A Decision–Supporting Model for Rehabilitation of Old Water Distribution Systems

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ABSTRACT : Flow carrying capacity of water distribution systems is getting reduced by deterioration of pipes in the systems. The objective of this paper is to present a managerial decision–making model for the rehabilitation of water distribution systems with a mininum cost. The decisions made by the model also satisfy the requirements for discharge and pressure at demanding nodes in the systems.

Replacement cost, pipe break repair cost, and pumping cost are considered in the economic evaluation of the decision along with the break rate and the interest rate to determine the optimal replacement time for each pipe. Then, the hydraulic integrity of the water distribution system is checked for the decision by a pipe network simulator, KYPIPE, if discharge and pressure requirements are satisfied. In case the system does not satisfy the hydraulic requirements, the decision made for the optimal replacement time is revised until the requirements are satisfied.

The model is well applied to an existing water distribution system, the Seoul Metropolitan Water Supply System (1st Phase). The results show that the decisions for the replacement time determined by the economic analysis are accepted as optimal and hydraulic integrity of the system is in good condition.

1. Introduction

Flow carrying capacity of water distribution systems is getting reduced by deterioration of pipes in the system.

Generally, there are three types of treatment for old pipes, Rehabilitation; Repacement; and

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Repair. Rehabilitation is to remove alien substances in the pipe and coats inside the deteriorated pipe. Replacement is to dig out an old pipe and lay a new pipe under the ground. Repair is to fix pipe breaks and leaks.

Shamir and Howard(1979) developed a procedure to schedule pipe replacement. Walski and Pelliccia(1982) developed a new criterion in replacing pipes that stated that if the current break rate of a pipe is greater than some critical break rate, the pipe should be replaced. Walski(1982, 1985) considered the economic analysis of the rehabilitation of water mains. O'Day(1982) provided an overview of the causes of water-main breaks and leaks. Sullivan(1982) discussed programs in Boston for rehabilitation, continuous maintenance, and replacement of the city's water-distribution system.

Models for determining the minimum cost solution to the rehabilitation and replacement problem of water-distribution-system components were presented by Woodburn et al. (1987) and later by Lansey et. al. (1992). These models allow replacement of a portion of a pipe and its rehabilitation that may not be realistic. The model by Kim(1992) and Kim and Mays(1994) uses integer (binary) variables to represent the decision for replacement and rehabilitation instead of using pipe lengths as decision variables. This model is interfaced with a hydraulic simulator, KYPIPE and is able to check hydraulic validity. However, the number of variables the model can use is limited and the model does not have the capability to make yearly-based decisions.

In spite of research works performed so far, none has been applied to a water distribution system in Korea. Therefore, the objective of this study is to develop a decision-making model for replacement, which is practical as well as theoretical.

2. Data Analysis

The model needs some data such as maintenance cost data, rehabilitation cost data, replacement cost data, pumping cost data, pipe breaks data, and pipe deterioration data. While rehabilitation cost data, replacement cost data, pumping cost data, pipe breaks data, and pipe deterioration data are obtained easily, maintenance cost data is difficult to procure. Therefore, the data of the US Army Corps of Engineers(1983) are used for maintenance cost data.

2.1 Maintenance & Repair Cost

Maintenance & Repair cost is that of pipe break recovery, derived from equipment cost, labor cost, and material cost.

$$C_B = 1300\left(\frac{D}{304.8}\right)^{0.62} \times 800 \tag{1}$$

where C_B is the repair cost per one break(Won /break), and D is the pipe diameter(mm).

2.2 Rehabilitation Cost

There are many methods for rehabilitation of pipes. In this study, the rehabilitation cost function is derived from the air sand method data for pipes ranging from 16mm to 155mm in diameter.

The regression function is

$$C_{rh}=210.187D+9181.11 \tag{2}$$

where C_{rh} is rehabilitation cost(Won /m).

2.3 Replacement Cost

The replacement cost is derived from the data of steel pipe replacements from 300mm to 2800mm in diameter.

The regression function in an unpaved area is

$$C_{ru}=0.22526\ D^2+269.092D+9859.21 \tag{3}$$

where Cru is replacement cost(Won /m) in an unpaved area.

The regression function in a paved area is

$$C_{rp}=0.237566\ D^2+380.649\ D+111178 \tag{4}$$

where C_{rp} is replacement cost(Won /m) in an paved area.

2.4 Pumping Cost

The pumping cost herein is the curtailment of pumping caused by the pipe treatment which increases conveyance of the pipe. The Hazen-Williams coefficient C is increased by it. Therefore, savings in the pumping power is

$$\Delta P=\gamma Q\,\Delta h_L \tag{5}$$

where P is the curtailed pumping power(kW).

The savings in a year is

$$C_p = 323770\,\Delta P \tag{6}$$

2.5 Pipe Break Function

The pipe break function is derived from the data of the Metropolitan Water Supply Project of KOWACO(Korea Water Resources Corporation).

The independent variable is the passing time after constructing or treating the pipe. The derived function is

$$y = 3.882 \times 10^{-6}\, e^{0.165x} \tag{7}$$

where y is the pipe break rate, x is the passing time.

2.6 The Prediction of Pipe Deterioration

It is impossible to derive an equation to predict the C value function from existing data mainly due to lack of sufficient data. Therefore, a new approach to derive the C value has been developed as follows :

Step 1. Assuming the C value in each pipe properly
Step 2. Simulating the pipeline with an assumed C value by hydraulic simulator, KYPIPE
Step 3. Comparing computed HGL(hydraulic grade line) with observed HGL
Step 4. Adjusting computed HGL to match the observed HGL by changing the C value
Step 5. If two values are similar, generating the C value with respect to each diameter and the passing time
Step 6. Deriving the multiple regression function from generated values

The derived multiple regression function of C is

$$C = 0.052Y^2 - 3.669Y + 0.015D + 119.086 \tag{8}$$

where Y is passing time(yr).

The statistical package, SAS, used to process the data shows a good fitness.

3. Theoretical Model

3.1 Basic Algorythm

At first, the optimal treatment time of each pipe is computed by cost analysis. Eq(9) is used for predicting the best time for pipe replacement. After determining the best replacement time, the hydraulic integrity is checked by KYPIPE(Kim, 1994). The model is constructed by the FORTRAN program which computes the best replacment time and checks hydraulic integrity from interfaced KYPIPE.

If the pipe cannot satisfy the required hydraulic conditions, the pipe replacing time is advanced. This process will continue until all the pipes satisfy all the hydraulic conditions of the system.

3.2 Optimal Replacement Time

Optimal replacement times of pipes are derived from pipe maintenance cost, pipe replacement cost, and pumping curtailment cost.

$$\underset{t_r}{\mathrm{Min}}\,[P_T(t_r)] = \underset{t_r}{\mathrm{Min}} \left[\sum_{t=t_p}^{t_r} \frac{C_m(t)}{(1+R)^{t-t_p}} + \left\{ \frac{C_r}{(1+R)^{t_r-t_p}} - \sum_{t=t_r}^{t_p+t_d} \frac{C_p}{(1+R)^{t-t_p}} \right\} \right] \qquad (9)$$

where t_r is optimal replacement time, $P_T(tr)$ is the cost at time t_r, t_p is present time, t_d is project year, C_m is annual maintenance cost, R is discount rate

4. Application

4.1 Study Area

The selected water distribution system is Seoul Metropolitan Water Supply Project(Phase 1), which can supply a maximum of 1.2 million tons per day.

The model simulates 2 types of water supply. One is maximum supply and the other is ordinary supply.

4.2 Area Specification

The number of nodes including the fixed grade node is 38, in which 8 are demand nodes. The surface level of the fixed grade node(Paldang intake station) is 87.7m. The number of pipelines is 43. There are pipes from 1500mm to 2800mm in diameter and three supply tunnels are 3500mm in diameter. The supply tunnels are assumed as steel pipes in computation. There are two pumping stations. One is Paldang intake station and the other is Kimpo booster station on line 36.

4.3 Some Assumptions

The interest rate is an important factor in cost analysis and assumed as 0.14. The damage cost in the case of water supply suspension is assumed to be 0.2 million won. There are three tunnels in the area ; all are assumed as steel pipes. The minimum allowable node pressure is set as 1.5kg/cm^2.

4. 4 Results

The computation results of maximum and ordinary supply are shown in Table 1 and Table 2. The first column of the tables is the pipeline number, the second column is optimal replacing time, the third is replacing cost, and the forth is the total cost.

From both cases, there is not any resulting hydraulic problem in checking with KYPIPE, which means the condition of pipe deterioration is not serious before the replacing time.

In Table 1, the total cost of maximum supply is less than that of ordinary supply. The reason is that the curtailment cost from pumping power savings of the former is greater than that of the latter.

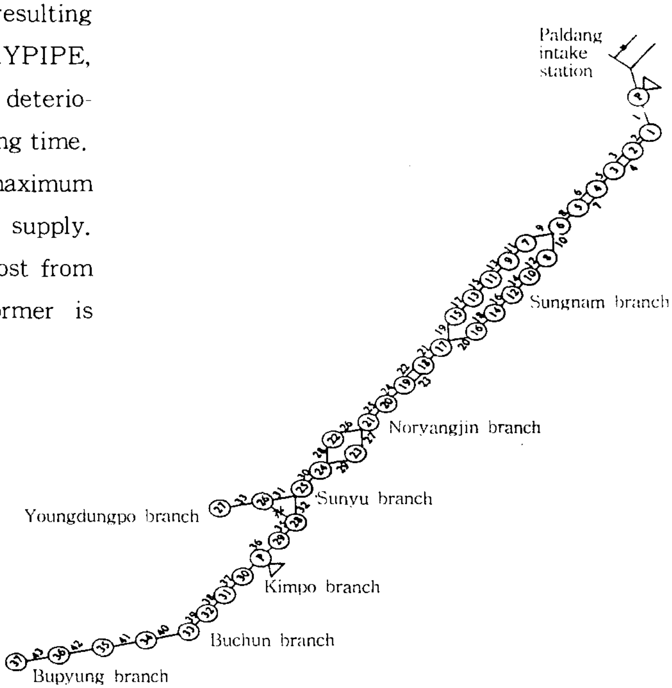

Fig. 1. Metropolitan Water Supply System (Phase 1)

Table 1. Results(Maximum Supply)

Pipe Number	Replacing time	Replacing cost(Won)	Total cost(Won)
1	2011	531,330,400	1,573,803,520
2	2014	1,191,706,496	4,082,490,368
3	2009	366,081,504	1,046,489,664
4	2009	366,081,504	1,046,489,664
5	2014	240,926,512	825,354,304
6	2009	801,968,000	2,292,525,568
7	2009	801,968,000	2,292,525,568
8	2014	232,309,168	795,833,472
9	2009	878,090,240	2,510,130,432
10	2009	878,090,240	2,510,130,432
11	2009	1,036,020,096	2,961,592,832
12	2009	1,036,020,096	2,961,592,832
13	2009	603,292,224	1,724,585,984
14	2009	603,292,224	1,724,585,984
15	2009	931,918,464	2,652,018,432
16	2009	931,918,464	2,652,018,432
17	2011	1,003,532,288	3,028,743,936
18	2011	1,003,532,288	3,028,743,936
19	2011	851,034,752	2,568,493,568
20	2011	851,034,752	2,568,493,568
21	2016	33,867,924	111,824,664
22	2011	388,622,816	1,172,895,872
23	2011	388,622,816	1,172,895,872
24	2016	474,150,944	1,565,545,216
25	2015	180,723,808	577,383,936
26	2012	466,813,280	1,467,356,928
27	2012	466,813,280	1,467,356,928
28	2012	297,063,008	933,772,608
29	2012	297,063,008	933,772,608
30	2008	31,242,416	134,477,232
31	2012	83,320,824	252,243,776
32	2012	83,308,608	252,231,552
33	2011	107,202,688	335,178,944
34	2013	7,232,266	21,942,494
35	2013	570,547,072	1,789,394,688
36	2013	452,502,816	1,419,175,040
37	2013	40,162,188	124,220,640
38	2009	222,198,048	617,879,744
39	2008	91,552,168	245,046,272
40	2008	34,971,640	92,934,448
41	2007	568,566,272	1,472,598,656
42	2007	1,301,685,248	3,371,392,256
43	2007	905,653,632	2,345,661,952
Summation		23,976,000,000	66,724,000,000

Table 2. Results(Ordinary Supply)

Pipe Number	Replacing time	Replacing cost(Won)	Total cost(Won)
1	2011	541,332,608	1,583,805,696
2	2014	1,194,079,872	4,084,863,744
3	2009	373,797,568	1,054,205,696
4	2009	373,797,568	1,054,205,696
5	2014	241,406,336	825,834,176
6	2009	818,871,424	2,309,428,992
7	2009	818,871,424	2,309,428,992
8	2014	232,771,824	796,296,128
9	2009	896,598,144	2,528,638,208
10	2009	896,598,144	2,528,638,208
11	2009	1,057,856,768	2,983,429,376
12	2009	1,057,856,768	2,983,429,376
13	2009	616,008,064	1,737,301,888
14	2009	616,008,064	1,737,301,888
15	2009	949,585,536	2,669,685,504
16	2009	949,585,536	2,669,685,504
17	2011	1,020,695,744	3,045,907,456
18	2011	1,020,695,744	3,045,907,456
19	2011	865,590,016	2,583,048,960
20	2011	865,590,016	2,583,048,960
21	2016	34,239,376	112,196,112
22	2011	395,269,440	1,179,542,528
23	2011	395,269,440	1,179,542,528
24	2016	479,351,264	1,570,745,600
25	2015	185,062,672	581,722,880
26	2012	476,578,560	1,477,122,176
27	2012	476,578,560	1,477,122,176
28	2012	303,277,248	939,986,816
29	2012	303,277,248	939,986,816
30	2008	48,551,072	151,785,888
31	2012	83,800,072	252,723,040
32	2012	83,784,728	252,707,680
33	2011	109,396,432	337,372,704
34	2013	7,228,826	21,939,056
35	2013	569,748,864	1,788,596,480
36	2013	451,869,760	1,418,542,080
37	2013	40,187,776	124,246,232
38	2009	222,276,368	617,958,080
39	2008	91,623,592	245,117,696
40	2008	34,984,328	92,947,128
41	2007	569,053,888	1,473,086,336
42	2007	1,302,801,664	3,372,508,672
43	2007	906,430,336	2,346,438,912
Summation		23,976,000,000	67,068,000,000

5. Conclusion

The objective of this study is to develop an optimal rehabilitation model for a deteriorated distribution system. The algorithm of the developed model is to determine the optimal rehabilitation time at first, and then to verify the hydraulic integrity by a pipe network simulator, KYPIPE.

Not like the other models of which main focus is to select the type of treatment and to determine the pumping capacity, the model developed in this study also determines by economic analysis the optimal replacement time(year) for the minimum operation and maintenance cost. It also guarantees a good hydraulic integrity of the water distribution system for the solution or the decision made.

The model has been applied to an existing water supply system, the Seoul Metropolitan Water Supply System(1st Phase). The optimal replacement time for the system obtained by the economic analysis did not result in any hydraulic problem to the system. It is concluded that the model developed in this study can be used as a decision-supporting one for rehabilitation schedules of old water distribution systems.

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