〈論 文〉

논관개용 관수로시스템의 최적설계
An Optimal Design of Paddy Irrigation Water Distribution System

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Abstract□ The water distribution system problem consists of finding a minimum cost system design subject to hydraulic and operation constraints. The design of new branching network in a paddy irrigation system is presented here. The program based on the linear programming formulation is aimed at finding the optimal economical combination of two main factors: the capital cost of pipe network and the energy cost. Two loading conditions and booster pumps for design of pipe network are considered to obtain the least cost design.

요 지 : 관수로시스템 최적설계는 수리학적 및 시스템 운영 제약조건 아래서 시스템의 전체비용을 최소비용으로 구하는 것이다. 본 연구에서는 논관개용 수지상배관 시스템설계에 관해 상술하였다. 이는 선형계획론을 이론적 배경으로 하여 관로의 비용과 에너지비용을 함께 고려함으로서 시스템 전체비용으로 구하는 것을 시도하였으며 논 관개용 관수로시스템 설계에 있어서 두개의 수요양상과 가압펌프를 고려함으로서 전체시스템의 최소비용을 구하였다.

1. Introduction

Irrigation conveyance systems for paddies are an integral part of the total irrigation systems. In Korea many irrigation water conveyance systems are gravity flow systems in which water flows from main and secondary canals to tertiary canals, and finally flows into paddy lands. Water is supplied to each sub-minor through farm outlets connected to the tertiary canals. Each sub-minor has one farm outlet. One tertiary canal delivers water to two minor blocks at the same time. A sub-minor block is defined as the minimum size block that can be managed for optimal irrigation and drainage practices. A minor block usually consists of 10–15 sub-minor blocks. The minor block is considered as the maximum unit that can be properly operated in the paddy field. Each main block consists of two minor blocks, which are separated by a tertiary canal. Each farm outlet is treated as demand node in the pipe network and one demand node supplies water to two sub-minors. The open channel systems have led to problems in water management. Conveyance losses and application losses in the canal systems lead to water deficit. Also, necessarily irrigation water has to be supplied in excess of crop water demand. As opposed to the canal system, the pipe system has negligible conveyance losses. Underground pressure conduit system has been in use

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in Korea for the past few years to save irrigation water as well as to facilitate better irrigation water management. As far as the network cost is concerned, the branching pipe network is the optimal layout. The branching network has low reliability because even if a single link is broken, many demand nodes will be disconnected from the source. However, in the paddy irrigation system the reliability is not a major issue. Thus, the consideration of tree networks remains important in the design of irrigation systems.

The main objective of irrigation conveyance system of paddy irrigation systems is to distribute water uniformly and timely over an irrigated area. Rice yields are affected by air temperature, sunshine hours, water temperature, fertilizer, pests, diseases, weed, typhoon, irrigation, drainage, and water management in the paddy fields. It is assumed that the adequate operation and management of water distribution system produces the maximum yield of rice. Therefore, the optimization model for paddy irrigation conveyance system is to minimize total cost of pipe network, which includes the costs of pipes, pumps, tanks, and energy. That is, the model is to minimize the total cost of network subject to the constraints of the system. Mathematical formulation for the paddy irrigation pipe network is similar to that of the municipal water distribution system in that the objective function of the model is to minimize the total cost of pipes and pumping while satisfying the continuity and minimum head requirements at each node. The differences between them include the way water demand is assessed at a node as well as the pressure head for fire demand that is not considered in the irrigation system.

In the following, dealing directly with irrigation network optimization is discussed. Perold (1974) used the hydraulic gradient method to determine the most economic pipe sizes for a gravity sprinkler system. Since the method operates on an arbitrarily by picked initial design and adjusts only portions of the network, it is inefficient for a large network. Geohring (1976) formulated a nonlinear mixed integer programming model for optimal design of a trickle irrigation system by minimizing the cost of trickle irrigation network while satisfying energy conservation constraints and operating policy constraints. Oron and Walker (1981) extended the work of Geohring for optimal design and operation of a sprinkler irrigation system. Both the models use geometric programming to obtain continuous diameters and apply a branch and bound technique for discrete diameters. Only a local optimum is found. Holzapfel and Marino (1990) presented a nonlinear optimization model for the design and management of drip irrigation systems. The above models account for optimizing in–farm irrigation networks.

For irrigation conveyance systems besides in–farm irrigation system, Labye et al. (1988) have presented a method for determining a layout of a tree network. The method consists of three distinct stages which are the proximity layout, the 120° layout, the least–cost layout. The final tree represents the shortest path tree connecting each demand node. However, this method does not consider topographic constraints in determining the layout. Since the method is based on a geometric scheme, the method would be inefficient and would converge slowly for large networks.

2. Model Formulation for Paddy Irrigation System

The following mathematical programming formulation Problem (P1) for multiple loadings is adopted for the paddy irrigation pipe network optimization.

$$\text{P1 : Minimize } \sum_{(i,j)}\sum_{m} C_{3(i,j)m}x_{3(i,j)m}+\sum_{l}\sum_{i\in s} C_{5i}H_{bi,l}$$

$$+\sum_{l}\sum_{i\in S} \frac{C_6\gamma \Delta T_{i,l}}{\eta_{i,l}} Q_{bi,l}H_{bi,l}+\sum_{i\in S} C_{7i}Hp_{i,l}$$

$$+\sum_{l}\sum_{i\in S} \frac{C_8\gamma \Delta T_{i,l}}{\eta_{i,l}} Qp_{i,l}Hp_{i,l} \qquad (1)$$

Subject to

$$-\sum_{k\ (i,j)\in L} Q_{(i,k),l}+\sum_{k\ (k,j)\in L} Q_{(k,i),l}=q_{i,l}$$

$$\text{for all } i\in N \text{ and } l\in \mathcal{L} \qquad (2)$$

$$-\sum_{(i,j)\in r(k)} \pm\sum_{m} J_{3(i,j)m,l}\, x_{3(i,j)m,l}+H_{bi,l}+Hp_{i,l}$$

$$\geq H^{\min}_{k,l}-H^{ele}_{bi}-Hp^{ele}_{i}$$

$$\forall\ i\in s, k\in N, l\in \mathcal{L}, \text{ and } i\in S \qquad (3)$$

$$\sum_{(i,j)\in P} \pm\sum_{m} J_{3(i,j)m,l}\, x_{3(i,j)m}=b_{P,l}$$

$$\text{for all } p\in p \text{ and } l\in \mathcal{L} \qquad (4)$$

$$\sum_{m} x_{3(i,j)m}-L_{(i,j)}=0 \qquad \text{for all } (i,j)\in L \qquad (5)$$

$$Q_{(i,j),l} \geq Q^{\min}_{(i,j),l} \qquad \text{for all } (i,j)\in L \qquad (6)$$

$$x_{3(i,j)m} \geq 0$$

$$H_{bi,l} \geq 0$$

$$Hp_{bi,l} \geq 0$$

Where:

$C_{3(i,j)m}$ = unit cost for the m th new diameter segment in a link (i,j)

$x_{3(i,j)m}$ = length of m th new diameter segment in link (i,j)

C_{5i} = booster pump capital cost per pumping head at node i

C_{7i} = pump capital cost per pumping head at node i

C_6 and C_8 = unit energy cost(\$ /kwh)

$H_{bi,l}$ = operating head of a booster pump at node i for the l th loading

$\mathcal{L}$ = a set of loadings

$HP_{i,l}$ = operating head of a source pump at node i under the l th loading

H^{ele}_{bi} = elevation of booster pump at node i

Hp^{ele}_{i} = elevation of source pump at node i

$Q_{bi,l}$ = pumping rate of a booster pump at node i under the l th loading

$Qp_{i,l}$ = pumping rate of a source pump at node i under the l th loading

$\Delta T_{i,l}$ = pumping period for pump at node i under the l th loading

γ = the specific weight of water

$\eta_{i,l}$ = pump efficiency for pump at node i under the l th loading

s = set of booster pumps

S = set of source pump nodes

$q_{i,l}$ = consumptive use or demand at node i for the l th loading

$H^{\min}_{k,l}$ = minimum pressure head required at node k under the l th loading

$Q_{(i,j),l}$ = link flow for the l th loading

$\gamma(k)$ = path through the network connecting a source pump node and demand node k

p = set of paths connecting source head nodes

L = number of links in the network

$L_{(i,j)}$ = the length of a link (i,j)

$b_{P,l}$ = head difference between the source pumping heads for path p connecting them for l th loading,

$b_{P,l}$ $=(Hp_{i,l}+Hp^{ele}_{i,l})_{beginning}-(Hp_{i,l}+Hp^{ele}_{i,l})_{end}$

N = the number of nodes in the network except source pump nodes.

The hydraulic gradient for the th loading from the Hazen–Williams equation is used along with the SI system of unit: $J_{3(i,j)m,l}=k3_{f(i,j)}$

$Q_{(i,j),l}^{1.852}\ D_{3(i,j),m}^{-4.87}$ in which $k3_f = 10.7/Q_n^{1.852}$, C_n is the Hazen–Williams coefficient for new pipe, $Q_{(i,j),l}$ is the given flow in link (i,j) for the l th loading, $D_{3(i,j)m}$ is the new diameter of m th segment in link (i,j).

The constraints will have to be duplicated for each demand pattern if more than one demand pattern are to be considered. The objective function may be linear or nonlinear depending upon the various types of components to be designed. The components represent pipes, pumps, valves, and elevated tanks. The optimal solution comprising flows, diameters, and energy heads, is obtained by minimizing the total cost subject to the constraints of the system.

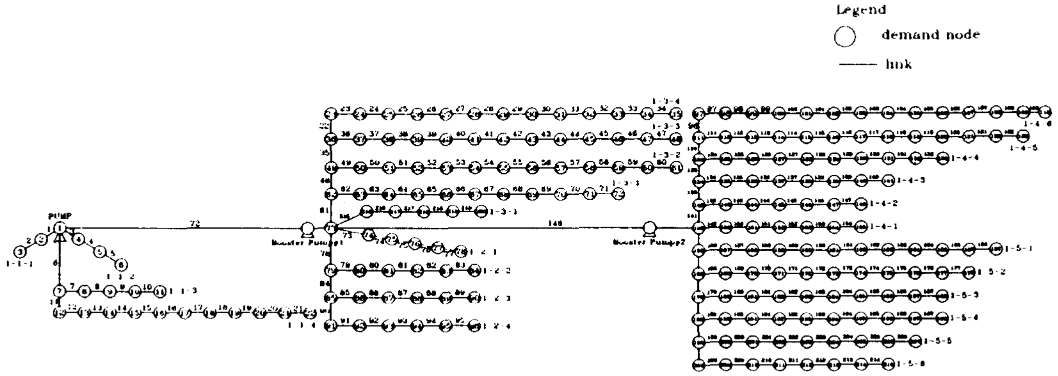
3. Analysis of Example Network

3.1 Description of Study Area and Existing Network

The study area is the Haenam estuary basin which is located in the southwestern part of the Korean peninsula. The Haenam agricultural development project has recently been completed by the Rural Development Corporation (RDC). This project includes construction of one sea dike with sluice gates, two pumping stations, irrigation pipelines and canals, and drainage channels. In addition to the construction of these irrigation facilities, implementation of upland and tideland reclamation is also part of the project. The watershed area by constructing the sea dike and sluice gates becomes 18,130 hectares. The sea dike has formed 1,960 ha–m of estuary reservoir with the top surface area of 505ha at normal water level. The normal water level is –0.5m and the dead water level is –4.0m. The available water depth of freshening reservoir is 3.5m during irrigation period with 1,273ha–m of effective storage and 687ha–m of dead storage. An area of 2,520ha of existing (668ha) and newly reclaimed paddy fields (1,852ha) is irrigated from the reservoir through the irrigation conveyance system. The area to be irrigated is divided into two Sections : 1,316 hectares of Section I is supplied by canals directly connected to the pumping station ♯1 and 1,204.33 hectares of Section II is supplied by pipeline and canal system directly connected to the pumping station ♯2. The area of Section II consists of three sub–command areas which are supplied by three pairs of pumps in the pumping station ♯2. Since each pair of pumps is separately operated, each pipe system can be independently considered. Thus, in this study a pipe network for command area ♯1(348.82 hectares) is selected for the optimal design. Figure 1 shows the selected pipe network in command area ♯1. As shown in Figure 1, the irrigation facilities are composed of a pair of pumps in the pumping station ♯2, and pipelines including 220 junction nodes.

Since each demand node along a tertiary pipe supplies water to 1 hectare of land, the crop water demand is computed based on unit irrigation requirement. The unit irrigation requirements for transplanting (q_t) and growing season (q_e) using real data (RDC, 1988) are given : $q_t = 0.00232 m^3/sec/ha$, $q_e = 0.001855 m^3/sec/ha$. The larger unit irrigation requirement, $0.00232 m^3/sec/ha$ is then adopted to compute design demand at each node : $Q = q \cdot 24/22 = 0.00232 m^3/sec/ha \cdot 24/22 = 0.00253 m^3/sec$. Since the total command area is 348.22 hectares, the design discharge for pump is computed : $Q_p = 0.00253 m^3/sec/ha \cdot 348.82 ha = 0.88252 m^3/sec$. Link length, minimum head, and demands are given in Table 1. As given in the Haenam project report (RDC, 1988), Hazen Williams friction coefficient is 140 for all links and exponents for discharge and diameter are 1.852 and –4.87

respectively. Polyethylene (PE) pipes are adopted in the study area and the pipes are buried over 1.5m deep. If the diameter of a pipe exceeds 700mm, coated steel pipes for preventing from corrosion are used.



Note 1-1-4
The first number indicates main pipe
The second number indicates secondary pipe
The third number indcates tertiary pipe

Figure 1. Selected Pipe Network in Haenam Project

Table 1. Selected Pipe Network in Haenam Project

Node number	Demand m^3/sec	Minimum head, *m*	Link number	Length, *m*	Node number	Demand m^3/sec	Minimum head, *m*	Link number	Length, *m*
1	−0.88252	0.1	1	50.0	21	0.00253	6.5	21	41.63
2	0.00253	6.5	2	25.75	22	0.00210	6.5	22	210.0
3	0.00130	6.5	3	50.0	23	0.0	0.5	23	50.0
4	0.00253	6.5	4	50.0	24	0.00253	6.5	24	50.0
5	0.00253	6.5	5	29.78	25	0.00253	6.5	25	50.0
6	0.00150	6.5	6	142.0	26	0.00253	6.5	26	50.0
7	0.0	0.5	7	50.0	27	0.00253	6.5	27	50.0
8	0.00253	6.5	8	50.0	28	0.00253	6.5	28	50.0
9	0.00253	6.5	9	50.0	29	0.00253	6.5	29	50.0
10	0.00253	6.5	10	33.55	30	0.00253	6.5	30	50.0
11	0.00169	6.5	11	213.0	31	0.00253	6.5	31	50.0
12	0.0	0.5	12	50.0	32	0.00253	6.5	32	50.0
13	0.00253	6.5	13	50.0	33	0.00253	6.5	33	50.0
14	0.00253	6.5	14	50.0	34	0.00253	6.5	34	53.75
15	0.00253	6.5	15	50.0	35	0.00272	6.5	35	213.0
16	0.00253	6.5	16	50.0	36	0.0	0.5	36	50.0
17	0.00253	6.5	17	50.0	37	0.00253	6.5	37	50.0
18	0.00253	6.5	18	50.0	38	0.00253	6.5	38	50.0
19	0.00253	6.5	19	50.0	39	0.00253	6.5	39	50.0
20	0.00253	6.5	20	50.0	40	0.00253	6.5	40	50.0

Node number	Demand m^3/sec	Minimum head, *m*	Link number	Length, *m*	Node number	Demand m^3/sec	Minimum head, *m*	Link number	Length, *m*
41	0.00253	6.5	41	50.0	84	0.00287	6.5	84	215.0
42	0.00253	6.5	42	50.0	85	0.0	0.5	85	50.0
43	0.00253	6.5	43	50.0	86	0.00253	6.5	86	50.0
44	0.00253	6.5	44	50.0	87	0.00253	6.5	87	50.0
45	0.00253	6.5	45	50.0	88	0.00253	6.5	88	50.0
46	0.00253	6.5	46	50.0	89	0.00253	6.5	89	56.85
47	0.00253	6.5	47	33.60	90	0.00287	6.5	90	210.0
48	0.00170	6.5	48	214.0	91	0.0	0.5	91	50.0
49	0.0	0.5	49	50.0	92	0.00253	6.5	92	50.0
50	0.00253	6.5	50	50.0	93	0.00253	6.5	93	50.0
51	0.00253	6.5	51	50.0	94	0.00253	6.5	94	50.0
52	0.00253	6.5	52	50.0	95	0.00253	6.5	95	74.45
53	0.00253	6.5	53	50.0	96	0.00376	6.5	96	224.0
54	0.00253	6.5	54	50.0	97	0.0	0.5	97	50.0
55	0.00253	6.5	55	50.0	98	0.00253	6.5	98	50.0
56	0.00253	6.5	56	50.0	99	0.00253	6.5	99	50.0
57	0.00253	6.5	57	50.0	100	0.00253	6.5	100	50.0
58	0.00253	6.5	58	50.0	101	0.00253	6.5	101	50.0
59	0.00253	6.5	59	50.0	102	0.00253	6.5	102	50.0
60	0.00253	6.5	60	35.25	103	0.00253	6.5	103	50.0
61	0.00178	6.5	61	214.0	104	0.00253	6.5	104	50.0
62	0.0	0.5	62	50.0	105	0.00253	6.5	105	50.0
63	0.00253	6.5	63	50.0	106	0.00253	6.5	106	50.0
64	0.00253	6.5	64	50.0	107	0.00253	6.5	107	50.0
65	0.00253	6.5	65	50.0	108	0.00253	6.5	108	50.
66	0.00253	6.5	66	50.0	109	0.00253	6.5	109	47.75
67	0.00253	6.5	67	50.0	110	0.00242	6.5	110	225.0
68	0.00253	6.5	68	50.0	111	0.0	0.5	111	50.0
69	0.00253	6.5	69	50.0	112	0.00253	6.5	112	50.0
70	0.00253	6.5	70	50.0	113	0.00253	6.5	113	50.0
71	0.00253	6.5	71	29.1	114	0.00253	6.5	114	50.0
72	0.00147	6.5	72	572.0	115	0.00253	6.5	115	50.0
73	0.0	0.5	73	50.0	116	0.00253	6.5	116	50.0
74	0.00253	6.5	74	50.0	117	0.00253	6.5	117	50.0
75	0.00253	6.5	75	50.0	118	0.00253	6.5	118	50.0
76	0.00253	6.5	76	50.0	119	0.00253	6.5	119	50.0
77	0.00253	6.5	77	37.5	120	0.00253	6.5	120	50.0
78	0.00189	6.5	78	213.0	121	0.00253	6.5	121	50.0
79	0.0	0.5	79	50.0	122	0.00253	6.5	122	44.16
80	0.00253	6.5	80	50.0	123	0.00223	6.5	123	312.0
81	0.00253	6.5	81	50.0	124	0.0	0.5	124	50.0
82	0.00253	6.5	82	50.0	125	0.00253	6.5	125	50.0
83	0.00253	6.5	83	54.75	126	0.00253	6.5	126	50.0

Node number	Demand m^3/sec	Minimum head, *m*	Link number	Length, *m*	Node number	Demand m^3/sec	Minimum head, *m*	Link number	Length, *m*
127	0.00253	6.25	127	50.0	170	0.00253	6.5	170	50.0
128	0.00253	6.25	128	50.0	171	0.00253	6.5	171	50.0
129	0.00253	6.25	129	50.0	172	0.00253	6.5	172	50.0
130	0.00253	6.25	130	50.0	173	0.00253	6.5	173	50.0
131	0.00253	6.5	131	50.0	174	0.00253	6.5	174	50.0
132	0.00253	6.5	132	40.6	175	0.00253	6.5	175	50.0
133	0.00205	6.5	133	312.0	176	0.00253	6.5	176	50.0
134	0.0	0.5	134	50.0	177	0.00253	6.5	177	63.75
135	0.00253	6.5	135	50.0	178	0.00322	6.5	178	214.0
136	0.00253	6.5	136	50.0	179	0.0	0.5	179	50.0
137	0.00253	6.5	137	50.0	180	0.00253	6.5	180	50.0
138	0.00253	6.5	138	50.0	181	0.00253	6.5	181	50.0
139	0.00253	6.5	139	50.0	182	0.00253	6.5	182	50.0
140	0.00253	6.5	140	44.75	183	0.00253	6.5	183	50.0
141	0.00226	6.5	141	215.0	184	0.00253	6.5	184	50.0
142	0.0	0.5	142	50.0	185	0.00253	6.5	185	50.0
143	0.00253	6.5	143	50.0	186	0.00253	6.5	186	50.0
144	0.00253	6.5	144	50.0	187	0.00253	6.5	187	61.0
145	0.00253	6.5	145	50.0	188	0.00308	6.5	188	214.0
146	0.00253	6.5	146	50.0	189	0.0	0.5	189	50.0
147	0.00253	6.5	147	48.85	190	0.00253	6.5	190	50.0
148	0.00247	6.5	148	878.0	191	0.00253	6.5	191	50.0
149	0.0	0.5	149	50.0	192	0.00253	6.5	192	50.0
150	0.00253	6.5	150	50.0	193	0.00253	6.5	193	50.0
151	0.00253	6.5	151	50.0	194	0.00253	6.5	194	50.0
152	0.00253	6.5	152	50.0	195	0.00253	6.5	195	50.0
153	0.00253	6.5	153	50.0	196	0.00253	6.5	196	50.0
154	0.00253	6.5	154	30.25	197	0.00253	6.5	197	38.6
155	0.00153	6.5	155	302.0	198	0.00195	6.5	198	215.0
156	0.0	0.5	156	50.0	199	0.0	0.5	199	50.0
157	0.00253	6.5	157	50.0	200	0.00253	6.5	200	50.0
158	0.00253	6.5	158	50.0	201	0.00253	6.5	201	50.0
159	0.00253	6.5	159	50.0	202	0.00253	6.5	202	50.0
160	0.00253	6.5	160	50.0	203	0.00253	6.5	203	50.0
161	0.00253	6.5	161	50.0	204	0.00253	6.5	204	50.0
162	0.00253	6.5	162	50.0	205	0.00253	6.5	205	50.0
163	0.00253	6.5	163	50.0	206	0.00253	6.5	206	51.0
164	0.00253	6.5	164	50.0	207	0.00258	6.5	207	210.0
165	0.00253	6.5	165	50.0	208	0.0	0.5	208	50.0
166	0.00253	6.5	166	52.5	209	0.00253	6.5	209	50.0
167	0.00265	6.5	167	212.0	210	0.00253	6.5	210	50.0
168	0.0	0.5	168	50.0	211	0.00253	6.5	211	50.0
169	0.00253	6.5	169	50.0	212	0.00253	6.5	212	50.0

Node number	Demand m^3/sec	Minimum head, *m*	Link number	Length, *m*
213	0.00253	6.5	213	50.0
214	0.00253	6.5	214	63.75
215	0.00322		215	10.0
216	0.20227	6.5	216	50.0
217	0.05	6.5	217	50.0
218	0.05	6.5	218	50.0
219	0.05	6.5	219	50.0
220	0.05	6.5		

3.2 Analysis of the Sample Network

The pipe network selected from the Haenam project has two hundred nineteen links. To obtain the annual cost of the system, the initial costs of all component of the system are converted into annual capital recovery cost by introducing the annual capital recovery factor. The annual capital recovery factor is given by: $R=\frac{i(1+i)^n}{(1+n)^n-1}=\frac{0.1(1+0.1)^{30}}{(1+30)^{30}-1}=0.106$, in which i is an interest rate per year, and n is a life span of system. The annual payment equivalent to a present sum of each component of system for life the span of the system at an interest rate i is computed: $c=C\cdot R$ where c is annual capital recovery cost a component, C is capital cost of the component, and R is annual recovery factor.

Table 2 shows commercially available pipe sizes, their capital and annul costs and their required thickness to withstand earth pressure and internal stress. The following annual capital recovery costs for other components are adopted based on realistic cost value for single loading condition: the unit cost of source pump, $C_7=\$163.6/m$; the unit energy cost, $C_8=\$0.03/kwh$. In the energy cost term, the average irrigation requirement per year is assumed to be 1200㎜. Total amount of water per year to be pumped is computed by multiplying the irrigated area, 348.82 hectares: $1200mm\cdot 348.82ha\cdot 10000m^2/1ha\cdot 1m/1000mm.=4,185,840m^3$. The average pumping period is then computed by dividing the design discharge of pump: $\frac{4,185,840m^3}{0.88252m^3/sec}=1,318hours$. Thus, $\frac{C_8\gamma\Delta T}{\eta}QpHp=\$422.18Hp$.

Tabel 2. Diameter and Cost Data for Haenam Irrigation Network

Diameter (㎜)	Thickness (㎜)	Capital cost($/m)	Annual cost($/m)
100	5.5	21.46	2.27
150	7.0	22.94	3.17
200	8.0	41.69	4.41
250	9.0	51.30	5.43
300	10.0	60.00	6.36
350	14.2	92.81	9.83
400	16.2	107.27	11.37
450	17.6	128.82	13.65
500	19.5	159.30	16.91
550	21.5	172.68	18.30
600	23.4	194.06	20.57
700	6.0	211.69	22.43
800	6.0	272.50	28.88

The design of tree networks of pumping system involves mainly three decisions: the selection of the tree layout from a given set of potential links, the selection of diameters of links, and the selection of pumping heads. It should be noted that block layout for paddy irrigation system is an important aspect because the optimal tree layout is restricted with the block layout for paddy irrigation system. The Problem P1 is a nonlinear, discrete, nonconvex programming problem, which may have several local minima. For unknown flows it is difficult to obtain the optimal solution to the Problem P1 because of the nonconvexity. The problem is compounded by large number of decision variable involved. For the Haenam system with 220 nodes, 219 links, 1 source pump, 2 booster pumps, and 13 candidate diameters, there are 2,850 decision variables (219×13, 1 source pump, 2 booster pumps) under a single demand pattern. However, if a certain layout is determined, and a set of flows are specified on this network feasible to the continuity equation (2), then the Problem P1 reduces to a linear programming problem. This linear program determines the associated optimal values for the heads at the nodes, the segmentation lengths of various diameters for the pipes, and pumping head for the pumps. Note that if there is only a single source node, then the flows are uniquely determined via the continuity equations (2). In fact, these equations reduce to a linear triangle system which may be easily solved. For multiple sources Linear Minimum Cost Flow(LMCF) model due to Rowell or Nonlinear Minimum Cost Flow (NMCF) model due to Rowell and Barnes may be used to determine the supply rate at each source node. If multiple demand patterns are considered, then the flow and energy head variables and constraints (equation 2, 3, and 4) should essentially be replicated below for each pattern.

In the present study Problem (P1) is solved for two loading conditions. In addition to the source pumps, two booster pumps are considered in the system. The booster pump ♯1 is located near node 73 : the booster pump ♯2, near node 149. Two loading conditions are considered: one loading for the peak demand (Q_p) during 220 hours per year, the other loading for the average demand ($Q_{Ave}=1/2Q_p$) during 1,098 hours per year. Table 3 shows the unit cost per pumping head for each pump under the l th loading. Table 4 just shows the optimal cost for pumps and pipes under two loadings. In this paper the optimal head at each node, flows, and the segmentation length of various diameters for the pipes are not shown. For two loadings, operating both source pump and booster pumps results in smaller costs than operating only

Table 3. Unit Cost per Pumping Head for Each Pump

Loading condition	Source pump ($/m/yr)		Booster pump ♯1 ($/m/yr)		Booster pump ♯2 ($/m/yr)	
	Pump	Energy	Pump	Energy	Pump	Energy
$l=1$	27.31	70.47	25.94	66.91	16.70	21.57
$l=2$	136.29	351.71	129.42	333.96	83.30	107.60
Single	163.60	422.18	155.36	400.87	100.063	129.17

Table 4. Optimal Cost under Two Loadings for Haenam Irrigation Network

Pump head(m)	Pump cost($)	Pipe cost($)	Total cost($)
$HP_{,l=1}=60.69$ $HP_{,l=2}=21.44$	16,397	60,053	76,450
$HP_{,l=1}=26.3$ $HP_{,l=2}=11.91$ $HP_{b1,l=1}=13.52$ $HP_{b1,l=2}=3.67$ $HP_{b2,l=1}=45.43$ $HP_{b2,l=2}=12.51$	15,466	57,696	73,162

source pumps. The cost of the optimal system is $ 73,162 per year, of which $ 57,696 is pipe cost, $ 8,383.59 is the source pump including energy cost, $ 2,955.84 is the booster pump ♯1 cost including energy cost, and $ 4,126.66 is the booster pump ♯2 cost including energy cost.

4. Conclusions

The advantage of simultaneous multiple loading is established in the paddy irrigation system. The traditional analyses have employed peak loading only which lasts only for a small period. In this study it is shown that if the average loading lasts over long time, it will dominate the design over the peak loading. In the paddy irrigation network two loading conditions are considered: one loading for the peak water demand, the other loading for the average demand. Multiple loadings are included by appropriate addition of the constraints corresponding to each loading pattern while retaining the pipe length variable to be the same in all loadings. The pipe length variables remain the same because the same pipes are utilized under all loadings.

Saving energy is important for pumping water distribution networks. The selection of undersized pumps would lead to the violation of minimum pressures within the distribution system. The selection of oversized pumps would lead to unnecessary capital and operational costs, and excessive pressures at nodes. Thus an optimal pump selection is necessary to provide adequate pressure in the distribution system. The advantages of booster pumps are: (a) to avoid designing source pumping station for abnormally high operating head; (b) to reduce maximum hydraulic heads over large service area; and (c) to reduce energy costs. It is observed that providing booster pumps may prove advantageous both in terms of reducing head on the source pump as well as in selecting pipe sizes.

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