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OPTIMUM SELECTION OF HYDRAULIC DEVICES FOR WATER HAMMER CONTROL IN THE PIPELINE SYSTEMS USING GENETIC ALGORITHM

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ABSTRACT

Genetic algorithms have been used to solve many water distribution system optimization problems, but have generally been limited to steady state or quasi-steady state optimization. However, transient events within pipe system are inevitable and the effect of water hammer should not be overlooked. The purpose of this paper is to optimize the selection, sizing and placement of hydraulic devices in a pipeline system considering its transient response. A global optimal solution using genetic algorithm suggests optimal size, location and number of hydraulic devices to cope with water hammer. This study shows that the integration of a genetic algorithm code with a transient simulator can improve both the design and the response of a pipe network. This study also shows that the selection of optimum protection strategy is an integrated problem, involving consideration of loading condition, device and system characteristics, and protection strategy. Simpler transient control systems are often found to outperform more complex ones.

INTRODUCTION

Distribution networks are an essential part of all water supply systems. The construction and maintenance of these pipeline systems cost many millions of dollars every year. Traditionally, optimization processes have focused on steady (or nearly steady) state conditions. Even though this preoccupation in most water supply projects is understandable, transient phenomena are themselves unavoidable and often crucial to system performance and reliability. Despite their intrinsic importance, transient considerations have frequently been ignored or relegated to a secondary role when supply systems are designed or constructed.

In order to protect a system from the impact of water hammer, various kinds of strategies are commonly suggested. Protection approaches range from installing specialized devices such as relief and reducing valves, air chambers and tanks to the selection of pipe properties and the modification of operational procedures. However, the selection, installation and operation of these hydraulic devices strongly depend on the specifics of the particular pipe system as well as on the experience/comfort of the designer/operator with the various approaches. Unfortunately, systematic exploration of such alternatives has been impractical in the past due to inherent computational challenges, due both to the analysis burden of individual options and due to the multi-dimensional nature of the search space. However, improved algorithms and faster computers have been gradually changing this situation, making the optimal determination of protection devices (position, size, and device characteristics) a more pressing and practical problem.

In this research, the optimum design of hydraulic devices in water distribution systems is considered. The genetic algorithm approach is used to obtain an optimal selection of hydraulic devices taking into account water hammer events in the system. The paper shows not only that the proper water hammer protection approach is important to relieve water hammer, but that the selection of even basic pipe properties such as diameter can be influenced by transient considerations. In other words, system operation and design form an integrated system of interdependent components.

PIPELINE OPTIMIZATION CONSIDERING TRANSIENTS

Traditionally pipeline optimization has been addressed using steady state optimization techniques. There are a wide variety of optimization techniques available to address the steady state behaviors of a distribution system. These methods range from linear and dynamic programming to the use of genetic algorithms. Linear programming [1] and nonlinear programming [2] have all been suggested to optimize components sizing and operational decisions for water distribution systems. Simpson et al. [3] compared genetic algorithms with complete enumeration and nonlinear programming in pipeline optimization.

Although these methods address many of the requirements of the general steady state optimization problem, they fail to acknowledge, or at least to directly consider, the transient component. Despite the intrinsic importance of water hammer events, only a few optimization approaches have been developed to account for transients [4, 5]. One successful approach for a simple pipeline was developed by Laine and Karney [6]. A complete enumeration scheme, as well as a probabilistic selection procedure, was developed to simulate and incorporate both transient and steady state concerns. This comprehensive optimization approach was explored through a case study involving a simple pipeline connecting a pump station to a storage reservoir. As here, simulations are performed using standard MOC formulations.

GENETIC ALGORITHMS FOR PIPELINE OPTIMIZATION

In the now well-known Genetic Algorithm (GA), the population is encoded as a binary string and genetic operators, inspired by biological evolution, are applied to the population in order to efficiently explore the search space. Compared to traditional gradient-based methods, the GA approach is less restrictive (e.g., continuity, differentiability to the second order, etc. are not required); such conditions can seldom be guaranteed in water distribution problems, particularly under transient states. In fact, the GA approach makes it possible to find global solutions to many hard optimization problems [7].

Since 1990 or so, a number of researchers have applied the GA technique to distribution system optimization. A relatively comprehensive approach for the use of genetic algorithms for steady state pipe network optimization has been developed [3, 8, 9]. The goal of this paper is to develop a comprehensive hydraulic device optimization model using GAs, considering transient conditions. Figure 1 shows conceptually the composition of the optimal hydraulic device model. As decision variables, the size, location and number of hydraulic devices are selected in GA program, and a transient simulation program analyzes the pipeline system with its associated hydraulic devices.

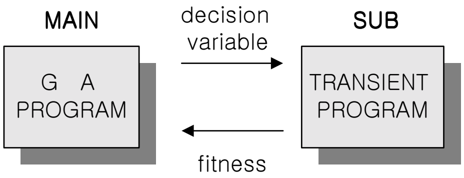


Fig. 1 Optimization of hydraulic device in pipeline system

In order to obtain an optimum selection of hydraulic devices for water hammer control, Carroll's [10] Genetic Algorithm is applied. Specifically, the probability of mutation is 0.02, the probability of (uniform) crossover is 0.5, the population size is 20, the length of each chromosome is 30, and simulations are run for 50 generations. Tournament selection and elitism (in which the best individual is copied to the next generation) are selected. To focus the discussion, a specific example system is used.

CASE STUDY

The network for the case study is shown in Figure 2. The system comprises three reservoirs at nodes 1, 6, and 16, twenty nine nodes, twenty-three pipes, and four valves. This is a gravity flow system that draws water from the higher reservoir to the downstream network. Three 0.3 m^3/s demands at nodes 3, 14 and 23, and one 0.2 m^3/s demand at node 17 are assumed for the specific case considered here. The length, diameter, Darcy-Weisbach (D.W.) friction factor and wave speed of the pipes are given in Table 1.

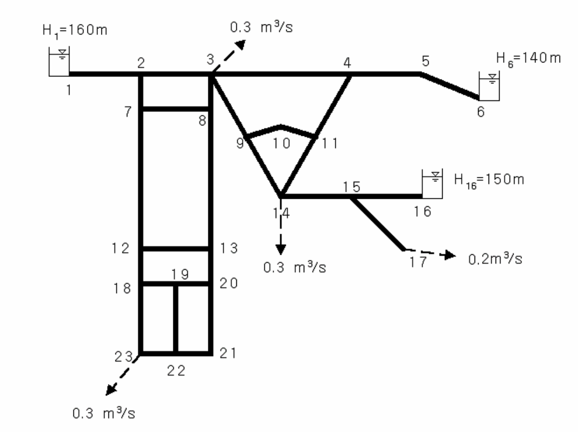


Fig. 2 Pipe network

Table 1 Pipe profile data

Pipe no.	Upst. node	Dnst. node	Len. (m)	Dia. (m)	D. W. fric. factor	Wave speed (m/s)
1	1	2	200	0.5	0.04	1000
2	2	3	200	0.5	0.04	1000
3	3	4	400	0.5	0.04	1000
4	4	5	200	0.5	0.04	1000
5	5	6	200	0.5	0.04	1000
6	2	7	100	0.5	0.04	1000
7	7	8	200	0.5	0.04	1000
8	3	8	100	0.5	0.04	1000
9	3	9	200	0.5	0.04	1000
10	9	10	100	0.5	0.04	1000
11	10	11	100	0.5	0.04	1000
12	4	11	200	0.5	0.04	1000
13	9	14	200	0.5	0.04	1000
14	11	14	200	0.5	0.04	1000
15	14	15	200	0.5	0.04	1000
16	15	16	200	0.5	0.04	1000
17	15	17	200	0.5	0.04	1000
18	7	12	400	0.5	0.04	1000
19	8	13	400	0.5	0.04	1000
20	12	13	200	0.5	0.04	1000
21	12	18	100	0.5	0.04	1000
22	13	20	100	0.5	0.04	1000
23	18	19	100	0.5	0.04	1000
24	19	20	100	0.5	0.04	1000
25	20	21	200	0.5	0.04	1000
26	19	22	200	0.5	0.04	1000
27	18	23	200	0.5	0.04	1000
28	21	22	100	0.5	0.04	1000
29	22	23	100	0.5	0.04	1000

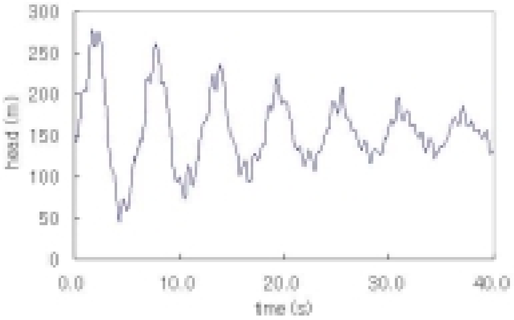


Fig. 3 Head trace at node 21

In order to introduce transient conditions into the case study, a variety of possible causes could be selected. For convenience, a rapid closure of a valve at nodes 3, 14 and 23 in half a second is chosen to characterize the transient performance of the system. Without any protection devices, the maximum pressure head (278.02 m) is generated at node 21 at 1.7 s and the minimum pressure head (45.7 m) is generated at node 21 at 4.3 s after the flow stoppage. Fig.3 shows the head trace of node 21 without any surge control devices; the rapid head increase in the beginning of the transient due to the rapid valve closure is obvious in the plot.

To demonstrate the interrelated character of the transient problem, several specific combinations of surge control devices and objective functions are explored and compared.

Case 1 – Two surge tanks

As hydraulic devices, two surge tanks are considered to relieve the water hammer. The diameter of the surge tanks is 3 m and the length, Darcy friction factor, and diameter of the connector are 30 m, 0.04, and 0.1 m, respectively. The objective function of the genetic algorithm is to minimize the maximum head (Fig. 4(a)) and, in a second run, to maximize

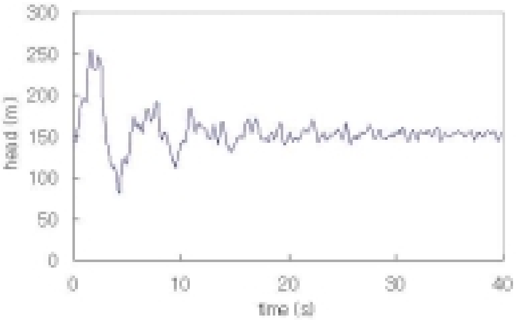
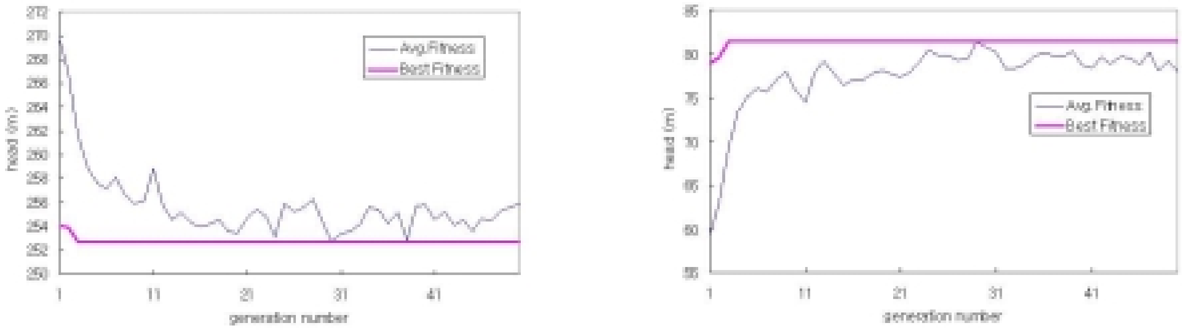
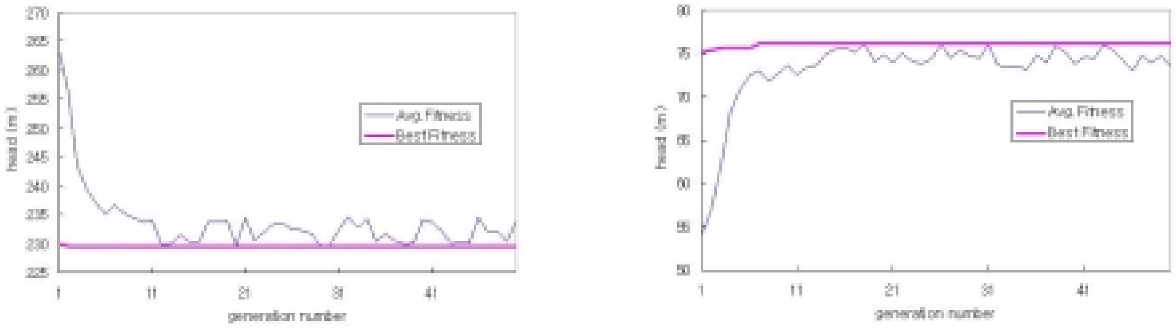


Fig. 5 Head trace at node 21 with two surge tanks



(a) (b)

Fig. 4 Evolution procedure of two surge tanks



(a) (b)

Fig. 6 Evolution procedure of one PRV and one surge tank the minimum head (Fig. 4(b)) in the system. After 50 generations, the optimal locations of the two surge tanks for both objectives are nodes 21 and 22, and the minimized maximum head is 252.8 m and the maximized minimum head is 81.5 m. The resulting nodal trace in Fig. 5 shows a significant 'quieting' of the transient response and visually demonstrates the effectiveness of surge tanks as a surge control strategy. However, such tanks are expensive, and it is often cheaper to use pressure relief valves (PRVs).

Case 2 – One surge tank and one PRV

The basic system is the same as case 1 except that one surge tank and one PRV replace the two surge tanks of case 1. The PRV operation or activation head is set at 180 m and the full opening area of PRV is 0.01 m^2 and the opening and closing time are 2 s and 30 s, respectively. Fig 6(a) and Fig 6(b) show the evolution procedure to minimize the maximum head and to maximize the minimum head in the system. After 50 generations, the optimal locations of the PRV and surge tank to minimize the maximum head are nodes 22 and 13, and the minimized maximum head is 229.5 m. The optimal locations of the PRV and surge tank to maximize the minimum head are nodes 22 and 18, and the maximized minimum head is 76.2 m. Interestingly, the response at node 21 (Fig. 7) clearly shows that not only is the transient improved from the no protection case, but that the response is actually better than for the "two surge tank" solution.

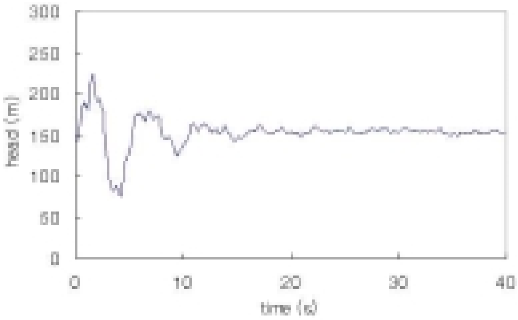


Fig. 7 Head trace at node 21 with one PRV (node 22) and one surge tank (node 13)

Case 3 – Three PRVs

In this case, to avoid the complication and investment of the surge tank, protection is provided by three PRVs only. The size and operation of each PRV is same as that of case 2. The objective function of the genetic algorithm is to minimize the difference between the maximum head and minimum head in the system. Fig. 8 shows the evolution procedure to minimize the difference and the minimum difference is 170.5 m. The optimal solution with up to three PRVs is, in fact, to have only one at node 21; the maximum head and minimum head are 234.2 m and 63.7 m, respectively. The response at node 21 is shown in Fig. 9 and indicates a less severe (improved) transient response compared with the no protection case. This solution is slightly less effective that the one involving surge tanks and PRVs.

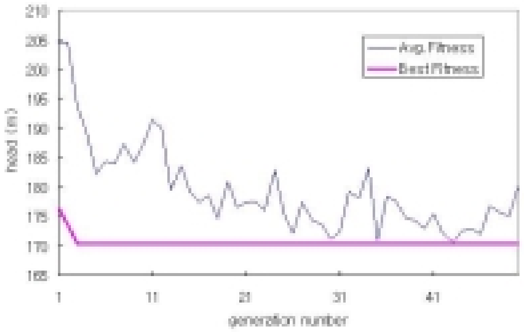


Fig. 8 Evolution procedure of three PRVs

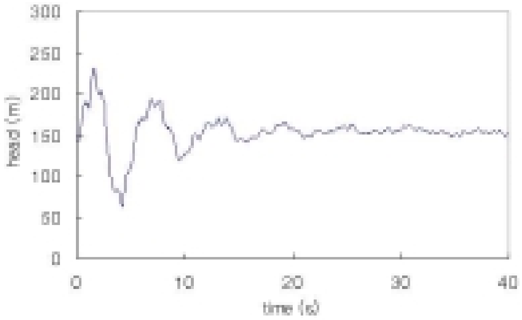


Fig. 9 Head trace at node 21 with one PRV (node 21)

Case 4 – Two large PRVs and two small PRVs

Two kinds of PRV are considered in this test. The full opening areas of the large and small PRVs are 0.02 m^2 and 0.005 m^2, respectively. Fig. 10 shows the evolution procedure to minimize the difference between the maximum head and minimum head in the system and the minimum difference is 173.7 m. The optimal location of four PRVs is node 22 with one large PRV only and the maximum head and minimum head are 229.3 m and 55.6 m, respectively. The nodal response at node 21 in Fig. 11 shows the effectively controlled head trace with one large PRV at node 22.

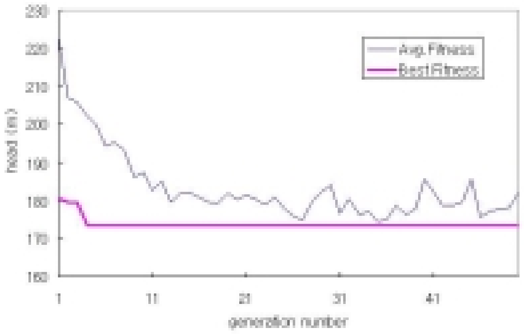


Fig. 10 Evolution procedure of two large PRVs and small PRVs

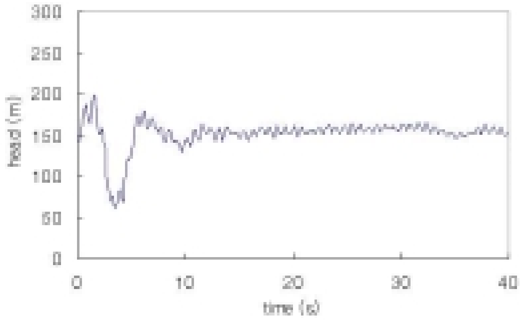


Fig. 11 Head trace at node 21 with one large PRV (node 22)

Case 5 – Two large PRVs and two small PRVs with milder transient event

One of the challenges of surge analysis is to select an appropriate design event (or events). Up until now, we have used a simple and quite severe surge loading associated with simultaneously and suddenly arresting demand. What impact would it make if this initiating event were better controlled?

The test condition is still the same as in case 4 except that a slow closing of the valve at node 23 in 3 seconds instead of a rapid closing is chosen to characterize the transient performance of the system. Fig. 12 shows the head trace at node 21 without any surge control device. It shows a gradual and smooth head increase compared with rapid valve closure. The maximum and minimum head without four PRVs are 194.70 m at 2.8 s (node 23) and 114.8 m at 6.0 s (node 21). Fig. 13 shows the evolution procedure to minimize the difference between the maximum head and minimum head in the system and the minimum difference is 74.3 m. The optimal location of four PRVs is node 22 with one small PRV only and the maximum head and minimum head are 184.2 m and 109.9 m, respectively. The nodal trace in Fig. 14 shows a further attenuated response, indicating the more subdued nature of the system's reaction to the milder event.

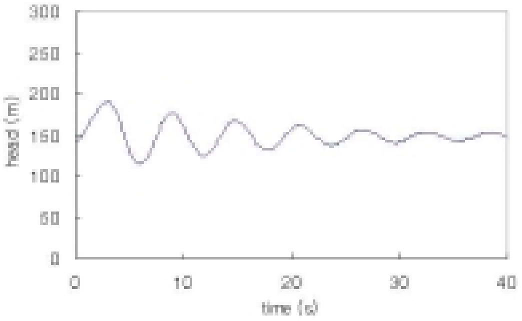


Fig. 12 Head trace at node 21 with slow transient

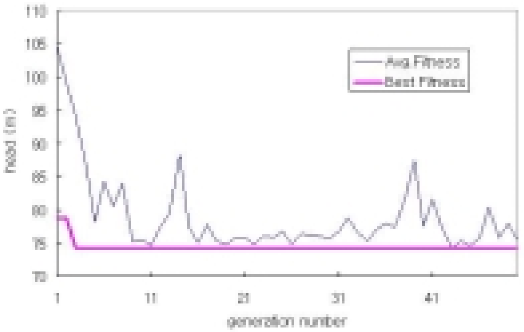


Fig. 13 Evolution procedure in the slow transient

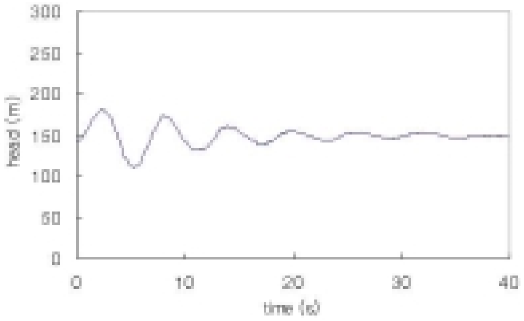


Fig. 14 Head trace at node 21 with one small PRV (node 22)

OUTCOMES AND DISCUSSION

Surge analysis is a complex topic and no attempt has been made here to be comprehensive. Clearly a more global approach would couple an economic evaluation of the protection system (considering capital and operating costs) with an economic assessment of system performance (taking into account the cost of high and low pressures). Moreover, it would involve a more complete range of surge protection strategies, a more complete consideration of loading conditions, and a more thorough consideration of penalty functions (to represent constraints). Such an approach is beyond the scope of a conference paper.

However, the case study does suggest certain tendencies. Table 2 shows a summary of surge control device, objective function, optimal location, maximum head and minimum head for the case study. The selection of hydraulic devices is clearly sensitive to the transient. Interestingly, some hydraulic devices do not relieve but actually deteriorate the water hammer response. Several observations arise from the case study:

1. Various kinds of objective functions can be applied to obtain a specific purpose. In this paper, three kinds of objective functions are used: (i) to minimize the maximum head, (ii) to maximize the minimum head, and (iii) to minimize the difference between the maximum head and minimum head in the system. In the case study, the objective functions to minimize the maximum head and to maximize the minimum head predict similar optimal location for hydraulic devices. Therefore, the objective

function to minimize the difference between the maximum head and minimum head appears a more defensible selection to consider the both maximum and minimum head. Significantly, any one of these choices effectively targets the transient envelope of the response and thus produces similar outcomes in the test system.

2. After several generations, Fig. 4 of case 1 and Fig. 6 of case 2 show that the average fitness decreases or increases rapidly by about 20 m. This behaviour suggests a high sensitivity to the “location” gene, and thus that an improper location of hydraulic devices could be useless or even harmful to the transient response. Thus, optimal location of hydraulic device is important. Clearly this represents a challenging criterion when facing a range of forcing events in complex systems.

3. In cases 3 and 4, having more PRVs actually caused a more severe minimum head in the system; having only one PRV at the ideal location showed superior protection for water hammer in this system. Particularly case 5 showed that a large PRV is worse than a small one, since the valve operation itself deteriorated the system’s response. Therefore, selecting both the optimal number and size of hydraulic devices is crucial to creating the best water hammer protection.

4. Not surprisingly, the case study shows that the selection of hydraulic devices to prevent water hammer is sensitive to the nature of the transient condition or loading considered. If a fixed number of devices are forced into the solution, such as by using a given number of relief valves, the transient response often deteriorates.

5. The suitable selection of hydraulic devices is crucial if water hammer pressure is to be effectively controlled.

CONCLUSIONS

One of the most complicated of routine flow problems in supply pipelines and distribution networks is the analysis of fluid transients. In the past, optimizing procedures for the design of fluid transmission pipelines have tended to focus on the steady state requirements of the system in spite of the fundamental importance of transients. This paper obtains optimum selection of hydraulic devices considering transients in the water distribution networks. Genetic algorithms are used as an optimization method to obtain the optimal location, size, and number of hydraulic devices in a pipeline system. A case study shows that reckless installation of hydraulic devices can be ineffective for relieving water hammer events, and may even degrade system response. Therefore, the proper size, location, and number of hydraulic devices to prevent water hammer is highly dependent on the transient condition. The optimal selection of hydraulic devices is not only crucial to system performance and reliability, but also effective in decreasing costs.

Table 2 Summary of case studies

Case	Protection	Objective function	Optimal location (node)	Max. head (m)	Min. head (m)
	none	-	-	278.0	45.7
1	two surge tanks	Minimize (max. head)	21, 22	253.8	81.5
		Maximize (min. head)	21, 22	253.8	81.5
2	one surge tank, one PRV	Minimize (max. head)	22 (PRV) 13 (surge tank)	229.5	72.5
		Maximize (min. head)	22 (PRV) 18 (surge tank)	231.7	76.2
3	three PRVs	Minimize (max. head – min. head)	21 (one PRV only)	234.2	63.7
4	two large PRVs, two small PRVs	Minimize (max. head – min. head)	22 (one large PRV only)	229.3	55.6
	none (slow transient)	-	-	194.7	114.8
5	two large PRVs, two small PRVs (slow transient)	Minimize (max. head – min. head)	22 (one small PRV only)	184.2	109.9

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