique, the population of potential solutions is called a ‘‘swarm’’ and it explores the search space by simulating the movement of a flock of birds searching for food. There is a global exchange of information among all individuals, which are called ‘‘particles’’, and each particle can profit from the discoveries of the rest of the swarm. PSO has been shown to be efficient in solving hard optimization problems and engineering applications, including neural networks training and Human Tremor analysis (Kennedy and Eberhart 2001). Many variants and techniques have been developed to improve further its performance.

In this paper, a version of the algorithm derived by adding an inertia weight to the original PSO dynamics has been used (Shi and Eberhart 1998). Assuming that the search space is D-dimensional, we denote by $X_i = (x_{i1}, x_{i2}, \ldots, x_{iD})$ the ith particle of the swarm and by $P_i = (p_{i1}, p_{i2}, \ldots, p_{iD})$ the best position this individual ever achieved within the search space. Let g be the index of the best particle in the swarm and $V_i = (v_{i1}, v_{i2}, \ldots, v_{iD})$ the velocity (position change) of the ith particle. The swarm is manipulated according to the equations.

$$v_{id} = wv_{id} + c_1 r_1 (p_{id} - x_{id}) + c_2 r_2 (p_{gd} - x_{id}) \tag{12}$$

$$x_{id} = x_{id} + v_{id} \tag{13}$$

where $d = 1,2,\ldots,D$; $i = 1,2,\ldots,N$ and N is the size of the population; w is the inertia weight; c_1 and c_2 are two positive constants; r_1 and r_2 are two random values into the range [0,1]. Equation (12) is used to calculate the ith particle's new velocity, taking into consideration three main terms: the particle's previous velocity, the distance of the particle's current position from its own best position, and the distance of the particle's current position from the swarm's best experience (position of the best particle). Then, the particle moves to a new position according to equation (13). The performance of each particle is measured using a predefined fitness function. The inertia weight w plays an important role for the convergence behaviour of the technique. It is used to control the impact of the previous history of velocities to the current velocity of each particle, regulating in this way the trade-off between the global and local exploration abilities of the swarm, since large values of w facilitate global exploration of the search space (visiting new regions) while small values facilitate local exploration (i.e. fine-tuning the current search area). The initialization of the swarm is done using a uniform distribution over the search space. By gradually decreasing the inertia weight from a relatively large value to a small value through the course of the PSO run, the PSO tends to have more global search ability at the beginning of the run while having more local search ability near the end of the run.

The goal of the paper is to develop a reasonably comprehensive pipeline optimization model using GA and PSO, considering both transient and steady states. Figure 3 shows the composition of an optimal hydraulic device model. As a decision variable, pipe diameters in the system are selected in a GA and PSO program, the hydraulic model then analyzes the pipeline system with the given set of specified pipe diameters.

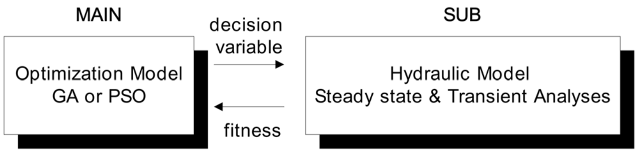

Figure 3. Optimization of hydraulic device in pipeline system.

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5. Case study: the New York City water supply tunnels problem

The case study is based on the well-known New York water supply tunnels. The case study network shown in figure 4 has been extensively studied for steady state conditions. The profile comprises 20 nodes, 21 pipes, one source, and 20 demand nodes. The system is a gravity driven and draws water from the reservoir to a downstream network. The purpose of the optimization is to identify pipes for installation in parallel with the existing 21 pipes to ensure that adequate pressure head is supplied as the demands are increased to a predefined level determined by population growth. A single demand pattern (2017.5 ft^3/s or 57 130 l/s) was considered for the improved tunnel system, and a corresponding minimum allowable total head and consumption were specified at each node. Details of the demand pattern and minimum head constraints are given in Dandy *et al.* (1996). The example is presented in traditional units since this is how it has appeared in previous works.

Since the system was first examined in 1969 by Schaake and Lai, numerous subsequent researchers have used it to demonstrate the capability of their respective techniques (Gessler 1982, Morgan and Goulter 1985, Dandy *et al.* 1996, Savic and Walter 1997, Lippai and Heaney 1999, Eusuff and Lansey 2003, Maier *et al.* 2003). However, these approaches for the NYC system focused on steady state optimization only. In this paper, not only the steady state problem is considered like previous approaches, but also the transient analysis is included in the optimization process. By doing so, it is shown that different decisions would be made, and the restrictive search based on limited operating conditions is likely suboptimal for a broader range of loadings.

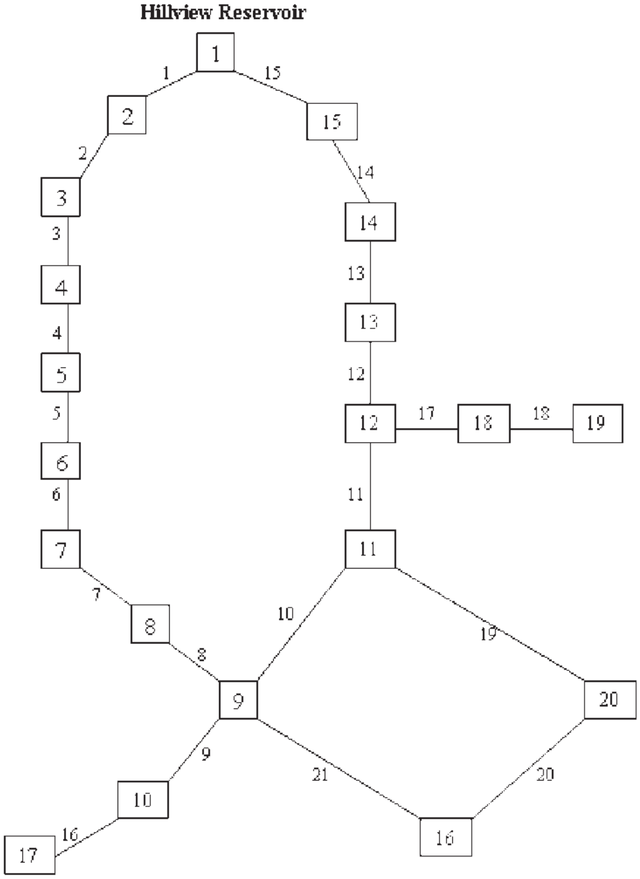
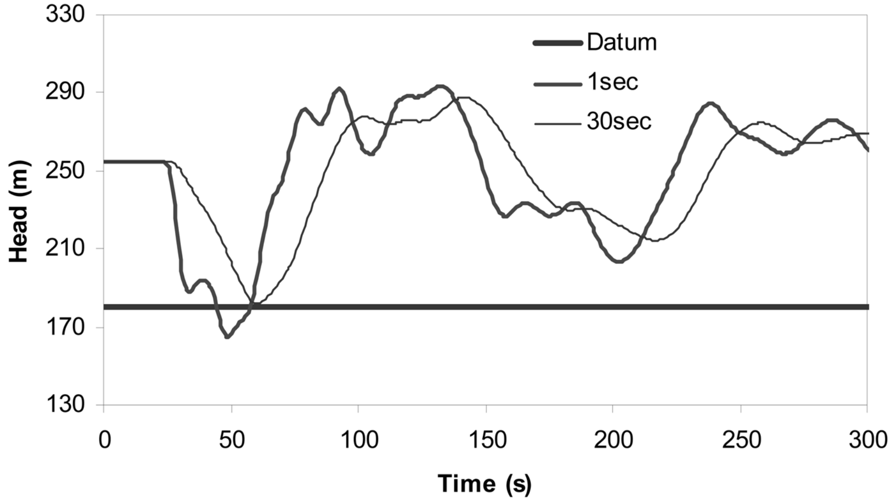


Figure 4. New York City water supply tunnels.

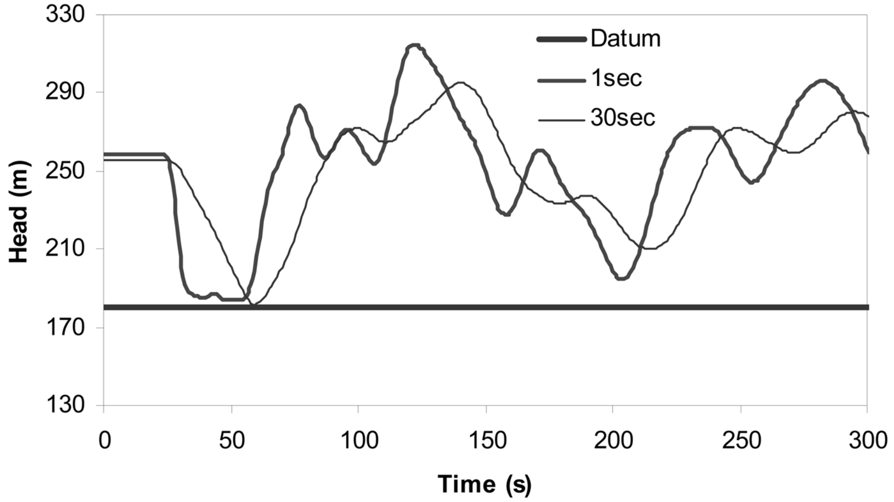
To introduce transient conditions into this case study, a variety of possible causes could be selected. For convenience, a valve opening to increase demand at node 10 (1 ft^3/s to 170 ft^3/s; 28 l/s to 4814 l/s) is chosen to characterize the transient performance of the system. In order to consider the severity of transients, two different valve opening times (1 and 30 s) are used here. This increased demand may represent a fire flow, a pipe burst, an operator error or temporary increased water consumption. The datum is assumed to be 180 ft for the whole system. Due to the demand increase at node 10, a reduced pressure wave moves through the system. This wave is reflected from the upstream reservoir and then propagates back and forth in the system, being tracked numerically using the method of characteristics. The different pipe lengths and sizes in the system create uneven computational lengths in the characteristic grids. The smallest Courant number in the system is 0.019 and it can be adjusted to unity by dividing the pipe into smaller computational units. The process of discretization is repeated until the smallest Courant number exceeds 0.75. After the discretization, the smallest Courant number and the computational time step are 0.755 and 1.11 s, respectively. For the uneven computational units, a linear timeline interpolation is used to obtain head and flow at a grid point in the characteristic mesh.

A typical goal of transient design, and the one specifically adopted here, is to keep the minimum pressure above the pipeline profile in order to avoid negative pressures. Based on the steady state optimization result of Maier *et al.* (2003), figure 5(a) shows the transient response in the system at node 19. It is not surprising that the optimal steady state solution does not satisfy the transient criterion, allowing the negative pressures to appear in the system. Negative pressure may cause the collapse of thin-walled pipes or reinforced concrete sections. It might also cause the backflow of dirty water (pathogen intrusion) into the distribution system through pipeline leaks (Karney 2003, Karim *et al.* 2003).

There are many strategies to protect a system from transient events. These range from direct control approaches such as adjusting the operation speed and modifying the system characteristics (system layout, pipe size, material and thickness) to the use of specialized surge



(a) Before optimization



(b) After optimization

Figure 5. Head trace at node 19.

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control devices. However, these systematic and global approaches are not considered here as this paper focuses on pipe diameters which are consistent with previous steady state optimizations. Also, the issue of operating speed for surge protection is given some attention. Altering the pipe diameter changes the velocity for a given flow rate. If the diameter is increased uniformly along a line, the resulting decrease in the velocity will reduce the magnitude of the initial pressure wave and the transient performance of a piping system can be improved. Since in the Joukowsky equation (14) the head change is directly proportional to velocity change, doubling the diameter reduces the magnitude of pressure fluctuations by a factor of about 4.

$$\Delta H = \frac{a}{g}\Delta V = \frac{a}{gA_p}\Delta Q \tag{14}$$

The two optimization methods, GA and PSO are considered to satisfy equations (1)–(8). In the GA, the probability of mutation is 0.02, the probability of (uniform) crossover is 0.5, the population size is 500, and simulations are run for 200 generations. Tournament selection and

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elitism (in which the best individual is copied to the next generation) are selected. The number of available pipe diameters is 16 (2^4) and the number of pipelines is 21 so the length of each chromosome is selected as 84. In the PSO, the population size and the maximum velocity are 500 and 3, respectively. From an empirical study of PSO (Shi and Eberhart 1999), a linearly decreasing inertia weight is used which starts at 0.9 and ends at 0.4, with $c_1 = 2$ and $c_2 = 2$. As in GA, a total of 200 runs for each experimental setting are conducted. The procedural flowchart for optimizing the pipeline system considering both steady and transient states is shown in figure 1. GA and PSO initialize the population about pipe diameters, and then calculate the cost of pipelines and the violation penalty cost for steady and transient head deficits. With the total cost, GA and PSO evaluate the fitness of the individual in the population and create a new population for the next generation.

During the simulation, nominally infeasible GA or PSO designs demonstrate substantial cost savings with some small violations of pressure head constraints. Infeasibility may be acceptable in some circumstances, particularly if a small hydraulic deficiency is accompanied by a large cost saving. The pressure violation penalty multipliers K_s and K_t are introduced to penalize a hydraulic grade line violation per foot of pressure head deficit for the steady state and transient analysis, respectively. The total head at all nodes is compared with the minimum allowable total head in steady analysis and the design datum in transient analysis. The selected values of penalty multipliers are important to find the near-optimal infeasible solutions. Generally, trial and error adjustment of the pressure violation penalty multiplier is necessary. In this paper, the penalty value (K = \$5.0 million/foot) of Dandy *et al.* (1996) is used for both the steady and transient analysis.

Table 1 presents the GA and PSO optimization results and shows each optimal pipe system for different transients. The pipe costs of GA and PSO optimizations considering transients is more expensive than that of the Maier *et al.* (2003) steady state design (\$38.64 million), but they ensure a greater capacity to safeguard against negative pressures than the optimal solutions of other studies focusing exclusively on steady state considerations. It also demonstrated, as one would expect, that the total costs of GA and PSO approach the steady state cost as the severity of the transients diminishes. Figure 6 depicts the evolutionary procedures of GA and PSO to find the optimal pipe size considering demand increases at node 10 for 1 and 30 s. Both optimization results show the convergence speed is fast for the first 20 s but become slow to converge to optimized pipe sizes. In this numerical test, PSO exhibits a faster convergence but produces a slightly less optimal result than GA. Figure 5(b) shows the head trace considering transient optimization design at node 19. Compared to figure 5(a), the transient responses are mild and no negative pressures appeared at node 19. Different random seed values would almost certainly generate at least some variation in these results. In total, over 100 000 transient simulations were executed to obtain results for this analysis.

Table 1. Optimization result considering transient.

	Pipe diameter, inches			
	GA		PSO	
Pipe	1 s	30 s	1 s	30 s
1, 2, 3, 4, 5, 6	–	–	–	–
7	108	120	–	–
8	–	–	–	–
9	144	–	144	–
10, 11, 12, 13, 14	–	–	–	–
15	–	–	–	120
16	108	96	108	84
17	120	108	120	96
18	72	72	72	96
19	84	84	84	72
20	–	–	–	–
21	72	72	72	72
Pipe cost (\$ million)	46.14	38.72	42.64	39.97
Steady head deficiency	0.02	0.25	0.77	0.02
Transient head deficiency	0	0	0	0
Total cost (\$ million)	46.27	39.97	46.49	40.06

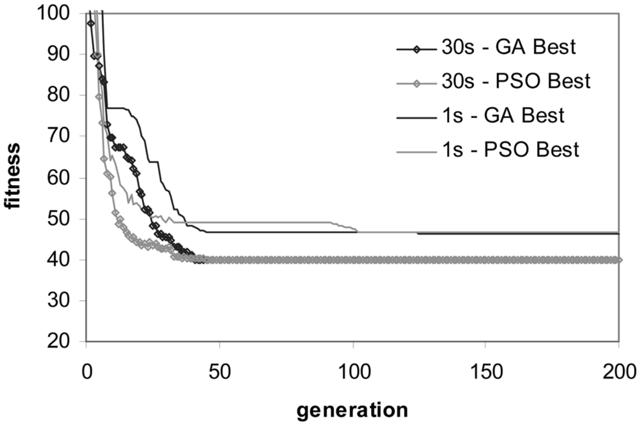

Figure 6. Evolutionary procedure for 1 s and 30 s demand increase.

5.1 *Discussion*

Fluid transient analysis is one of the more challenging and complicated flow problems in the design and operation of a WDS. Even though there are many strategies from system design and operational consideration to surge control devices, the complexities of transient analysis render the systematic approaches difficult. This case study focuses on

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a particular pipeline optimization problem that considers a small set of transient results. While the surge protection strategy of this study is limited, several interesting and specific observations arise from it:

1. Various kinds of transient protection methodologies may be implemented for specific purposes. Generally, pipe diameter is selected first based on steady state design considerations, and then surge protection devices are included in the system. However, this simplified design construction is not only expensive, but also can not take into account the specific system characteristics due to transients; in fact, such an approach may make the response worse. Initial system design for surge protection is the first effective way to remove or, at least, relieve surge damage. This paper focuses on system design considerations, more specifically the selection of pipe diameters.
2. This study of pipeline optimization follows previous investigations in using pipe diameter as a decision variable, but differs by including transient considerations in the optimization procedure. The objective of transient analysis in the case study was to keep the minimum pressure above the pipeline to avoid negative pressure. The Joukowsky equation indicates that the selection of pipe diameters is clearly sensitive to the system design for transient and steady state. Interestingly, the total cost of transient design for the 30 s valve opening in the case study ($39.97 million) is closer to the cost of the Maier *et al.* (2003) steady state design ($38.64 million), which indicates that the initial system design for surge protection is crucially important in reducing cost in addition to curtailing surge damage.
3. One of the other strategies to prevent water hammer is to take into account system operation like adjusting valve opening and closing times. Steady state system designs can be vulnerable in the case of rapid transients (e.g. sudden valve closure). In this study, two transients (valve opening at node 10 for 1 and 30 s) are introduced to compare the degree of transient severity. The total cost of transient analysis is more expensive than the steady state design of Maier *et al.* (2003) since negative pressures are disallowed in the system. However, the cost of the transient analysis converges to the cost reported in Maier *et al.* (2003) as the valve opening time increases. It also indicates that a successful transient design might be obtained by adjusting operating speed without changing the system characteristics.
4. Two optimization methods, GA and PSO, are applied to minimize the total cost considering steady state and transient design in the pipeline system. Both programs are population-based stochastic optimization approaches and show similar evolution in their quest to obtain the optimal pipe diameters. After 50 generations, both show similar optimal results with respect to total cost. The GA shows a slightly better total cost while the PSO converges more quickly. It is difficult to say categorically which one performs better since each optimization method has its own characteristics; however, when each algorithm has the same population size and number of iterations, PSO performed as well as the GA in this test. The role of the random seed also influences evaluations for individual studies.
5. The infeasible GA and PSO designs in table 1 demonstrate substantial cost savings for some small violations of the pressure head constraints. In the case studies with GA and PSO, slightly infeasible steady state designs that violate the minimum allowable total head are tolerated in this system, while no transient head violations are permitted. It may indicate that the transient constraints are more important than those for steady state and that the infeasibility of the steady state design is acceptable if large cost savings are realized.
6. Although this paper is limited to the selection of pipe diameters for surge protection, there are many other design criteria like system topography, pipe material, pipe thickness, surge protection devices selection and location. Also, the design of water distribution networks needs to achieve several other objectives in order to minimize operating cost and risks and to maximize reliability and water quality. The goal is to find the best solution, which corresponds to minimum or maximum values of a single objective function that lumps all different objectives into one. Usually, it is not possible to improve on one objective without making the other objective worse. Therefore, a multi-objective decision support structure should be attempted for the ultimate goal of WDS design.

6. Conclusions

Transient fluid analysis is a complicated problem and so is the optimization of a transient control strategy for water distribution systems. The purpose of this paper is to obtain the optimal design of a pipe network considering both steady and transient states. Two global optimization methods, genetic algorithms (GA) and particle swarm optimization (PSO), are employed to find optimal pipe diameters in a system with allowance for water hammer conditions. In this application, both approaches exhibit similar evolution histories and optimal results. The case study of the New York City tunnels problem shows that the previous approaches considering steady state design only are inadequate for coping with water hammer events. Therefore, the proper sizing of pipe diameters to prevent water hammer is highly dependent on the transient

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conditions encountered and the other specific characteristics of the system being studied. The optimal selection of pipe diameter is not only crucial to system performance and reliability, but also effective in decreasing costs. Although this paper introduces the optimal selection of pipe diameters for a surge protection strategy, a more global and comprehensive approach is ultimately necessary. System optimization should also consider the transient properties (operation speed), system characteristics (system topography, pipe material and thickness) and transient protection devices, in addition to pipe size. That would offer a more complete range of systematic surge protection strategies.

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