06JEI00068
1726-2135/1684-8799

www.iseis.org/jei

Journal of Environmental Informatics 7(2) 66-74 (2006)

A Sewer System Optimization Hydraulic Design Model

H. T. Weng* and S. L. Liaw

Graduate Institute of Environmental Engineering, National Central University, Chungli 32054, Taiwan

ABSTRACT. In this study, a branched gravity sewer system design problem is treated as a serial multi-stage multi-option system, composed of a series of sewer pipes and manholes. An optimal hydraulic design is made possible by selecting from the several different commercial pipe sizes available as options for each sewer pipe stage, which are determined by a detailed hydraulic analysis, the goal of which is to meet the design criteria at a minimal cost. In this work a 0-1 mixed integer optimization model is adopted, which uses an efficient screening algorithm, the intelligent Bounded Implicit Enumeration (BIE) algorithm, to develop the Sewer System Optimization Model (SSOM) which in turn can be used to find the optimal hydraulic design. In the modeling one also has to provide a set of design variables (corresponding to the various construction modes) for urban sewer system design problems. This approach can lead to obtaining design results that compared with other optimization models and techniques are more practical and cost-effective. Finally, a case study of a 73-manhole project is conducted to verify the optimal hydraulic design found by the SSOM model.

Keywords: Bounded Implicit Enumeration, 0-1 mixed integer programming, multi-stage multi-option system, standard commercial diameter, system layout

1. Introduction

A sewer system generally takes advantage of gravity to collect and transport sewage from house to treatment plant, through a network of hydraulically designed pipes which include household connection pipes, as well as secondary and trunk sewer pipes. The sewer pipe-network, the manholes, the pumping stations and other related appurtenances are all connected. Once the layout of a sewer network is determined, the main effort of the optimal hydraulic design program is to select the size and the slope of the sewer pipes that best meet the design criteria and regulatory standards, at a minimal cost.

The design principles and processes of sewer systems may be simple, but to find the least-cost system layout and best hydraulic design is surely not an easy problem for design engineers. The process of sewer system planning and design may be divided into two major phases: (1) the selection of the network layout; and (2) the hydraulic design of the sewer pipes for the selected layout (this requires the determination of the discharge rates, the pipe sizes, the slopes, and the piping invert elevations) (Tekeli and Belkaya, 1986).

In practice, sewerage projects are often planned by manually generating a network layout that will meet the needs of the population to be served, that also fits the street layout and the local topography in the sewage tributary area. A hydraulic design is then made and the pipe sizes and excavation depths for this specific layout are found. However for an optimal analysis procedure, a branched gravity sewer system hydraulic design problem could be viewed as a serial of multi-stage multi-option system composed of a series of sewer pipes and manholes. The number of the possible design alternatives is always very huge and consequently the process for finding the optimal solution long.

Obviously, the results of the manual generation process are also limited by the designing engineer's experience and intuition and only a very small number of possible alternatives can actually be evaluated. Sometimes the final design is deficient. There is no guarantee that it is the best design. The finding of an optimal sewer system is more difficult for engineers, particularly with the large networks necessary for an urban sewer system.

The dependency on manual calculation limits the evaluation of alternatives and this has inspired many computerized optimization model studies. Mathematical models and algorithms can be solved with the aid of high speed computer calculations, which alleviates the need for the time-consuming manual computations necessary to find cost-effective designs. In fact, much effort has already been made to develop models to find optimal hydraulic designs prior to the construction of new branched sewer systems. Such models are better than traditional approaches in terms of effectiveness and efficiency. However, the available models for completing hydraulic designs require extensive computation necessitating excessive execution time. The developing of a complete hydraulic design optimization model collocated with an efficient algorithm had been the goal of computerized optimization model studies for many years. The selection of an efficient "screening algorithm" to solve these sewerage multi-design problems is the key point for the efficient resolution of an "optimization model". In particular the discrete optimization techniques, i.e.

* Corresponding author: tyng@ms14.hinet.net

dynamic programming and integer programming have often been used.

In the past three decades, many examples of computerized hydraulic design optimization models or screening algorithms have been developed. Some of these models are mentioned as follows: non-linear programming (Holland, 1966, 1967; Swamee, 2001); linear programming (Deiniger, 1973); dynamic programming (Merrit and Bogan, 1973); convex separable mixed integer programming; dynamic and linear programming (Wen and Kuo, 1982); non-uniform state increment dynamic programming (NIDP) (Orth and Hsu, 1984); bounded implicit enumeration (BIE) (Liaw and Lin, 1990, 1991; Weng et al., 2001); heuristic approach (Charalambous and Elimam, 1990); GIS-based approach (Agbenowosi, 1995; Greene et al., 1999).

Unfortunately, most of the previously developed optimization models have been programmed based on the traditional open-cut method, therefore it is not practical to apply them to modern sewerage construction. More complete optimization models, which consider different design variables that are responsive to the various construction modes, are introduced. In Taipei city, for example, where narrow heavily built-up urban streets are the norm, construction using the traditional open-cut method has almost been completely replaced by the novel trenchless (non-digging) technologies (such as the Shield Driving Method, the Jacking Method, or the Micro Tunneling Method) to overcome the existing obstructions. Thus, a good optimization model for an urban sewer system needs to both satisfy the hydraulic design criteria and to avoid construction hindrance problems that occur in the real world.

The Sewer System Optimization Model (SSOM) was established with the afore-mentioned practical problems in mind. It is a 0-1 mixed integer optimization program, using the intelligent Bounded Implicit Enumeration (BIE) algorithm, and can be run on a personal computer. The development of the SSOM has already been partially discussed by Weng and Liaw (2003) who made a case study of the construction of a practical Taipei sewer system. In the case of urban sewerage design, any existing on-site construction problems must be considered before-hand. Possible hindrances can be avoided through selecting the appropriate construction mode. Thus, they developed an optimization model for an urban hydraulic sewer system design based on the Micro Tunneling method. When the SSOM results were compared with the traditional design approach we see that the model had the effect of saving construction costs, about 12% on piping and 40% on the pumping heads. In addition, Weng and Liaw (2005) recently developed the sewer system layout optimization model, GA/SSOM/LH. They established a combinatorial algorithm process for considering the problems of "network layout" and "hydraulic design" optimization simultaneously, by combining the fundamental principles of the GA, to generate possible "network layouts", based on SSOM for checking the "hydraulic design". In both of these solution procedures a screening process is performed to find the best sewer system layout by checking the overall least-cost hydraulic design for several possible alternate network layouts. Next, how the SSOM can be applied to a common hydraulic design module of a complicated sewer system layout optimization model for new urban sewerage construction in Taiwan is described in detail.

2. Fundamentals of the Applied SSOM Hydraulic Processes

A branched gravity sewer system can be viewed as a serial multi-stage multi-option system. For each sewer pipe stage, there are several different commercial pipe sizes available as options. The best choice of commercially available standard diameter is not only determined by evaluating many detailed hydraulic processes, to find the one that best meets the design criteria at a minimal cost, but also considers the available sizes on the market. In the established SSOM, the hydraulic design problem can be efficiently solved by using the Bounded Implicit Enumeration (BIE) screening algorithm. Therefore, we must build the proper algorithm scheme for the basic hydraulic design problem before SSOM optimization can be done.

2.1. Building the Basic Hydraulic Design Problem

The basic hydraulic design problem scheme of the SSOM, based on fundamental hydraulic processes, is shown in Figure 1. In the scheme, the sewer pipe stage makes up the section between the manholes or the pumping stations. For each pipe, there are several different standard commercial diameters available as options. Each specific pipe size, D_{ij}, corresponds to a minimal slope, S_{ij}, which is obtained by comparing the four designed slopes associated with: (1) the minimal depth of cover; (2) the maximal flow velocity; (3) the minimal flow velocity of a partial flow (Benson, 1985); and (4) the hydraulic force due to gravity (Orth and Hsu, 1984; Orth, 1986; Lin, 1990). Moreover, any existing on-site construction problems must be considered, hopefully avoiding any hindrances by selecting the appropriate construction mode. Therefore, one needs to consider a set of different design variables that corresponding to various construction methods.

As shown in Figure 1: (1) Cases *#1*, *#2* and *#3* utilize the different construction modes, such as the open-cut approach and the trenchless technologies, which can be easily selected. For an urban sewer system design case, the hindrances need to be considered so as to avoid the on-site construction problems; (2) the constraints *#1*, *#2* and *#3* point out the response to the limitations for each stage, such as passing through a predetermined elevation or designating the site of a pumping station; (3) the D_{ij} (meter) indicates the commercial standard diameter of the *j-th* option of *i-th* stage; the S_{ij} (%) indicates an optimal slope for the specified diameter D_{ij}, where the stage i = 1, 2,…, n and the option j = 1, 2, …, m; (4) the {D_{ij}, S_{ij}} points out the associated values of D_{ij} and S_{ij} which were obtained from a hydraulics process for one selected construction mode case; (5) the associated couples {*Di1*, *Si1*}, {*Di2, Si2*}, …, and the {*di1*, *si1*}, {*di2*, *si2*}, …, for Cases *#1* and *#2,* respectively,

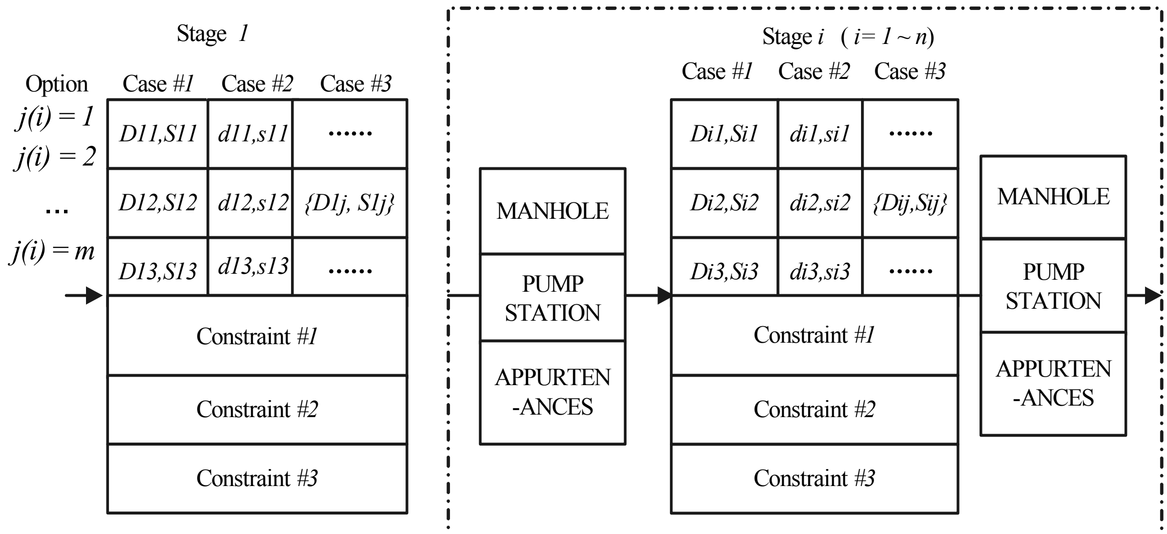


Figure 1. The basic SSOM hydraulic design problem.

represent the associated $\{D_{ij}, S_{ij}\}$ responses to the different construction modes.

In addition, for an optimal purpose, the associated values for the D_{ij} and the S_{ij} are then produced from the sewer pipes cost-slope relationship curve. The fundamentals of the sewer pipes cost-slope relationship curve are illustrated as follows.

2.2. The Resultant Sewer Pipe Cost-Slope Relationship Curve for Each Stage

Assuming a constant inflow flow-rate and a fixed upstream depth, the $\{D_{ij}, S_{ij}\}$ associated with each stage can be figured out using the cost-slope relationship curve, which can in turn give the minimum cost for different standard commercial diameters. Here, the hydraulics of the associated $\{D_{ij}, S_{ij}\}$ includes two main formulization steps:

2.2.1 Searching for Feasible Diameters

Given a constant flow rate, Q, the minimum feasible diameter ($D_{\min}$) and maximum feasible diameter ($D_{\max}$) can be derived by using the Continuity Equation to calculate the minimum flow velocity ($V_{\min}$) and maximum flow velocity ($V_{\max}$). Given the minimum and maximum feasible diameters, the standard commercial diameters, D, can be selected on the basis of what is available commercially. The formulas for basic hydraulic analysis are presented by Equations (1-a) to (1-c).

(1) Continunity Equation:

$$Q = \frac{\pi}{4} D^2 V \tag{1-a}$$

(2) Maximum feasible diameter:

$$D_{\max} = \left(\frac{4Q}{\pi V_{\min}} \right)^{0.5} \tag{1-b}$$

(3) Minimum feasible diameter:

$$D_{\min} = \left(\frac{4Q}{\pi V_{\max}} \right)^{0.5} \tag{1-c}$$

where $D_{\min} \leqq D \leqq D_{\max}$; $D_{\max}$ is the maximal feasible diameter; $D_{\min}$ is the minimal feasible diameter; D represents the standard commercially available diameters.

2.2.2 Selecting an Optimal Slope

Given a fixed upstream depth, the Manning's Formula can be used to determine the four designed slopes, S_p, $S_{\min}$, S_c, and $S_{\max}$. The equations applied to an optimal slope are described as follows:

(1) The partial flow slope (S_p): As the actual flow-rate (Q) is less than the capacity carried through the minimum standard commercial diameter (D_m) (see subsection 2.2.1) it is necessary to adjust the slope to be larger, and the flow velocity is no less than the $V_{\min}$. Thus the requirement of the limited $V_{\min}$ shown in Equation (2-a) will be met. Then the S_p can be calculated by Equation (2-b):

$$Q \leq \frac{\pi}{4} D_m^2 V_{\min} \tag{2-a}$$

$$S_p = 3.49 n^2 D^{0.14} Q^{-0.73} V_{\min}^{2.7} \quad \text{(2-b)}$$

where n is the roughness coefficient of the piping as determined with the Manning's formula; the D_m is the minimum commercially available standard diameter.

(2) The minimum slope (S_{min}): As sewage in the pipe is transported by gravity and the diameter is fixed, the steeper of the slope, the larger the amount of flow that can be carried away. The slope should be the minimal slope where the flow rate is equal to the demand flow:

$$S_{\min} = \frac{\left(\frac{nQ}{0.312}\right)^2}{D^{\frac{16}{3}}} \quad \text{(2-c)}$$

(3) The minimal slope of coverage (S_c): This is the slope obtained from the upstream crown elevation of the pipe compared to the ground elevation minus the minimal depth of cover at the downstream crown elevation. In brief, it is the minimum amount of soil cover that meets the design criteria.

(4) The maximal velocity slope (S_{max}): Use the limited maximal flow velocity (V_{max}) in the Manning formula to calculate the maximal slope:

$$S_{\max} = \left(\frac{nV_{\max}/0.397}{D^{2/3}}\right)^2 \quad \text{(2-d)}$$

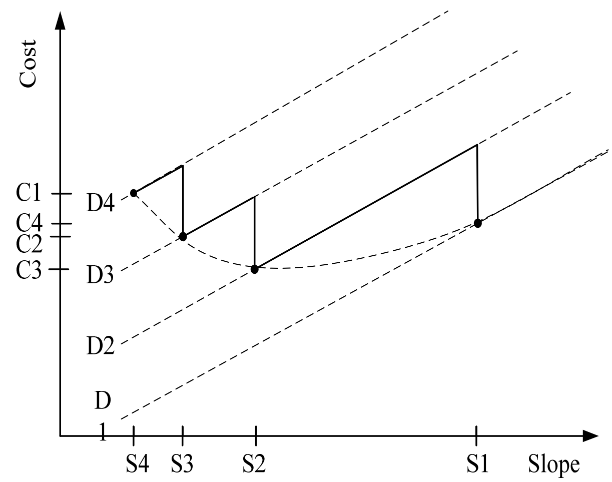
(5) As mentioned above, it can be concluded that the selection of the optimal slope can be completed while comparing the following four conditions:

- Slope = S_p means that the flow rate (Q) is no more than the calculated minimal flow velocity and the minimal diameter;
- $S_c < S_{min}$, that is the minimum coverage requirement is met, and no less than the minimal slope obtained with the Manning formula, S_{min} is selected;
- $S_{min} \leqq S_c \leqq S_{max}$ indicates that the S_c is selected to meet the requirement of minimal coverage;
- $S_{max} < S_c$ indicates what happens when the topography is steep or rough. The S_{max} that meets the minimal cover depth requirement and the limited maximal flow velocity is selected. The established falling manhole and the top elevation of the up-stream pipe can be calculated by reversing the minimal cover depth down stream.

2.2.3 The Sewer Pipes Cost-Slope Relationship Curve

Through a procedure comparing the design criteria and the minimized cost, the optimal slope, S_{ij}, one of the four designed slopes, can be assigned to the selected D_{ij}. The resulting four relations, one for each stage, given the selected standard commercial diameter options, are shown in Figure 2.

The broken lines in Figure 2 represent the cost per linear meter for the four commercial pipe sizes, D_1, D_2, D_3 and D_4, depending on the mean depth. The aforementioned fluid formula defines the minimum slope for each pipe size for the given discharge. The continuous line indicates the cost-slope relationship. An increase in the slope beyond the necessary minimum results in greater depth and thus increased cost. It can be shown that the minimum slopes for this set of pipe sizes are located on a unimodular curve (Orth, 1986). Therefore, during the optimization process, the best possible minimum slope is selected for each standard diameter. This will be the optimal slope (S_1, S_2, S_3, or S_4). In this case, {D_1, S_1}, {D_2, S_2,}, {D_3, S_3} and {D_4, S_4} are the optimization process options for each stage.



Note: (1) Given a constant flow-rate, Q, (cubic meters per second, M^3/sec); (2) then $D_4 > D_3 > D_2 > D_1$, from maximum to minimum standard diameters, (meters); (3) $S_4 < S_3 < S_2 < S_1$, the optimal slopes, (%); assigned to $D_4 > D_3 > D_2 > D_1$, respectively.

Figure 2. The sewer pipe cost-slope relationship curve.

3. The Establishment of the SSOM Model

The Sewer System Optimization Model (SSOM) as illustrated in Figure 1 is a 0-1 mixed integer nonlinear programming model that can deal with the essentials of the various construction methods and provide a set of design variables for the hydraulic design of a practical urban sewer system. Several assumptions are made for practical application, of the optimization model: (1) a sewer system represents a branched gravity sanitary sewer system; (2) pumping station may be used to hydraulically lift the water-head; (3) the piping between any two manholes follows a flat surface; (4) the sewer pipes are circular and made of the same material; and (5) the pipe flow is always full. The suggested maximum commercial standard diameter can also be estimated for partially filled pipes.

Given the aforementioned design criteria and the assumptions, the established SSOM, with 0-1 mixed integer programming, which is a nonlinear program with an objective function for an optimal procedure, is used to determine the minimum construction cost. The objective function of the SSOM is subject to the limitation of several practical design regulatory standards and additional hydraulic design criteria, before the ultimate goal of cost-effectiveness is achieved. The prototype of the established SSOM is shown as Equation (3) and some of constraints needed and limitations are represented by Equations (4-a) through (4-d):

Objective:

$$MinZ = \sum_{i=1}^{n}\sum_{j=1}^{m} Cost\left(D_{ij}, S_{ij}, Hup_i\right) X_{ij} + \sum_{i=1}^{n} MHc\left(Hup_i\right) + \sum_{i=1}^{n} PS_i\left(Q_i, H_i\right) \tag{3}$$

Subject to:

$$X_{ij} = 0,\ 1\ ;\quad i = 1,\ 2,\ ...,\ n\ ,\quad j = 1,\ 2,\ ...,\ m \tag{4-a}$$

$$\sum_{i=1}^{n} X_{ij} = 1\ ;\quad i = 1,\ 2,\ ...,\ n\ ,\quad j = 1,\ 2,\ ...,\ m \tag{4-b}$$

$$\begin{matrix} H_{\min} \le Hup_i \le H_{\max} \\ H_{\min} \le Hum_i \le H_{\max} \end{matrix}\ ;\quad i = 1,\ 2,\ ...,\ n \tag{4-c}$$

$$D_{i-1,j} \le D_{i,j}\ ;\quad i = 1,\ 2,\ ...,\ n\ ,\quad j = 1,\ 2,\ ...,\ m \tag{4-d}$$

where D_{ij} is the diameter of the j-th option of the i-th stage, S_{ij} is the optimal slope for a certain diameter, H_i and Q_i are the pumping heads and flow-rates of the i-th stage; X_{ij} is the 0-1 variable for the j-th option of the i-th stage if this option is selected, X_{ij} is equal to 1; H_{max} and H_{min} are the maximum and minimum coverage depth constrains for the entire sewer system: Hup_i and Hdm_i are the depths (inverted depths) for digging upstream and down stream of the pipe during stage i.

Equation (3) is the single objective equation of the SSOM that minimizes the total cost Z, including the cost of pipes $Cost(D_{ij}, S_{ij}, Hup_i)$, of manholes $MHc(Hup_i)$, and of pumping stations $PS_i(Q_i, H_i)$. In practice, the cost of the sewer system is estimated based on pre-established cost function. For most cases, the total piping cost, i.e. $Cost(D_{ij}, S_{ij}, Hup_i)$, can be shown as a function of pipe size obtained from the associated $\{D_{ij}, S_{ij}\}$ and digging depths (inverted depth) Hup_i, which will be affected by pipe length, pipe material and construction mode case considering the entire construction area. The total manhole cost $MHc(Hup_i)$ is a function of the digging depth, as well as Hup_i, and the pumping station cost is a function of the pumping heads H_i for a flow-rate Q_i if the pumping station is needed. In set of constraints, Constraints (4-a) and (4-b) are 0-1 constraints for multi-stage multi-option problems. Constraint (4-c) is to assure that the digging depth of each pipe will not exceed the minimal and maximal coverage depth. Constraint (4-d) requires that the size of a downstream pipe should be no less than that of its upstream pipe.

4. The Application of the BIE Algorithm in the SSOM Program

The traditional Total Enumeration (TE) algorithm is the most basic and simple optimization algorithm for finding a global solution. However, it also seems to be the least efficient, since it has to assess all the alternatives to obtain the best one. The intelligent Implicit Enumeration (IE) algorithm and Bounded Implicit Enumeration (BIE) algorithm have been developed to cover this deficiency.

During the searching procedure, the IE algorithm will store an upper-bound and delete any subsystem that is not the best program. The upper-bound is an objective function value of a feasible solution, which is updated continuously during the searching procedure. As for the minimization, the rest of the stages will be neglected and terminated if the subsystem evaluated, or the objective function value of the system is not less than the upper-bound. Based on the principals, the objective function value of each newly feasible solution will be less than the upper-bound so the new objective function value is the new upper-bound. The latest upper-bound is the objective function value of the optimization while the proceeding of searching is completed.

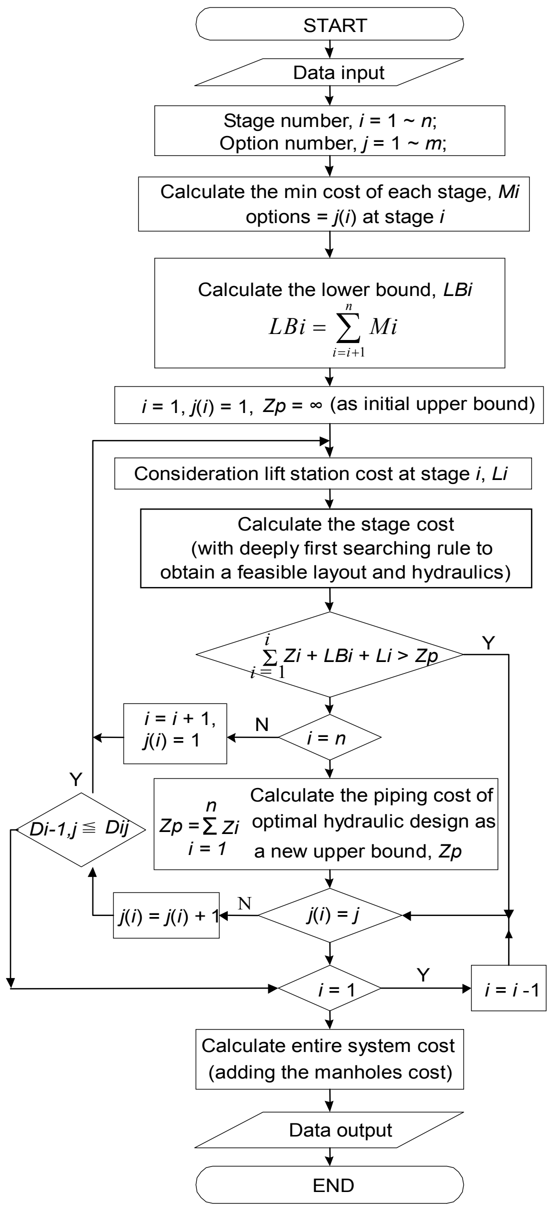
The BIE algorithm is an improved IE algorithm; it is effective and efficient for dealing with the serial multi-stage multi-option optimization problems (Chang and Liaw, 1990). Besides the upper-bound used in IE algorithm, the BIE algorithm uses an additional set of lower-bounds to further eliminate inferior combinations of options in the search for the optimal solution. A flowchart of the BIE algorithm, used in SSOM program, is shown in Figure 3.

For a sewer system design problem, the number of stages, n, is the number of sewer pipes. For each of the stages or sewer pipes, the minimal cost is obtained by selecting the minimal pipe diameter and the minimal pipe excavation depth for stage considered. The lower-bound of a particular stage is the sum of the minimal cost of remaining stages. For example, the lower-bound of *Stage #1* is the sum of the minimal cost of *Stages #2* to *#n*. The computer program for the SSOM, which written with the FORTRAN language, includes one main process and six sub-processes. The execution file occupies about 40 Kbytes on a Microsoft FORTRAN Power-Station Compiler (version 4.1). Therefore the memory-space required for programming is small and can easily be preceded with using a general personal computer.

5. Case Study

5.1. The Sewer Design Case

Figure 4 shows the layout of the sewer design, hereafter known as the DDDP sample. This is a branched sewer system consisting of 72 sewer stages (pipes) and 73-manholes. The known necessary input data for proceeding with the hydraulic design, the amount of collected sewerage area for each manhole, the length of piping required for each stage, and the ground level along piping-line illustrate the cost-effectiveness and programming-efficiency of SSOM with DDDP and the NIDP model (refer to Table 1).



Note: (1) M_i is the minimal cost of options for each stage; (2) LB_i is the lower bound; (3) L_i is the pumping cost for the lift station; (4) Z_p is the upper bound having an infinitive positive value as the initial solution; (5) Z_i is the cost of piping and will be saved that as a new upper bound for the 1st run.

Figure 3. A flowchart of the BIE algorithm applied to the SSOM program.

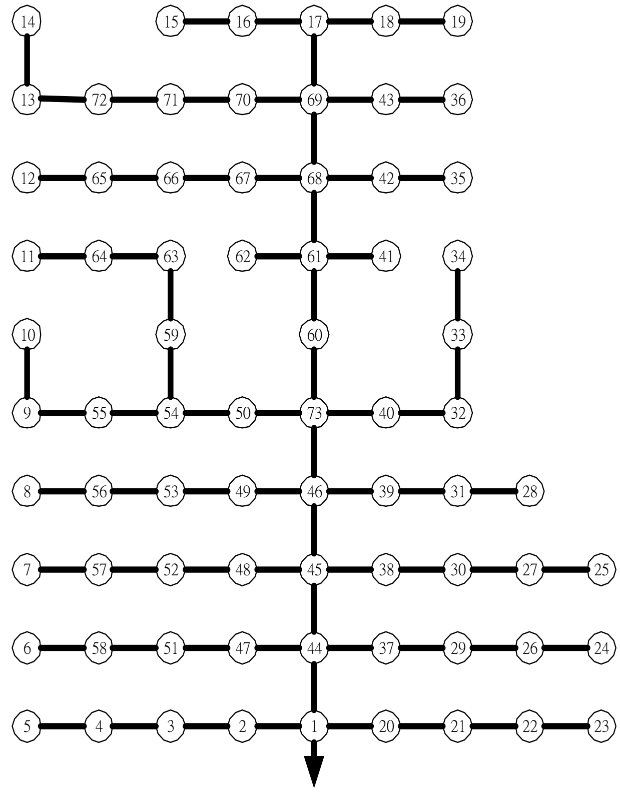


Figure 4. The layout of the DDDP model (72-pipes 3882 m).

This sewer design was first solved with the DDDP model (Wen and Shih, 1983) and then after which the NIDP model (the AIT model) is used to calculate the inflow of the DDDP sample, to achieve a new optimal solution, saving 15% of the total construction cost (Orth and Hsu, 1984). Here, the cost function of this DDDP approach is applied to calculate the optimal design cost. The optimal design costs obtained by the DDDP and the NIDP Models were about NT$17,520,500 and NT$14,187,700, respectively.

5.2. The Hydraulic Design Criteria and Cost Functions

The hydraulic design criteria and cost functions obtained by the adaption of the DDDP approach for the case study are as follows:

(1) Hydraulic design criteria:

Roughness coefficient of Manning's Formula: $n = 0.015$;

Minimum coverage depth: $H_{\min} = 0.9$ meters;

Maximum coverage depth: $H_{\max} = 10$ meters;

Minimum velocity: $V_{\min} = 0.6$ meters per second;

Maximum velocity: $V_{\max} = 3.0$ meters per second.

(2) Cost functions:

We adapted the cost functions proposed by Wen and Kuoa (1982) for this case; Equation (5) deals with installing sewer pipe and Equations (6-a) to (6-e) with manholes.

Table 1. The Results of the Optimal Hydraulic Designs Obtained with the SSOM, NIDP and DDDP Models

Manhole #		Flow-rate	Length	UGL	DGL	Slope (%)			Diameter (M)			Velocity (M/sec)		
from	to	(M)	(M)	(M)	(M)	SSOM	NIDP	DDDP	SSOM	NIDP	DDDP	SSOM	NIDP	DDDP
1	1	20884.4	0	4.81	4.81	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	1	1159.0	80	4.79	4.81	0.37	0.40	0.62	0.20	0.20	0.20	0.60	0.63	0.74
3	2	747.3	80	4.79	4.79	0.51	0.50	0.63	0.20	0.20	0.20	0.60	0.61	0.67
4	3	461.1	80	4.74	4.79	0.72	0.70	0.95	0.20	0.20	0.20	0.60	0.61	0.68
5	4	160.5	80	4.76	4.74	1.56	2.00	1.96	0.20	0.20	0.20	0.60	0.62	0.61
6	58	301.1	80	4.98	4.83	0.98	1.00	1.19	0.20	0.20	0.20	0.60	0.60	0.64
7	57	295.0	80	4.80	4.75	1.00	1.20	1.06	0.20	0.20	0.20	0.60	0.64	0.61
8	56	307.1	80	4.80	5.00	0.97	1.00	1.20	0.20	0.20	0.20	0.60	0.61	0.65
9	55	719.2	82	4.90	5.05	0.52	0.50	0.50	0.20	0.20	0.20	0.60	0.61	0.63
10	9	396.4	78	4.90	4.90	0.80	0.80	1.04	0.20	0.20	0.20	0.60	0.61	0.66
11	64	554.9	80	4.90	5.00	0.87	0.90	0.95	0.20	0.20	0.20	0.60	0.61	0.62
12	65	301.1	80	4.90	5.25	0.98	1.00	1.11	0.20	0.20	0.20	0.60	0.60	0.63
13	72	786.6	80	5.07	5.20	0.49	0.50	0.58	0.20	0.20	0.20	0.60	0.62	0.66
14	13	337.0	133	5.08	3.07	0.90	0.90	0.98	0.20	0.20	0.20	0.60	0.60	0.62
15	16	496.1	80	5.22	5.25	0.68	0.65	0.68	0.20	0.20	0.20	0.60	0.60	0.60
16	17	803.3	80	5.25	5.30	0.48	0.45	0.62	0.20	0.20	0.20	0.60	0.60	0.68
17	69	1560.3	135	5.30	5.45	0.30	0.35	0.53	0.20	0.20	0.20	0.60	0.61	0.74
18	17	496.1	80	5.35	5.30	0.68	0.65	0.70	0.20	0.20	0.20	0.60	0.60	0.62
19	18	172.9	80	5.40	5.35	1.47	1.80	2.00	0.20	0.20	0.20	0.60	0.61	0.63
20	1	1105.1	75	4.77	4.81	0.38	0.40	0.64	0.20	0.20	0.20	0.60	0.62	0.74
21	20	691.0	80	4.77	4.77	0.54	0.50	0.62	0.20	0.20	0.20	0.60	0.60	0.65
22	21	402.4	80	4.74	4.77	0.80	0.75	0.96	0.20	0.20	0.20	0.60	0.60	0.65
23	22	129.2	60	4.70	4.74	1.82	2.50	2.56	0.20	0.20	0.20	0.60	0.63	0.64
24	26	258.8	70	4.77	4.77	1.10	2.20	1.15	0.20	0.20	0.20	0.60	0.62	0.61
25	27	129.2	78	4.77	4.86	1.82	2.50	2.26	0.20	0.20	0.20	0.60	0.63	0.61
26	29	769.8	80	4.77	4.87	0.50	0.50	0.00	0.20	0.20	0.20	0.60	0.62	0.66
27	30	530.9	90	4.86	4.93	0.65	0.65	0.80	0.20	0.20	0.20	0.60	0.61	0.66
28	31	154.2	80	5.02	5.02	1.60	2.00	1.95	0.20	0.20	0.20	0.60	0.61	0.60
29	37	1292.5	80	4.87	4.81	0.34	0.35	0.63	0.20	0.20	0.20	0.60	0.60	0.77
30	38	1056.4	80	4.93	4.84	0.39	0.40	0.66	0.20	0.20	0.20	0.60	0.61	0.74
31	39	588.4	80	5.02	5.01	0.60	0.60	0.67	0.20	0.20	0.20	0.60	0.61	0.64
32	10	1034.6	81	5.05	5.05	0.40	0.40	0.62	0.20	0.20	0.20	0.60	0.61	0.72
33	32	724.8	78	5.05	5.05	0.52	0.50	0.68	0.20	0.20	0.20	0.60	0.61	0.68
34	33	360.9	80	5.20	5.05	0.86	0.85	0.87	0.20	0.20	0.20	0.60	0.60	0.61
35	12	313.1	80	5.25	5.30	0.95	1.00	0.98	0.20	0.20	0.20	0.60	0.61	0.61
36	43	319.1	80	5.25	5.35	0.94	1.00	0.95	0.20	0.20	0.20	0.60	0.61	0.60
37	44	1791.9	80	4.81	4.81	0.53	0.52	0.80	0.20	0.20	0.20	0.60	0.65	0.90
38	45	1555.1	80	4.84	4.91	0.30	0.40	0.60	0.20	0.20	0.20	0.66	0.65	0.78
39	46	1132.1	80	5.01	5.01	0.37	0.40	0.65	0.20	0.20	0.20	0.60	0.62	0.75
40	73	1303.2	90	5.05	5.05	0.34	0.35	0.43	0.20	0.20	0.20	0.60	0.60	0.66
41	61	325.1	78	5.20	5.20	0.93	1.00	1.04	0.20	0.20	0.20	0.60	0.62	0.62
42	68	886.6	80	5.30	5.30	0.45	0.45	0.65	0.20	0.20	0.20	0.60	0.62	0.70
43	69	892.1	80	5.35	5.45	0.44	0.45	0.57	0.20	0.20	0.20	0.60	0.62	0.67
44	1	19613.8	124	4.81	4.81	0.18	0.46	0.34	0.60	0.50	0.60	0.80	1.13	1.19
45	44	17078.9	115	4.91	4.81	0.14	0.35	0.73	0.60	0.50	0.45	0.70	0.98	1.50
46	45	14678.0	120	5.01	4.91	0.10	0.26	0.40	0.60	0.50	0.45	0.60	0.84	1.24
47	44	1888.5	80	4.85	4.81	0.59	0.58	0.80	0.20	0.20	0.20	0.70	0.69	0.91
48	45	1832.6	80	4.82	4.91	0.56	0.54	0.72	0.20	0.20	0.20	0.67	0.67	0.86
49	46	1901.2	90	5.01	5.01	0.60	0.59	0.69	0.20	0.20	0.20	0.70	0.69	0.85
50	73	3509.7	90	5.10	5.05	0.62	0.60	0.61	0.25	0.25	0.25	0.83	0.81	0.93
51	47	1371.9	80	4.78	4.85	0.32	0.35	0.62	0.20	0.20	0.20	0.60	0.61	0.77
52	48	1345.5	80	4.81	4.82	0.33	0.35	0.62	0.20	0.20	0.20	0.60	0.61	0.77
53	49	1395.6	80	5.00	5.01	0.32	0.35	0.61	0.20	0.20	0.20	0.60	0.61	0.77
54	50	3277.1	80	5.10	5.10	0.54	0.52	0.68	0.25	0.25	0.25	0.77	0.76	0.97
55	54	991.0	90	5.05	5.10	0.41	0.40	0.50	0.20	0.20	0.20	0.60	0.60	0.66
56	53	867.2	80	5.00	5.00	0.45	0.45	0.60	0.20	0.20	0.20	0.60	0.61	0.68
57	52	836.7	80	4.75	4.81	0.47	0.45	0.63	0.20	0.20	0.20	0.60	0.61	0.69
58	51	853.4	80	4.83	4.78	0.46	0.45	0.70	0.20	0.20	0.20	0.60	0.61	0.72
59	54	1913.8	78	5.00	5.10	0.61	0.59	0.75	0.20	0.20	0.20	0.70	0.70	0.89
60	73	8589.9	78	5.10	5.05	0.16	0.15	0.78	0.45	0.45	0.35	0.62	0.61	0.30
61	60	8092.8	80	5.20	5.10	0.27	0.26	0.83	0.40	0.40	0.35	0.74	0.73	1.32
62	61	325.1	80	5.00	5.20	0.93	1.00	1.20	0.20	0.20	0.20	0.60	0.62	0.66
63	59	1255.3	78	5.10	5.00	0.35	0.35	0.36	0.20	0.20	0.20	0.60	0.60	0.60
64	63	645.6	80	5.00	5.10	0.56	0.55	0.57	0.20	0.20	0.20	0.60	0.61	0.62
65	66	864.5	80	5.25	5.40	0.45	0.45	0.46	0.20	0.20	0.20	0.60	0.60	0.62
66	67	1403.5	80	5.40	5.35	0.32	0.35	0.57	0.20	0.20	0.20	0.60	1.60	0.75
67	68	1918.9	80	5.35	5.30	0.61	0.59	0.79	0.20	0.20	0.20	0.71	0.70	0.90
68	61	7213.6	130	5.30	5.20	0.21	0.20	0.57	0.40	0.40	0.35	0.66	0.65	1.11
69	68	4699.7	120	5.45	5.30	0.42	0.40	0.52	0.30	0.30	0.30	0.77	0.75	0.96
70	69	2244.0	80	5.55	5.45	0.83	0.81	0.42	0.20	0.20	0.25	0.83	0.81	0.75
71	70	1730.5	80	5.40	5.45	0.50	0.48	0.52	0.20	0.20	0.20	0.64	0.63	0.74
72	71	1050.9	80	5.20	5.40	0.39	0.40	0.48	0.20	0.20	0.20	0.60	0.61	0.66
73	46	1241.4	124	5.05	5.01	0.19	0.18	0.67	0.50	0.50	0.40	0.73	0.71	1.33

The cost functions for installing sewer pipe:

$$C_p = 0.051 + 0.383 \times D^2 + 0.0137 \times H^2 \tag{5}$$

The cost functions for manholes:

$$C_m = 0.725 \times h^{0.548} \qquad D \le 0.25\ m\ ; \tag{6-a}$$

$$C_m = 0.8155 \times h^{0.579} \qquad 0.25\ m < D \le 0.8\ m\ ; \tag{6-b}$$

$$C_m = 1.1503 \times h^{0.484} \qquad 0.8\ m < D \le 1.2\ m\ ; \tag{6-c}$$

$$C_m = 1.7772 \times h^{0.355} \qquad 1.2\ m < D \le 1.65\ m\ ; \tag{6-d}$$

$$C_m = 2.1533 \times h^{0.313} \qquad 1.65\ m < D\ ; \tag{6-e}$$

In addition: C_p = pipe construction cost in ten thousand NT$/m; C_m = the manhole construction cost in ten thousand NT$/m; D = the pipe diameter in meters; H = the mean pipe excavation depth in meters; h = the manhole depth in meters.

6. Results and Discussion

In this SSOM case study, both the hydraulic design criteria and cost functions are applied just the same as in the DDDP and NIDP models. Thus the resultant optimal hydraulic designs are compared with each other and discussed as follows.

6.1. A comparison of the Optimal Results

(1) In Table 1 the optimal cost of the hydraulic design obtained by the SSOM model, compares well with that obtained by the DDDP and NIDP Models. The best sewer design obtained from the SSOM model had a total construction cost of NT$13,806,280, compared to NT$17,520,500 for the DDDP model and NT$14,187,700 for the NIDP model, a saving of about 27 and 3%, respectively.

(2) By utilizing the fundamentals of optimal hydraulic processes with the SSOM we were able to build a multi-stage multi-option hydraulic design that incorporated an improved traditional enumeration algorithm, an intelligent BIE algorithm, to search for the optimal solution. According to the associated $\{D_{ij}, S_{ij}\}$ for each stage, this 72-stage sewer design would produce the most feasible solution, with a total of 1,620,000 combinations, assuming a full sewer system. However the computer time needed to find the optimal design solution, even on a general personal computer, was only a few seconds (about 0.01 seconds in this case), and it needed little memory (only 736 Kbytes). The performance of the SSOM model, compared to the DDDP and NIDP Models was more efficient.

6.2. Discussion

Due to the fact that the BIE solution algorithm used in the SSOM is similar to the traditional design procedures, it is easy to modify to fit different sewer system design problems. Therefore, the SSOM provides a set of design variables that correspond well with the various construction modes for urban sewer system design problems. The designer has extensive selections to respond to practical construction requirements, which facilitates finding the most optimal design for trunk or branched sewer systems. It is important to note that the SSOM is an acceptable option to designers since the obtained optimization solution is not very different than the traditional judgment and selection process.

7. Conclusions

In this study, a 0-1 mixed integer optimization model, capable of using various construction modes, was developed for the branched gravity sewer systems hydraulic designs. A Bounded Implicit Enumeration (BIE) algorithm was used to develop the Sewerage System Optimization Model (SSOM). The SSOM can provide a set of varied options and constraints, from which the designer can make a selection, based on the practical requirements and construction environment, to obtain the most optimal design for a trunk with branched sewer system. The results generated are very easy to understand and practical to use, and, since the memory-space required for programming is small, can be obtained with a personal computer. This makes the method a convenient way for design engineers to evaluate optimal alternatives prior to decision making.

In our 73-manhole case study, the SSOM hydraulic design was shown to be more cost-effective than either the AIT or DDDP model designs. In terms of time saved, the SSOM is clearly more efficient method. Optimal hydraulic designs can be found for huge municipal sewer systems both speedily and accurately. The overall least-cost hydraulic design for an urban sewer system was easier to find with the SSOM than with other models. Given its advantages, the SSOM could become an essential tool for designing new urban sewer systems in Taiwan.

Acknowledgments. Many thanks to Mr. William Chung, the project manager of CTCI Corporation in Taiwan, who contributed to the practical design parameters and to Dr. B.L. Lin, assistant professor of the Department of Civil Engineering at the Ming-Hsin University of Science and Technology of Taiwan, for his efforts at programming, during the development of the model.

References

Agbenowosi, N. (1995). *GIS based Optimal Design of Sewer Networks and Pump Stations*, M.Sc. Dissertation, Virginia Polytechnic Institute and State University, Blacks-burg, VA, USA.

Benson, R.E. (1985). Self-cleaning slope for partially full sewers. *J. Environ. Eng. Div., ASCE*, 111(6), 925-928.

Charalambous, C. and Elimam, A.A. (1990). Heuristic design of sewer networks. *J. Environ. Eng.*, 116(6), 181-1199.

Chang, S.Y. and Liaw, S.L. (1990). Bounded Implicit Enumeration for wastewater treatment systems. *J. Environ. Eng.*, 116(5), 910-926.

Dajani, J.S. and Hasit, Y. (1974). Capital cost minimization of drainage networks. *J. Environ. Eng. Div.*, *ASCE*, 100(EE2), 325-337.

Deininger, R.A. and Su, S.Y. (1973). Modeling regional wastewater treatment systems. *Water Res.*, 7(4), 633-646.

Greene, R., Agbenowosi, N. and Loganathan, G.V. (1999). GIS-based approach to sewer system design. *J. Surv. Eng.*, 125(1), 36-57.

Holland, M.E. (1966). *Computer Models of Wastewater Collection System*, Ph.D. Dissertation, Harvard University, Cambridge, USA.

Liaw, S.L. and Lin, B.L. (1991). Optimization of sewer system (II): Hydraulic design, in *Proc. of International Conference on Computer Application in Water Resources*, Tamkang University, Taiwan, 2, pp. 77-84.

Liaw, S.L. and Lin, B.L. (1990). *An Optimization Model for Sewer System Layout and Design*, M.Eng. Dissertation, Tamkang University, Taiwan (in Chinese).

Merrit, L.B. and Bogan, R.H. (1973). Computer-base optimal design of sewer system. *J. Environ. Eng. Div.*, *ASCE*, 99(EE1), 35-53.

Orth, H.M. and Hsu, C.L. (1984). *Computer aided Design for Large Sewerage Systems*, M.Eng. Dissertation, A.I.T., Thailand.

Orth, H.M. (1986). *Model-based Design of Water Distribution and Sewage Systems*, 1st Edition, John Wiley & Sons, New York, USA.

Swamee, P.K. (2001). Design of sewer line. *J. Environ. Eng.*, 127(9), 776-781.

Tekeli, T. and Belkaya, H. (1986). Computerized layout generation for sanitary sewers. *J. Environ. Eng. Div.*, *ASCE*, 112(4), 500-515.

Wen, C.K. and Kuo, H.W. (1982). *The Comparison and Application of Dynamic Programming and Linear Programming in the Sewer System Design*, M.Eng. Dissertation, National Chenkong University, Taiwan (in Chinese).

Wen, C.K. and Shih, C.S. (1983). *Discrete Differential Dynamic Programming and Zero-one Programming to Develop the Computer Program for Optimal Sanitary Sewer system Design*, M.Eng. Dissertation, National Chenkong University, Taiwan (in Chinese).

Weng, H.T., Lin B.L., Yu, R.F., Lu, P.C. and Liaw, S.L. (2001). The application of BIE algorithm to optimize a municipal sewer systems hydraulic design model, in *Proc. of 14th Environment Planning and Management Conference of CIEnvE*, Taiwan (in Chinese).

Weng, H.T. and Liaw, S.L. (2003). An optimization model for sewer hydraulic design base on novel trenchless technology, in *Proc. of IWA Asia-Pacific Regional Conference*, Bangkok, Thailand.

Weng, H.T. and Liaw, S.L. (2005). Establishing an optimization model for sewer system layout with applied Genetic algorithm. *J. Environ. Inf.*, 5(1), 26-35.