Optimal Design for Capacity Expansion of Existing Water Supply System

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1. Introduction

Pipe flows affect the total cost of the pipe network. The global optimum can be obtained through the linear programming in tree pipe network with a single source, because the supply rate and pipe flows are uniquely determined. However, since supply rates or pipe flows are not uniquely determined in tree pipe network with multiple sources or in looped pipe networks, it is not easy to get the global optimum for the networks.

Fujiwara and Khang (1990) and Kessler and Shamir (1991) proposed a two-phase procedure. The conventional optimization methods are relatively complicated, converge slowly, and find only a local optimum. Loganathan et al. (1995) used two global-search schemes, Multistart and Annealing, to permit a local-optimum-seeking method to migrate among various local minima. Ahn et al. (1995) and Ahn and Loganathan (1998) proposed stochastic optimization to find a near global optimum for two or three looped pipe networks.

In this study a two-phase search scheme is suggested to find a near global optimum over the whole feasible region and an existing pipe network is considered to test the proposed approach. The optimal link flows and the optimal pipe diameters for capacity expansion are determined in the sample existing network. It is observed that either convex or nonconvex relationship of cost-hydraulic gradient for links yields either adjacent pipe diameters or nonadjacent pipe diameters respectively, and that the property of cost-hydraulic gradient for pipe expansion of existing network affects the total expansion cost of the sample network.

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2. Model Formulation

The following mathematical programming formulation model 1 (M1) is adopted for looped pipe networks.

(M1) : Minimize $\sum_{(i,j)} \sum_{m=1}^{M} C_{(i,j)m}\, x_{(i,j)m}$ (1)

Subject to

$$\sum_{j} Q_{(i,j)} - \sum_{j} Q_{(j,i)} = q_i \quad \text{for } i \in \{N-S\} \tag{2}$$

$$H_s - H_k^m - \sum_{(i,j)\in r(k)} [\pm \sum_m (J_{1(i,j)m}\, x_{(i,j)m}] \geq 0 \quad \text{for } s \in S, \text{ and } k \in \{N-S\} \tag{3}$$

$$\sum_{(i,j)\in p} \pm \sum_m J_{(i,j)}\, x_{(i,j)m} = b_p \quad \text{for } p \in P \tag{4}$$

$$\sum_m x_{(i,j)m} - L_{(i,j)} = 0 \text{ for } (i,j) \in B \tag{5}$$

$$x_{(i,j)m} \geq 0$$

where $C_{(i,j)m}$ is unit cost for the m th diameter segment in a link (i,j); $x_{(i,j)m}$ is length of the m th diameter segment in a link (i,j); H_s is the fixed head; B is the set of links; $L_{(i,j)}$ is the length of link $(i,j) \in B$; N is the set of nodes; S is the set of fixed head nodes; $\{N-S\}$ is the set of junction nodes; $Q_{(i,j)}$ is flow rate through link $(i,j) \in B$; q_i is demand at node i; $r(k)$ is a path through the network connecting a source node and demand node $k \in \{N-S\}$; $H_k^{\min}$ is minimum pressure head required at node k; p is path connecting fixed head nodes; P is set of paths connecting source nodes; b_p is zero in the loop and is head difference between the source heads.

The hydraulic gradient due to the frictional head loss is calculated from the Hazen-Williams equation with the SI system of unit: $J_{1(i,j)} = k_{1(i,j)} Q_{(i,j)}^{1.852} D_{(i,j)}^{-4.87}$, for each pipe in which $k_{1(i,j)} = 10.7/\ C^{1.852}$, C is the Hazen-Williams coefficient, $Q_{(i,j)}$ is the given flow in link (i,j), and $D_{(i,j)}$ is the diameter of m th segment in link (i,j).

3. Two-Phase Search Scheme

The two-phase search scheme consists of global search phase and local search phase. The stochastic probing algorithm in the spirit of Laud et al. (1992) has been used in the global search phase. The stochastic probing algorithm is to find the location of a near global loop flow vector q^*. The method begins with the construction of a probing probability distribution, with the density function $P \sim N(q,\ \sigma)$, where q is location parameter and σ is scaling parameter. The costs of $f(q)$ are evaluated at a few loop flows q sampled from the density function. The updating location of loop flow q and scale σ are based on Gibbs-like distribution and the entropy of the current distribution, respectively. In the local search phase, the Multistart algorithm used by Loganathan et al. (1995) has been adjusted to efficiently improve a local optimum obtained through the global search phase.

Because flows in the looped network are generated by perturbing the optimal loop flows, a probability density function for loop change flows with mean zero is a good initial choice for two loop pipe network (Ahn et al, 1995).

4. Analysis of Example Network

The sample network, the Songtan water distribution system, as shown in Figure 1 is the expanded water distribution network in Pyongtack(Pyongtack city, 1998), Korea, which is solved using the proposed procedure. The link lengths, the design heads, the demands, and the existing pipe diameters are given in Table 1. The Hazen - Wiliiams friction coefficient is 100 for all links and exponents for discharge and diameter are 1.85 and -4.87 respectively. Table 2 shows commercially available pipe sizes, their capital cost, and annual costs.

The decision variables of the Songtan optimization model based on Model 1 are the unknown segment lengths of known twelve different candidate diameters while satisfying the design requirements. The algorithm TREESEARCH (Loganathan et al., 1990) is first applied to obtain the optimal tree layout and the link flows. The global tree network is obtained by deleting links 3, 6, 8, 12, 15, 20, and 21. The procedure for two-phase search scheme is then implemented to search the feasible region beginning with the perturbed optimal tree link flows as initial flows. The LP Model is solved by the linear programming subroutine DLPRS from the International Mathematical and Statistical Libraries (IMSL).

A probing distribution for loop change flows with mean zero was a good initial choice for two loop pipe network(Ahn et al., 1995). However, the stochastic probing for the sample network yields a number of infeasible solutions with respect to mean zero of loop flows, which may be due to the expansion of existing network having seven loops. Thus, the initial loop flows are chosen from the results of a hydraulic simulator for the existing pipe network. It has been found that the stochastic probing method with the initial loop flows obtained from the existing pipe network migrates successfully to various local optima.

If the relationship of the cost versus hydraulic gradient for the expanded links is said to be a nonconvex function, the total cost in the Korean currency for capacity expansion of the Songtan water distribution system is 48,674,990 Won/year; whereas the total cost is 48,741,387 Won/year in case of a strictly convex. The optimal head losses for a link are same for both two functions. The two-phase search scheme has been applied to search a near optimal loop flows over the whole feasible region. The stochastic probing method improves loop flows at each stage and the optimal loop flows are finally refined by the local search phase. The optimal loop flows in m^3/s (∇Q_1, ∇Q_2, ∇Q_3, ∇Q_4, ∇Q_5, ∇Q_6, ∇Q_7)=(0.309274, 0.267971, 0.25724, 0.018668, 0.017050, 0.194002, 0.022930) are obtained with the procedure.

5. Summary and Conclusions

A two phase search scheme for expanding a looped pipe network has been described. A sample pipe network is employed to test the proposed procedure. The TREESEARCH algorithm is first used to determine the optimal tree layout. The two-phase search scheme then perturbs link flows to obtain loop flows for the optimal design of the pipe network. The two phase search scheme iteratively improves the objective function by finding successive better points and by being escaped out of a local optimum. The optimal solution obtained from both convex and nonconvex cost-gradient functions are all hydraulically feasible, since the optimal head losses for existing links are same for the two functions. The solution by the nonconvex function is better than the one by the convex function. It has been also found that in the perturbation stage, selecting the initial loop flows as the loop flows obtained from the existing network moves efficiently towards a better local optimum. The results show that the proposed method can yield a lower cost design than the conventional design method. In conclusion, the proposed method can be efficiently used to design the pipe expansion of existing networks.

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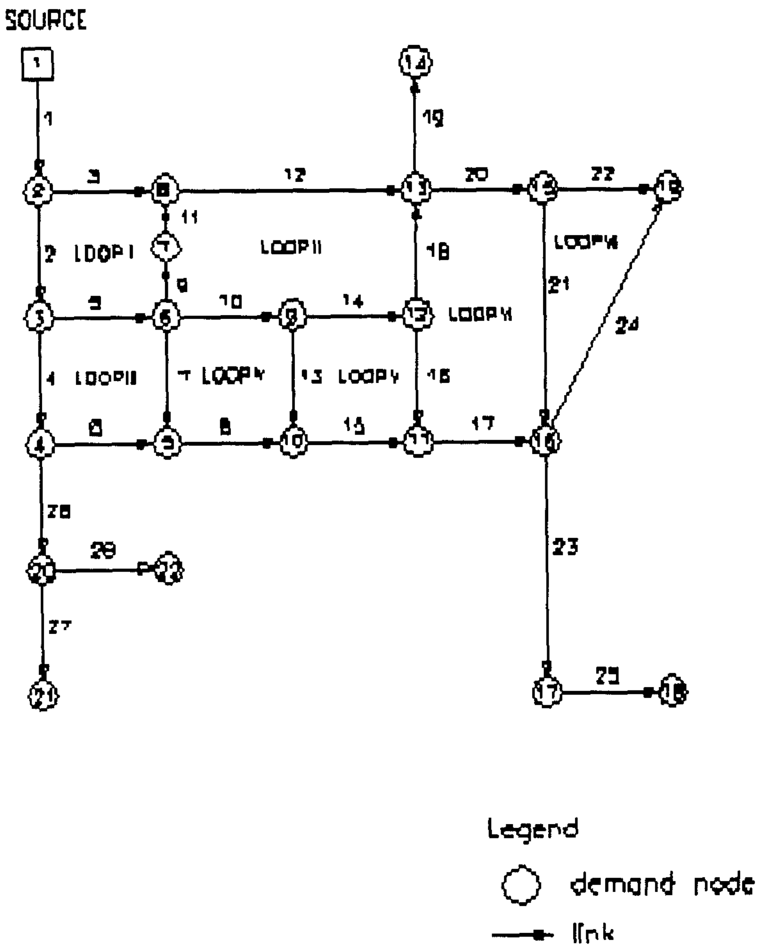

Fig. 1. Sontan Water Distribution System

Table 1. Node and Link Data of Songtan Water Distribution Network

Node number	Demand (m^3/s)	Minimum Head, El. m	Link number	Length, m	Existing Pipe Diameter, cm
1	-0.57754	80.0	1	260.0	70.0
2	0.01842	65.0	2	483.0	70.0
3	0.02500	48.1	3	683.0	60.0
4	0.00789	50.5	4	475.0	15.0
5	0.01191	39.9	5	620.0	60.0
6	0.02391	55.0	6	535.0	30.0
7	0.00254	55.0	7	520.0	15.0
8	0.04159	56.5	8	510.0	31.8
9	0.02657	48.6	9	286.0	10.0
10	0.00887	38.0	10	624.0	60.5
11	0.01302	39.5	11	226.0	10.0
12	0.00639	39.0	12	1010.0	60.0
13	0.07931	45.0	13	476.0	20.0
14	0.07931	62.4	14	376.0	50.0
15	0.05090	43.0	15	496.0	20.0
16	0.06231	42.0	16	217.0	20.0
17	0.00949	31.0	17	585.0	20.0
18	0.08172	48.5	18	286.0	30.0
19	0.01941	46.0	19	1060.0	30.0
20	0.00017	51.0	20	700.0	45.0
21	0.00323	77.0	21	487.0	60.0
22	0.00575	68.3	22	691.0	40.0
			23	300.0	0.0
			24	834.0	20.0
			25	800.0	0.0
			26	1274.0	0.0
			27	450.0	0.0
			28	150.0	0.0

Table 2. Diameter and Cost Data for Songtan Project

Diameter, cm	Annual cost Won/m/year	Diameter, cm	Annual cost Won/m/year	Diameter, cm	Annual cost Won/m/year
8.0	9116	25.0	14257	50.0	25222
10.0	9096	30.0	16069	60.0	28707
15.0	10720	35.0	17594	70.0	33800
20.0	12718	40.0	21075	80.0	39588

지하수분과 연구활동 계획서

1. 제목: 우수침투에 의한 지하수함양

2. 연구목적:

인구의 증가와 산업의 발달에 따라 물 수요는 증가하고있는 반면 토지의 개발이 확장됨으로 인하여 지하수 함양량은 감소하고 있다. 이에따라 강우시에 직접유출이 증가함으로 인하여 홍수피해가 늘어나며 침투수량의 감소로 지하수유출이 줄어들어 갈수시에는 하천수의 유지유량확보가 어려워 수량 뿐만 아니라 수질의 악화로 심각한 사회 문제를 유발시키는 등 수자원 관리에 어려움이 많다. 뿐만아니라 지하수의 부적절한 사용이나 관리로 인하여 지하수재해가 발생하고 있다. 지하수함양에 의하여 지하수를 증강하면 수자원관리를 원활히 하고 지하수재해의 예방이나 지하수위의 회복, 지하수의 적극적 이용을 할 수 있다. 지하수 함양방법은 여러 가지 있으나 최근 도시화나 개발에 의하여 지하수 함양량이 줄어들고 있어 지하수환경이 열악해져가고 있다. 이를 만회하고 수자원의 확보와 지하수의 증강을 위해서는 우수침투에 의한 지하수함양이 유효하다. 본 연구에서는 홍수시의 유출 억제와 갈수유량 증대를 도모함으로써 수자원을 보다 효율성 있게 이용하며 줄어드는 지하수함양을 만회하고 적극적인 지하수이용을 위한 방안으로 우수침투에 의한 지하수함양기법과 그 효과에 대하여 고찰하고자 한다.

3. 연구내용 및 방법

(1) 지하수함양량의 감소에 의한 영향에 대하여 검토한다.
(2) 우수침투기법에 대하여 살펴보며 적용사례를 조사한다.
(3) 지하수함양량 증가가 지하수체에 미치는 영향에 대하여 검토한다.
(4) 지하수함양의 유용성에 대하여 고찰한다.

4. 기대효과:

(1) 수문환경보전에 유용함
(2) 홍수와 갈수의 경감대책 수립에 유용함
(3) 수자원의 효율적 활용
(4) 지하수재해를 예방함
(5) 지하수위회복 방안 마련
(6) 지하수를 적극적으로 이용할 수 있는 방안 마련