AN OPTIMIZATION MODEL OF SEWERAGE REHABILITATION

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ABSTRACT

Due to low visibility, sewer systems are difficult to monitor, maintain and rehabilitate. To prevent failures, environmental pollution, and wastewater treatment overflow, regular renovation of sewerage is necessary. However, sewerage renovation usually costs an immense amount of money and is hampered by a limited budget. Thus, efficient planning of maintenance and renovation for sewerage upkeep is demanded. In this paper, an optimization model has been built to find an appropriate rehabilitation strategy consisting of a renovation method and a substitute material for each pipe failure under a limited budget. The optimization model was designed to search for a Pareto curve (or trade-off front) consisting of a set of optimal solutions with desirable rehabilitation effectiveness at the least cost. This paper employs genetic algorithms (GA) to obtain a Pareto curve at a low computation cost for large and complex sewer systems. This optimization model was applied to a sewerage system in the 15th district of Kaohsiung City, Taiwan. Compared with the experts' manual estimation, the optimization model saved about 20% of the rehabilitation cost for Kaohsiung City.

Key words: sewerage rehabilitation, optimization, genetic algorithm, Pareto curve.

I. INTRODUCTION

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Sewer systems are important for a modern city, but are often overlooked because of difficulty of maintenance, monitoring, and rehabilitation caused by underground burial. However, sewages are apt to get cracks and defects due to corrosive wastewater inside and complex surroundings outside. Serious cracks and leaks may result in the inflow to sewer treatment plants exceeding the design rate due to infiltration of rainfall or underground water. Also, the leakage of sewerage from failed pipes may cause a health hazard with the possible contamination of groundwater and soil. Negligence concerning these failures increases maintenance and rehabilitation costs significantly. In order to prevent worse failures and continue to provide designed functions, regular rehabilitation of sewages is necessary (Hernebring *et al.*, 1998). Pipe rehabilitation can reduce either water infiltration into or leakage of sewage and increase the efficiency of treatment facilities and wastewater reuse opportunities (Wirahadikusumah *et al.*, 1998; Bakir, 2001; Gupta *et al.*, 2001). In addition to the construction of new municipal infrastructure, to appropriately allot limited budget on rehabilitation of the present infrastructure is another important job (Abraham *et al.*, 1998; Sægrov *et al.*, 1999; Gokhale and Hastak, 2000; Gupta *et al.*, 2001; Ariaratnam and MacLeod, 2002). Generally, sewage authorities adopt a simple rehabilitation strategy that allots rehabilitation capital to “critical sewers”, which are those pipes where collapse repair costs could be expected to be the highest (Fenner, 2000). In Taiwan, city governments used to fix all failed pipes (both critical and non-critical pipes) to keep the sewage system in good condition. However, when financial support runs into a limit, an optimization model to find the best sewerage rehabilitation plans becomes a valuable tool. Many researchers indicate that both rehabilitation method and substitution material affect rehabilitation cost and service life when sewage rehabilitation is executed (Ouellette and Schrock, 1981; Reyna, 1993; Gupta *et al.*, 2001). Therefore, this paper presents an optimization model of sewage system rehabilitation. This system has been successfully implemented in a district of Kaohsiung City, Taiwan. An appropriate rehabilitation method and substitution material for each failed pipe is expected to extend service life and control rehabilitation costs.

In this research, our trade-off problem is a multi-objective optimization minimizing rehabilitation cost and maximizing service life. Feng *et al.* (1997) and Li *et al.* (1999) combined GA (genetic algorithm) with Pareto curve and machine learning approaches, respectively, to solve construction time-cost trade-off problems (TCTP) which are also multi-objective optimization problems. Recently, Zheng *et al.* (2004) also used GA to solve TCTP based on an adaptive weight approach that efficiently searched for optimal solutions through a wide solution space to assist decision-makers in deciding an optimal total project time and cost. Goldberg and Kuo (1987) applied GA to the steady state optimization of a serial liquid pipe. Dandy *et al.* (1996) presented an improved GA for pipe network optimization. Savic and Walters (1997) applied GA to the problem of least-cost design of water distribution networks. In addition, GA also was used to solve a trade-off problem involving pavement maintenance and rehabilitation (Fwa *et al.*, 1996). All these results show that the performance of GA is satisfactory and efficient even though only a small portion of the total solution space was searched. Thus, GA was employed for determining rehabilitation methods and substitution materials for sewage system rehabilitation in this paper. This GA-based optimization model was established to search an optimal Pareto curve (or trade-off curve) consisting of multiple optimal rehabilitation plans varying with service lives and rehabilitation costs.

II. STUDY SITE

The sewerage system of the 15th district of Kaohsiung City in southern Taiwan was selected to be the study site. The sewerage system covers an area of about 0.5 km^2 and services 12,000 people. Fig. 1 is the layout of the sewerage system which has a designed underground depth of between 1.5 m and 3.0 m, and pipe diameters including 200 mm, 250 mm, 300 mm, 350 mm, 500 mm, and 700 mm (70% 200 mm and 14% 500 mm). Most of the pipes are made of RCP (Reinforced Concrete Pipe) in the sewerage system.

A CCTV (Closed-Circuit Television) inspection of this sewage system was executed in 1999 by Kaohsiung City Government prior to house connection. Those inspection records provide the distribution and patterns of sewerage failures for our optimization model of sewage rehabilitation. A settlement of sewage was found as a major problem due to the geological condition of soft alluvium.

III. SEWAGE REHABILITATION

Sewage rehabilitation is to ensure the movement of the designed capacity of wastewater. Aboveground inspection, flow monitoring, flow measurement, manhole and sewer inspection, simulation, cleaning of pipes, and internal inspection should be performed before undertaking a construction plan of sewage rehabilitation (Gupta *et al.*, 2001). After the implementation of the prior tasks, the external and internal conditions of sewer pipes can be known, and then the identification of appropriate rehabilitation methods and substitution materials becomes the most important consideration affecting the cost-effectiveness of a rehabilitation plan (Ouellette and Schrock, 1981; Gupta *et al.*, 2001). Four rehabilitation methods and four substitution materials are available in our sewerage rehabilitation plans and are briefly addressed as follows.

1. Rehabilitation Methods

Nowadays the four most popular rehabilitation methods include renewal, renovation, trenchless replacement, and excavation replacement. Rehabilitation costs of each pipe are quantitatively estimated for four rehabilitation methods as follows. The cost of trenchless replacement and excavation replacement is the sum of inspection cost, rehabilitation method cost, substitution material cost, and social cost in separate equations, whereas the costs of renewal and renovation are estimated in one empirical equation.

(i) Renewal

Both external and internal conditions can be improved through grouting, spray-on lining, link-seal, shotcrete, coating, and epoxy, especially for repairing a slight crack by chemical or concrete grouting (Abraham and Gillani, 1999). External cracks and joint openings are renewed from the ground surface by excavation; however, nowadays more and more external remedies can be performed from the inside due to the mature development of trenchless technologies (Ouellette and Schrock, 1981; Chin and Lee, 2005). The main effects of renewal include (1) making the displaced joints and non-support sewers more stable; (2) reinforcing damaged sewers; and (3) sealing up the chinks of the damaged sewers prevents infiltration and inflow. The rehabilitation cost (*C*) depends on the diameters of sewer pipes (*D*) and can be roughly estimated based on investigation data from Kaohsuing, amassed by the city government in 1999 (Kaohsiung City Government, 1999):

$$C = 20660 + 74.1 * D, \tag{1}$$

where *C* = cost per meter (NTD/m); *D* = diameter (mm).

(ii) Renovation

Renovation inserts a new pipe material into the old deteriorated sewer pipe and has become a popular trenchless rehabilitation method (Ariaratnam and MacLeod, 2002). Renovation includes cured-in-place pipe (CIPP), close fit lining, and sliplining which use flexible tubing to create a new pipe within the original pipe. The tubing is also inserted into the old deteriorated sewer pipe from a manhole without need for special excavations, so that there is little traffic control trouble, low labor intensity, and rapid completion (Ouellette and Schrock, 1981). The rehabilitation cost can be estimated by an empirical equation as (Kaohsiung City Government, 1999):

$$C = 5400 + 60 * D. \tag{2}$$

(iii) Excavation and Trenchless Replacement

Excavation and trenchless replacement both replace existing pipes with new pipes. Replacement cost is much higher than other rehabilitation methods, but can efficiently extend service life of pipes. Due to alternative rehabilitation methods and various substitution materials for replacement, rehabilitation costs (C) of trenchless replacement and excavation replacement can be estimated as a sum consisting of inspection cost (C_i), rehabilitation method cost (C_r), substitution material cost (C_m), and social cost (C_s) as:

$$C = C_i + C_r + C_m + C_s, \tag{3}$$

$$C_r = 30 * D + 16300, \quad \text{for trenchless} \tag{4}$$

$$\begin{aligned} C_r &= 0.0118 * D^2 + 742.7 * H^2 + 1.18 * D * H \\ &\quad -1578.5 * H + 1.9 * D + 5810 \end{aligned}, \quad \text{for excavaiton} \tag{5}$$

where C_r = cost per meter (NTD/m); H = depth under the ground (m).

In this paper, inspection cost is about 400 NTD/m according to the past inspection cases executed in Kaohsiung City; rehabilitation method costs of trenchless repair and repair needing excavation can be estimated by Eq. (4) and Eq. (5), respectively (Ouyang, 2001); and substitution material costs vary with the substitution materials according to categories of pipe as in Table 1. It is always difficult to quantify social cost due to its uncertainty. Generally, trenchless repair costs more than repair with excavation in rehabilitation cost, whereas trenchless causes lees environmental impact and has a lower social cost than excavation. Based on a quantitative analysis of social costs for underground pipeline construction in Taiwan, rehabilitation costs of trenchless repair and repair with excavation are multiplied by the coefficients, 0.3 and 0.8, to approximately estimate the social costs, respectively (Yu, 2003).

2. Substitution Materials

In Taiwan, RCP (Reinforced Concrete Pipe) was adopted in most sewage pipe constructions because of its lower cost. However, RCP sewer pipe has a high probability of failure while being attacked by surrounding impacts, such as traffic loads or earthquakes. In addition to RCP, HDPE (High Density PE), GRP (Glassfiber Reinforced Plastic), and VCP (Vitrified Clay Pipe) are also taken into consideration to substitute for failed sewer pipes nowadays. Table 1 lists the costs of the substitution materials based on our survey of the Taiwan market. The characteristics of the substitution materials are briefly summarized in Table 2.

IV. A GA-BASED OPTIMIZATION MODEL FOR SEWAGE PIPE REHABILITATION

This section shows how a GA-based optimization model is established for making a sewage rehabilitation plan by minimizing rehabilitation cost and maximizing service life. In order to solve this trade-off problem, a Pareto curve must be found first. Most real-life problems, such as sewage rehabilitation, are complicated by large scale so that the traditional optimization methods, such as exhaustive search or linear programming, require extensive computational time when searching for optimal trade-off solutions. GA, an evolutionary optimization technique has been considered as a robust and powerful tool in various engineering problems for the last couple of decades (Balla and Lingireddy, 2000; McCrea and Navon, 2004). The search techniques of GA are stochastic, based on the mechanism of natural selection and natural genetics (Feng *et al.*, 2004). There are three major advantages in applying GA to optimization problems. First, GA doesn’t need complicated mathematical requirements and many model coefficients for optimization are friendly for general users.

Unlike many optimization algorithms based on nonlinear programming and optimal control theory, there is no requirement for objective functions to be differentiable for GA (Sharif and Wardlaw, 2000). Secondly, the periodicity of evolutionary operators makes GA very effective at searching for global solutions and provides multiple solutions (Gen and Cheng, 1997; Caldas and Norford, 2002). GA can quickly and reliably find out optimal solutions (Goldberg, 1989; Gen and Cheng, 1997; Goldberg, 2000). A series of steps to establish a GA-based optimization model for sewage rehabilitation is as follows (Dandy *et al.*, 1996; Chipperfield *et al.*, 2004; Yang and Yang, 2004).

Step 1: Preprocess

A sewer pipe (defined as a segment of pipeline between two manholes) in good condition needs no rehabilitation. Also, a sewer pipe that has a failure with a crack length ≤25% of the pipe length can be excluded from the following optimization processes, because renewal such as chemical grouting or concrete grouting is the best way to fix the crack (Liao, 2000). Rehabilitation methods and substitution materials can be determined, prior to repair, for these two kinds of sewer pipes, which need no GA operation for rehabilitation optimization.

2. Chromosome Coding

Genetic algorithm operation starts with encoding strings, so-called chromosomes. A chromosome represents a solution of problems and is encoded by a binary, integer or real number. In this paper, a chromosome is encoded by integer numbers representing two decision variables, including rehabilitation method (RM_i) and substitution material (SM_i). A model for encoding a chromosome is shown as Fig. 2, in which the code of RM_i can be one of 1 (renovation), 2 (trenchless replacement), or 3 (excavation replacement); the code of SM_i can be one of 1 (HDPE), 2 (RCP), 3 (GRP), and 4 (VCP). Among them, HDPE is the most common material for renovation, assigned to those pipes that need to be rehabilitated by renovation (Ouellette and Schrock, 1981). Fig. 3 presents the relationship between substitution materials and rehabilitation methods.

3. Generating an Initial Population

GA randomly generates an initial population (*N*) representing the number of possible solutions (typically *N*=100 to 1000; *N*=500 in this research). A large population size means a broad searching space that requires extensive computational time.

4. Estimation of Total Rehabilitation Cost

Through Eq. (1) to Eq. (3), the rehabilitation cost of a pipe can be estimated. Then, the total rehabilitation cost for the entire sewer system is quoted by summing up the rehabilitation cost of every pipe.

5. Estimation of Rehabilitation Efficiency

The longest service life of pipes at the least cost is the objective of this optimization. Ideally, the service life of downstream pipes should be longer than upstream ones. This research takes the geometric importance of pipes into consideration based on Strahler's theory, which is commonly used to classify individual river segments in a basin by assigning stream orders to the river segments. Using Strahler's theory, Garbrecht and Martz (1997) proposed channel ordering for automated interpretation of channel networks, Vorosmarty *et al.* (2000) assigned stream order to individual river segments to classify and explore the geomorphometric characteristics of potentially-flowing rivers, and Schmidt (2005) classified sampling sites to investigate dissolved uranium content in the watershed. Considering a sewer system as a drainage basin, we gave the upper pipes a grade 1 and the conjunction pipes a grade 2, and so on. Fig. 4 is the weighting scheme for the importance of a pipe according to its position on a branched network in the sewerage system in the 15th district of Kaohsiung City by applying Strahler's theory. The rehabilitation efficiency can be calculated by the weighted service life of a pipe as:

$$E = \frac{\sum_{i=1}^{n} G_i Y_i}{\sum_{i=1}^{n} G_i}, \qquad (6)$$

where E = rehabilitation efficiency; n = the total number of pipes; Y_i = service life of the i^{th} pipe; and G_i = geometric grade of the i^{th} pipe.

6. Computation of Fitness

After steps 4 and 5, each genetic string can be located in the solution space along the dimensions of rehabilitation cost and service life. A genetic string with a low rehabilitation cost and a high service life has a large fitness number. The larger the fitness is, the higher the probability of the genetic string being copied to the next generation is. The fitness (f_j) of genetic string j (GS_j, j = 1 to N) within the parent population is calculated as:

$$f_j = d_{\max} - d_j, \tag{7}$$

$$d_j = \min_k \left(\left\| GS_j - PS_k \right\| \right), \tag{8}$$

$$d_{\max} = \max(d_j), \tag{9}$$

where d_j is the minimum distance between genetic string j and each Pareto string (PS_k), which is a genetic string on the Pareto curve; and $d_{\max}$ is inserted to assure the fitness being always positive (Sarkar and Khajehpour, 2002) (see Fig. 5). The closer to the Pareto curve a genetic string is, the larger its fitness is. Each Pareto string has the maximum fitness due to a zero-distance to the Pareto curve.

7. Generation of the Next Population

The next population is produced by copying the genetic strings which have a fitness in the fittest 40% of the parent population by tournament selection and randomly generating the other 60% of genetic strings. All strings on the Pareto curve of a population have the largest fitness and the first priority of survival for the next generation.

8. Crossover Operator

Crossover is the partial exchange of genes between two parent strings to form two offspring strings. The forms of crossover include single-point crossover, multi-point crossover, and uniform crossover. This research adopts single-point crossover. The crossover operator exchanges the genes in two selected parent strings after the crossover point that is randomly selected within the strings. To find an optimal Pareto curve quickly, high crossover probabilities (P_c=0.5 to 1.0) are suggested (Dandy *et al.*, 1996). In this paper the genetic operation was run with crossover probabilities of 0.5, 0.6, 0.7, and 0.8.

9. Mutation Operator

Mutation is designed to avoid local optimal solutions and is randomly applied with a low probability of 0.001, typically in the range of 0.001 to 0.01. In this paper, uniform mutation was adopted to efficiently enlarge the searching space (Chipperfield *et al.*, 2004).

10. Termination Criterion

Processes addressed in steps 4 to 9 are repeated to generate successive generations until a new generation has no further enhancement toward a lower cost or 700 generations are completely generated.

V. RESULTS AND ANALYSIS

Inspection of the failures of sewer pipes is an essential process to provide adequate information for determining a sewage pipe rehabilitation strategy. A GIS-environment database for basic parameters, such as diameters, depths, pipe lengths, failure lengths, pipe grades, and failure conditions was established as reference. Based on the inspection record of the sewerage system in the 15th district of Kaohsiung City, there were 59 of 63 failed pipes within the sewerage system which needed to be evaluated for one of three alternative rehabilitation methods and one of four alternative substitution materials. Thus, the solution space is formed of $2^{59}\times4^{59}$ (or 1.9×10^{53}) possible rehabilitation plans.

Crossover probabilities of 0.5, 0.6, 0.7, and 0.8 were tested to obtain optimal Pareto curves that took about 200 seconds on Pentium IV 1.3G PC for each case. Fig. 6 shows that the difference between four found optimal Pareto curves is not significant. In other words, crossover probabilities were not a major factor influencing the optimization result. The overall optimal Pareto curve consists of the best rehabilitation plans from each test and ranges from 23.5 0 to 23.80 million NTD varying with adopted rehabilitation methods and materials for the complete rehabilitation shown as Fig. 7. Based on experts' manual design, Kaohsiung City Government in 1999 finished a complete rehabilitation for this sewer system at the total rehabilitation cost of about 28 million NTD. In comparison, the optimization model offered a complete rehabilitation plan at a reduction of 20% from the expert's estimate. Besides, a social cost was considered in our model estimation but was excluded in the government's rehabilitation cost. Thus, it is shown that the Pareto curves found by the optimization model can provide acceptable and sophisticated rehabilitation plans at less cost.

All of the Pareto solutions are optimal rehabilitation plans varying with service life and rehabilitation cost. In other words, the Pareto solutions achieve a maximum service life of sewage pipes under a specific total rehabilitation cost. The service life of pipes is rapidly increased by the increase of the total rehabilitation cost. Up to 23.6 million NTD, the rehabilitation effectiveness increases slowly with the increase of total rehabilitation cost. This Pareto curve provides information to the municipal authority and provides a quantitative reference to determine the rehabilitation budget for a planned sewage pipe service life.

In this Pareto curve each rehabilitation plan consists of an appropriate rehabilitation method and substitution material for each failed pipe that can be visually displayed in GIS. Fig. 8 shows the layout of rehabilitation methods and substitution materials for the 14th best rehabilitation plan. The optimization results reveal that excavation replacement has a higher probability to be employed in this rehabilitation plan. On the other hand, renovation has an employment probability of only about 20% in the rehabilitation plan, whereas trenchless replacement is not employed because of its high increase in construction cost with low reduction in social cost in this area. As to the selected substitution materials, about 50% of failed pipes are replaced by VCP to maintain the capacity to collect a great amount of sewage, especially the failed pipes with higher geometric grades. Applying this optimization model, decision-makers can clearly determine appropriate rehabilitation methods and substitution materials for failed pipes.

VI. CONCLUSIONS

Due to the complexity of a sewer infrastructure, the trade-off problem of sewer rehabilitation is a large scale optimization problem. A GA-based optimization model proposed in this paper was proven to be capable of producing optimal rehabilitation plans. Each rehabilitation plan provides for each failed pipe, both appropriate rehabilitation method and substitution material that are considered as the most important factors affecting the overall efficiency. This paper set a population size of 500, total generations of 700, a mutation probability of 0.01, and the crossover probabilities of 0.5, 0.6, 0.7, and 0.8 to obtain the optimal Pareto curve. The Pareto curve provides optimal rehabilitation plans by assigning an appropriate rehabilitation method and substitution material to each failed pipe to achieve the longest service life at the least cost. The optimization model reduced the rehabilitation cost to a range of 23.4 to 23.8 million NTD for a complete rehabilitation for the sewerage system in the 15th district, whereas the Kaohsiung City Government spent 28 million NTD on a complete rehabilitation in 1999. Compared with the traditional experts' estimation, the optimal model reduced, by about 20% the rehabilitation cost for the district in Kaohsiung City, which proved the utility of the automatic optimization model. Moreover, the social cost was considered in our model which was not covered in the city government's expense.

In this research, rehabilitation cost was estimated as a total of inspection cost, rehabilitation method cost, substitution material cost, and social cost. However, most of the cost estimates were referenced to a market survey or to empirical equations that, especially the social cost estimate, should be studied with more effort in the future to improve quotation accuracy. Also, practical construction limitations should be considered so to make the optimal rehabilitation plans more feasible.

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Table 1 Prices of the pipe materials

Diameter	RCP	HDPE	GRP	VCP
225mm	900	800	1250	1300
250mm	954	978	1435	1545
350mm	1280	1900	2400	2700
450mm	1700	3300	3500	4600

Note: unit of price=NTD (New Taiwanese Dollar); 1 NTD = 0.033 US dollar

Table 2 Characters of the pipe materials

Items	RCP	HDPE	GRP	VCP
Property	Rigid	Flexible	Flexible	Rigid
Diameter (mm)	DN150~DN3000	DN40~DN400	DN25~DN2400	DN100~DN1200
Service life (years)	25	50	75	100
Manning’s N value	0.015	0.011	0.008	0.012
Unit length (m)	2.3	5	6~12	1.5~3

Note: DN stands for nominal diameter (source from Chinese National Standards)

Figure captions

Fig. 1. Layout of the sewerage in the 15th district of Kaohsiung City

Fig. 2. An example for possible chromosome coding

Fig. 3. Encoding rule for rehabilitation methods vs. substitution materials

Fig. 4. Geometric grades of sewer pipes

Fig. 5. Fitness evaluation of genetic strings

Fig. 6. Pareto curves resulting from P_cs of 0.5, 0.6, 0.7 and 0.8

Fig. 7. Optimal Pareto curve of sewer rehabilitation

Fig. 8. GIS Displays of rehabilitation optimization results

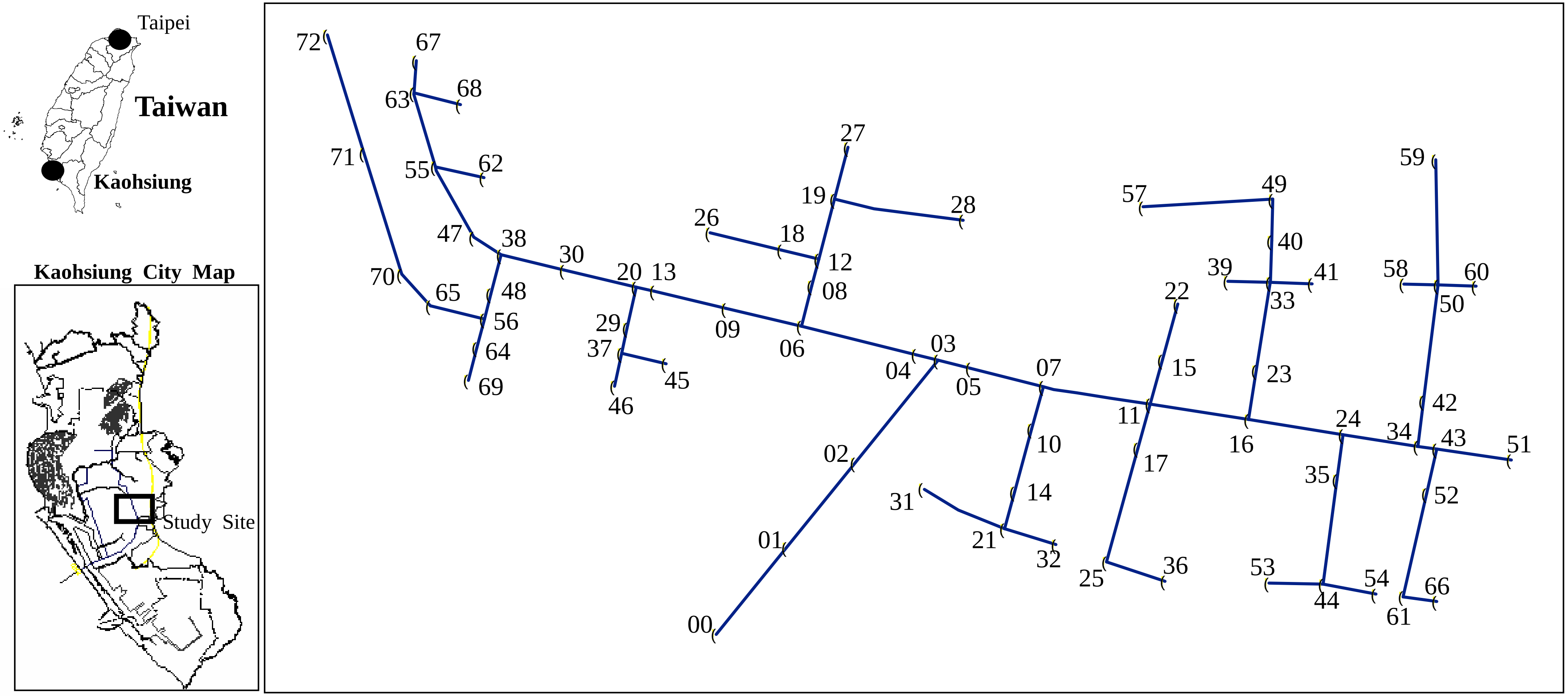


Fig. 1. Layout of the sewerage in the 15th district of Kaohsiung City

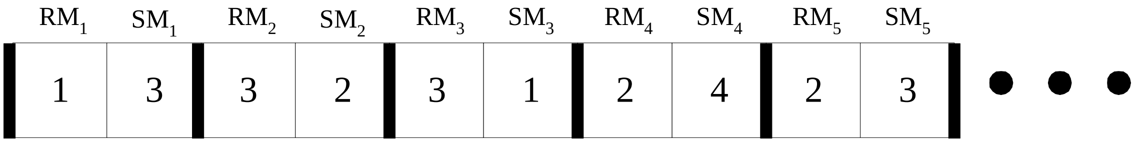


Fig. 2. An example for possible chromosome coding

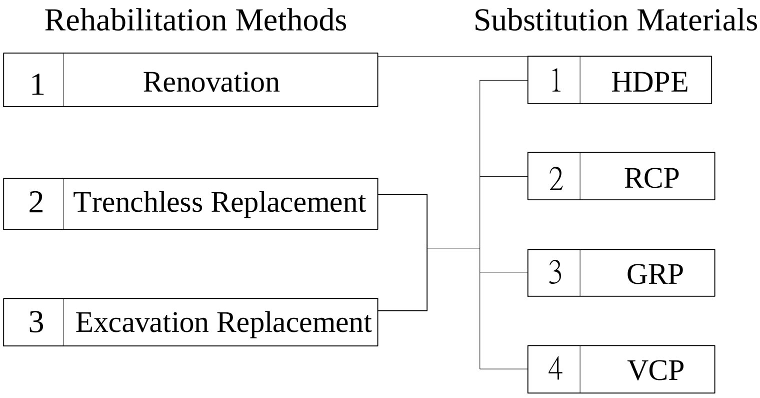


Fig. 3. Encoding rule for rehabilitation methods vs. substitution materials

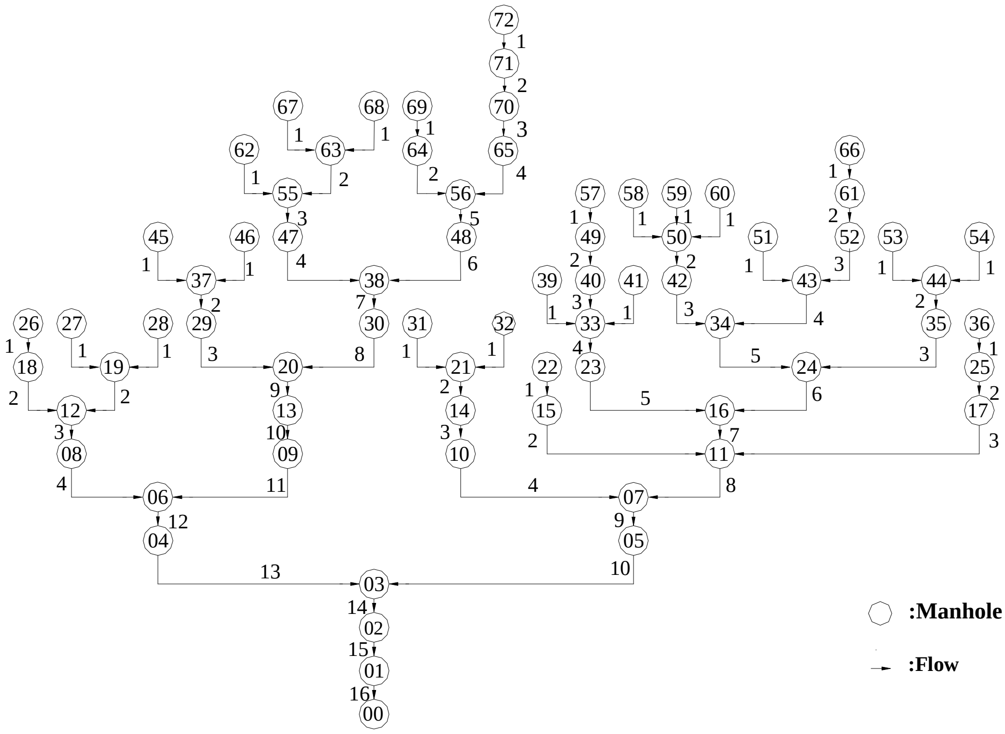


Fig. 4. Geometric grades of sewer pipes

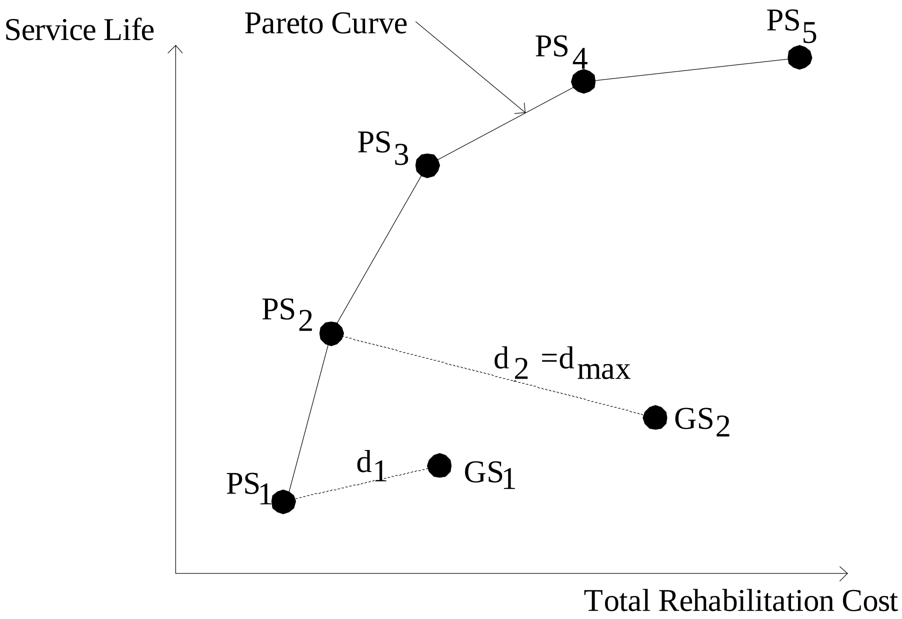


Fig. 5. Fitness evaluation of genetic strings

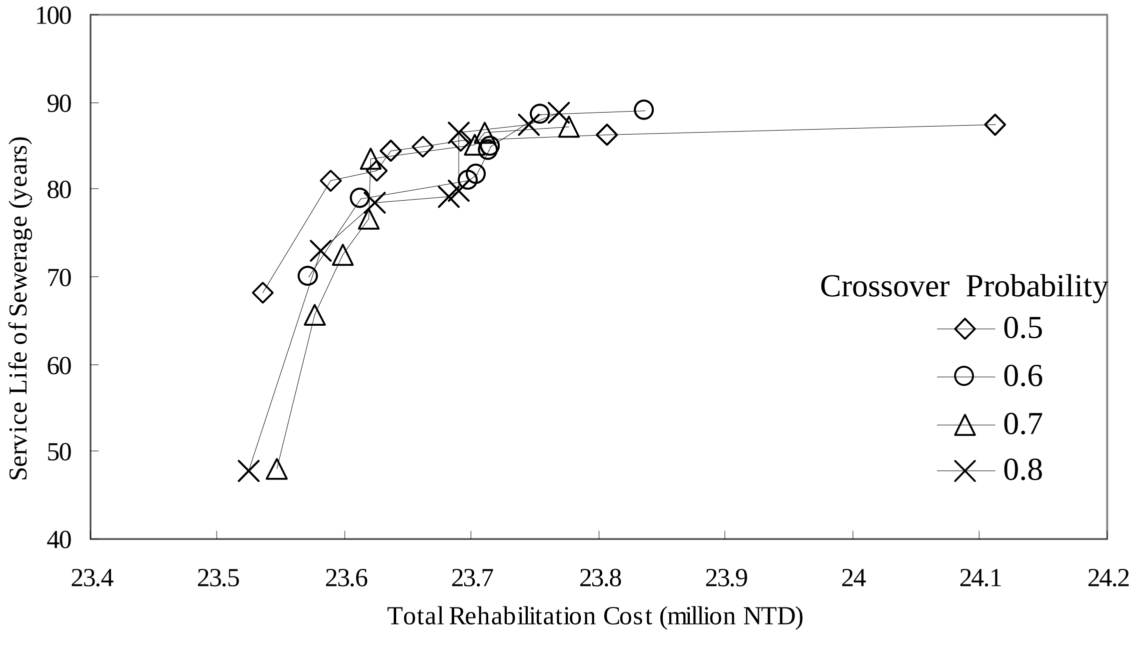


Fig. 6. Pareto curves resulting from crossover probabilities of 0.5, 0.6, 0.7 and 0.8

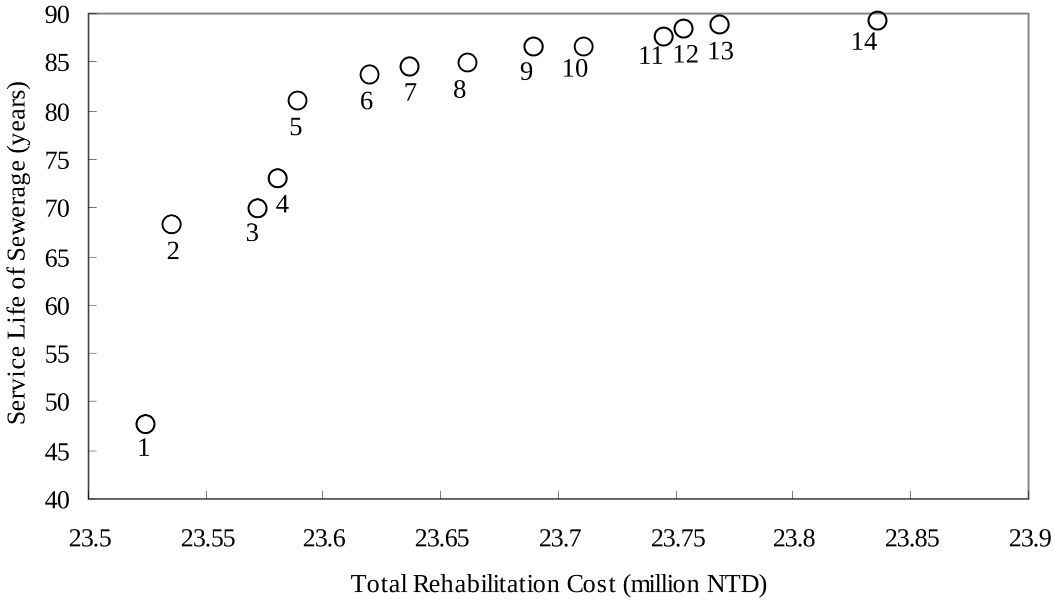
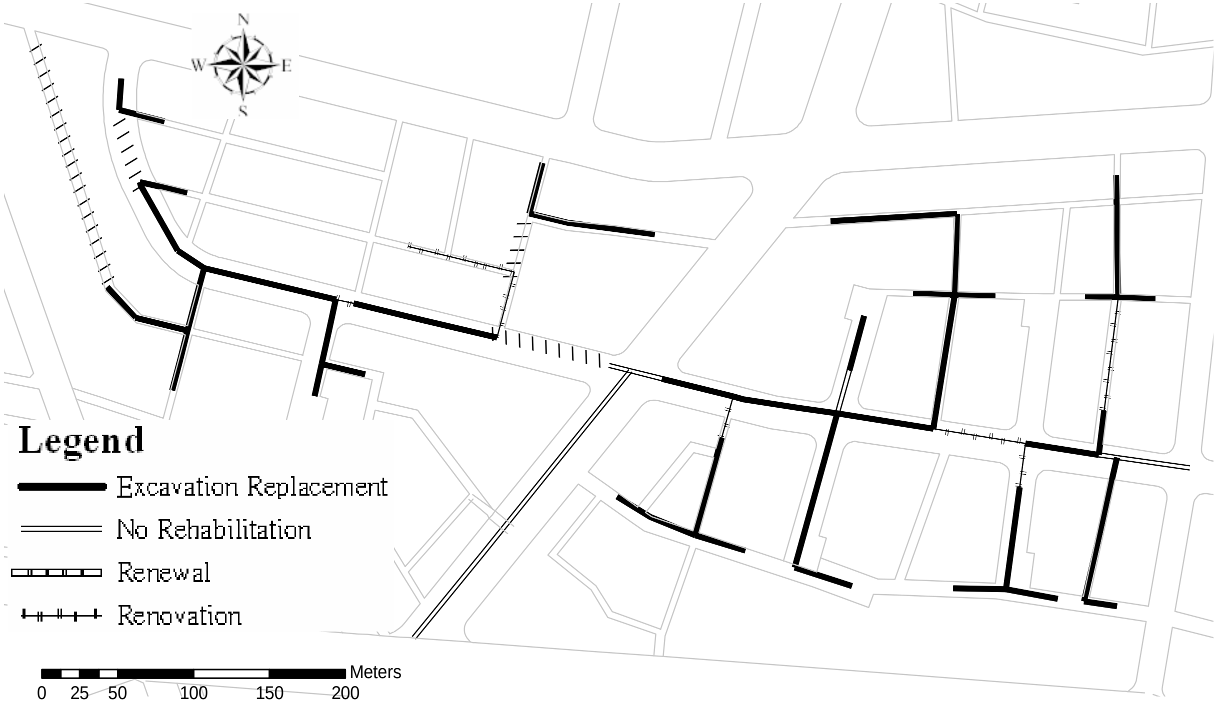


Fig. 7. Optimal Pareto curve of sewer rehabilitation



(a) Layout of rehabilitation methods

(b) Layout of substitution materials

Fig. 8. GIS displays of rehabilitation optimization results