OPTIMIZATION OF SEWER DESIGN USING ANT COLONY OPTIMIZATION

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ABSTRACT

Due to rapid urbanization coupled with population growth facilities, enactment of pollution control laws and increasing awareness towards sanitation, the problem of waste water collection and disposal is becoming difficult and requires large amount of money .The cost of a sewage collection network constitutes a major fraction of the overall cost of waste disposal. Thus, substantial sums of money can be saved by improving sewerage system design. Diameter and slope are the two major components that contribute to the cost of sewerage system. In this paper, a new and powerful intelligent evolution method, called ant colony optimization (ACO) is adopted for solving the optimization problem by formulating an objective function. The proposed algorithm is coded using FORTRAN. Then, ACO algorithm has been applied to the design of sewerage system through the optimization of the objective function. The obtained results reveal that the proposed method is promising in the optimal design of the sewerage system.

Keywords: Ant Colony Optimization, Constraints, Penalty Function, Sewerage System

I. INTRODUCTION

Increase in the population and the corresponding increase in the load of sewerage system make it essential to design the sewer lines properly and as it is the basic need for every individual, cost optimization is very important for better service. In the last decade or so, due to increasing concern for water quality, sustainability and integrated wastewater management, the scope of sewerage system design has been expanded to involve the environment, ecology, management and even social aspects. More sophisticated hydrologic and hydraulic computer models became available to be incorporated with optimization techniques for a more precise design, although their embedded routing methods and numerical schemes are basically the same as those previously developed. Computer packages for automated design also emerged, such as which greatly relieve engineers from the tedious design process and enable design to be more interactive and intuitive via graphical displays and animations [1]. The traditional method for designing gravity wastewater collection systems is largely based on trial and error which is very time consuming. Designers typically use charts and specialized rules to determine the diameters and slope of sewers when designing wastewater collection networks. Suitable diameters and slope combinations are selected for all pipes between manholes, so that the wastewater can be transported without violating any hydraulic constraints. Since there is a large range of pipe slopes, diameters and coefficients in the hydraulic relationships, designers can usually only evaluate a small number of network options that do not violate any of the constraints. However, since many of the costs and constraints are non-linear, there are no simple procedures to find the least cost design for pipeline networks. Linear programming has been applied to minimize the total cost of sewers subject to constraints [2]. Since this optimization method does not incorporate commercially available diameters, there is no guarantee of optimality for standard commercial pipe diameters. The topic of optimal sewer design has been studied by many researchers. Its concept was first proposed in the mid 1960s [3,4] when advances in the computer power shined light on engineering research. Various early optimization techniques were developed, including Linear Programming (LP) [5,3], Non-linear Programming (NLP) [4], and Dynamic Programming (DP) [6]. Recently, Dorigo et al. (1996) proposed a new evolutionary optimization method, namely the ant algorithm, based on the collective behavior of the ants in their search for food. Ant algorithms were first proposed for the solution of difficult combinatorial optimization problems like TSP and QAP. This method has been shown to outperform other evolutionary optimization methods including Genetic Algorithms (GA).

1.1 Ant Colony Optimization Algorithm

The basic steps on the ACO algorithms may be defined as follows [7]:

1) m ants are randomly placed on the n decision points of the problem and the amount of pheromone trail on all options are initialized.
2) A transition rule is used for ant k at each decision point i to decide which option is to be selected. The transition rule used in the original ant system is defined as follows [7]:

$$Pij(k,t) = \frac{\{[\tau_{ij(t)}]^{\alpha}[\eta_{ij}]^{\beta}\}}{\sum_{j=1}^{J}\{[\tau_{ij(t)}]^{\alpha}[\eta_{ij}]^{\beta}\}} \quad \text{.......} 1$$

where p_{ij} (k ,t) is the probability that the ant k selects option l_{ij} (t) for the ith decision at iteration t; $\tau_{ij(t)}$ is the concentration of pheromone on option l_{ij} (t) at iteration t; $\eta_{ij} = 1/(c_{ij})$ is the heuristic value representing the cost of choosing option j at point i, and α and β controls the relative weight of the pheromone trail and heuristic value referred to as pheromone and heuristic sensitivity parameter, respectively [7].

3) The cost f(φ) of the trial solution generated is calculated. The generation of a complete trial solution and calculation of the corresponding cost is called a cycle (k).
4) Steps 2 and 3 are repeated for all m ants of the colony at the end of which, m trial solutions are created and their costs are calculated. Generation of m trial solution and the calculation of their corresponding costs is referred to as an iteration (t).
5) The pheromone is updated at the end of iteration. The general form of the pheromone updating used in the ant system is as follows [7]:

$$\tau_{ij}(t+1) = \rho\tau_{ij}(t) + \Delta\tau_{ij} \quad \text{.......} 2$$

where $\tau_{ij}(t+1)$ is the amount of pheromone trail on option j of the ith decision point, i.e. option l_{ij}, at iteration t+1; $\tau_{ij}(t)$ concentration of pheromone on option l_{ij} at iteration t; $0 \le \rho \le 1$ is the coefficient representing the pheromone evaporation and $\Delta\tau_{ij}$ is the change in pheromone concentration associated with option l_{ij}. The main role of pheromone evaporation is to avoid stagnation, that is, the situation in which all ants end up doing the same tour. In addition, evaporation reduces the likelihood that high cost solutions will be selected in future cycles [8].

II. METHODOLOGY DESCRIPTION

2.1 Objective Function

2.1.1 Cost of Pipe

This includes cost of their transportation, jointing material, handling, etc. It is calculated per unit length of sewer i.e. (₹/m)

Cost of pipe=∑ length of different diameter pipes*respective unit cost of pipes

2.1.2 Cost of Earthwork

This includes cost of digging, refilling, shuttering etc. It is calculated by multiplying volume of earthwork and cost of earthwork per unit volume (₹ /m3)

- If depth of excavation ≤ 1.5m

  Cost of earthwork up to 1.5 m depth has been taken as ₹ 69 /m^3.

  Cost of earthwork= length * depth of excavation* 69
- If depth of excavation ≥ 1.5m and depth of excavation < 3.0m

  Cost of earthwork from 1.5 m to 3.0 m depth has been taken as ₹ 79 /m^3Cost of earthwork= (length*1.5 *69) + (length*(depth of excavation - 1.5)* 79

2.1.3 Cost of Manhole

This will include cost of providing complete manhole. The cost of manhole depends on depth of excavation and diameter of sewer.

Cost of manhole = ∑no of manhole at different depths*unit cost of manhole for that depth

2.1.4 Total Cost

The total cost ($TCOST_i$) of ith link would be

$TCOST_i$ = Cost of $sewer_i$ + Cost of $manhole_i$ + Cost of $earthwork_i$

Therefore objective function f (X) to be minimized for total N links

$$f(\mathrm{D, Depths, Depthe}) = \sum_{i=1}^{N} \{(TCOST_i)\}$$

2.2 Constraints

2.2.1 Part Full Flow Constraint

For a given discharge, diameter and maximum allowable depth of flow there would be a unique value of required slope Sr. In other words actual slope of sewer should not be less than this designed required slope. The actual slope of i th link ($Slope_i$ expressed as 1 in N)of length LG_i follow following constraint:

$Slope_i - Sr_i \leq 0$

2.2.2 Minimum Diameter Constraint

The diameter of a link should not be less than the minimum prescribed size (D_{min}) [9]

$D_{min} - D_i \leq 0$; Dmin = 0.2 m in the present paper.

2.2.3 Diameter Progression Constraint

The diameter of i^{th} link (D_i) should not be less than diameter of previous link (D_{i-1}) [9]

$D_{i-1} - D_i \leq 0$

2.2.4 Minimum Velocity Constraint

The velocity of flow in the i^{th} link (V_i) should not be less than predefined minimum self cleansing velocity (V_{min}) [9]

$V_{min} - V_i \leq 0$

V_{min} = 0.6 m/s has been adopted in the present paper. V_i is a function of discharge (Q), slope and diameter (D).

2.2.5 Maximum Velocity Constraint

The velocity of flow in the i^{th} link (V_i) should not be greater than maximum permissible velocity for the pipe material (V_{max}) [9]

$V_i - V_{max} \leq 0$; V_{max} = 3.0 m/s has been adopted in the present paper.

2.2.6 Minimum Cover Constraint

There should be some minimum cover (C_{min}) [9] over the buried sewer line to avoid damage to the sewer line.

$C_{min} - (Depthe_i - D_i) \leq 0$

In which $Depthe_i$ = depth of excavation at downstream of ith link; C_{min} = minimum allowable cover, taken as 0.9 m in the present paper.

2.2.7 Maximum Depth Constraint

The depth of excavation should not exceed practical limits of laying the sewer line depending upon site conditions (depmax)

$Depthe_i - depmax \leq 0$; depmax = 5 m has been adopted in the present paper.

2.2.8 Invert level progression

The invert level of ith link should also not be above the invert level of previous link [9]

$(Depthe_i - D_i) - (depths_{i+1} - D_{i+1}) \leq 0$

in which $Depthe_i$ = depth of excavation at downstream of i^{th} link and $Depths_{i+1}$ = depth of excavation at upstream of $i+1^{th}$ link

2.2.9 Non Negativity Constraints

The values of decision variables diameter, depth of excavation at upstream and downstream level should not be negative [9] that is

$- D_i \leq 0$

$- Depths \leq 0$

$- Depthe \leq 0$

2.3 Penalty Function

In present study there are three condition in which penalty has been assigned:

2.3.1 Penalty Due To Depth in Excesses Of Permissible Maximum Depth

Penalty due to depth for a link =∑penalty parameter*(average depth-maximum depth)

If depth is in excesses of permissible maximum depth

Penalty due to depth for a link = 0

If depth is less than permissible maximum depth

2.3.2 Penalty Due To Minimum Velocity

Penalty due to minimum velocity in a link = ∑penalty*(minimum velocity-actual velocity)

It will be added if the velocity is less than the minimum velocity limit in a link

2.3.3 Penalty Due To Maximum Velocity

Penalty due to maximum velocity in a link = ∑penalty*(actual velocity- maximum velocity)

It will be added if the velocity exceeds the maximum velocity limit (that is 3 m/s)

Total Penalty cost PC:

PC= ∑Penalty due to depth + Penalty due to maximum velocity + Penalty due to minimum velocity

2.4 Overall Expression

The problem of optimization of a sewer line with 'N' number of links may be expressed as

$$f(\text{D, Depths, Depthe}) = \sum_{i=1}^{N} \{(TCOST_i + PC)\}$$

Subject to constraints,

$g(1)_i = \text{Slope}_i - Sr_i \leq 0$

$g(2)_i = D_{min} - D_i \leq 0$

$g(3)_i = V_{min} - V_i \leq 0$

$g(4)_i = V_i - V_{max} \leq 0$

$g(5)_i = C_{min} - (\text{Depthe}_i - D_i) \leq 0$ For i=1 to N

$g(6)_i = \text{Depthe}_i - \text{depmax} \leq 0$

$g(7)_i = - D_i \leq 0$

$g(8)_i = - \text{Depths} \leq 0$

$g(9)_i = - \text{Depthe} \leq 0$

$g(10)_i = D_{i-1} - D_i \leq 0$ For i= 1 to N-1

$g(11)_i = (\text{Depthe}_i - D_i) - (\text{depths}_{i+1} - D_{i+1}) \leq 0$

III. PRESENT APPROACH

Since the method requires the interior feasible initial solution, a program was developed based on concept of feasible diameter and slope set. The algorithm considers diameter and slope of sewer as discrete variables. The values taken as input for diameter correspond to the commercially available diameters.

Part full flow: From Manning formula and continuity equation, we get-

$$q = a\,v = a\,1/n\,(a/p)^{2/3}\,(S)^{1/2} \quad \ldots\ldots\ldots 3$$

Where, q = discharge (cum/sec); a = area of flow (sq.m): p = wetted perimeter (m)

1. ***Constant K***: K should be less than 0.318.

$$CK = QnD^{-8/3}S^{-1/2} \quad \ldots\ldots\ldots 4$$

2. ***Cross Sectional Area:*** The cross sectional area of flow can be calculated from angle of flow 'θ':

$$A = D^2\,\frac{\theta - \sin\theta}{8} \quad \ldots\ldots\ldots 5$$

3. ***Depth Ratio:*** Depth ratio (DR)can be calculated by

$$\frac{h}{D} = \frac{1}{2}\left[1 - \cos\left(\frac{\theta}{2}\right)\right] \quad \ldots\ldots\ldots 6$$

4. ***Hydraulic Mean Depth:*** Hydraulic mean depth can be calculated by

$$HMD = 0.25D\,(\theta - \sin\theta)/\theta \quad \ldots\ldots\ldots 7$$

5. ***Depth of Flow:*** Depth of flow can be calculated by

Depth=DR X D ……………………………………………………………**8**

6. ***Theta***: Saatci A. (1990) [10] gave an expression for computing values of ‘θ’ directly for given values of D, Q and S:

$$\theta = \frac{3\pi}{2}\sqrt{1-\sqrt{1-\sqrt{0.0217\pi}}} \quad \ldots\ldots\ldots 9$$

3.1.1 Flowchart for Ant Colony Optimization

Values of some parameters taken for the flowchart given below are:

a. α =1; the parameter controlling relative importance of pheromone intensity

b. IANTIN=1000; the initial no. of ants

c. β =0; the parameter controlling the local heuristics

d. ρ = 1; the parameter of pheromone persistence

e. $Pe = \frac{\{[\tau_{e(t)}]^{\alpha}[\eta_e]^{\beta}\}}{\sum_{i=1}^{i+1}\{[\tau_{j(t)}]^{\alpha}[\eta_j]^{\beta}\}}$

f. $ph_i = Cost_{max}/Cost_i$

g. $p_i = \frac{ph_i}{\sum_{i=1}^{N_j} ph_i}$

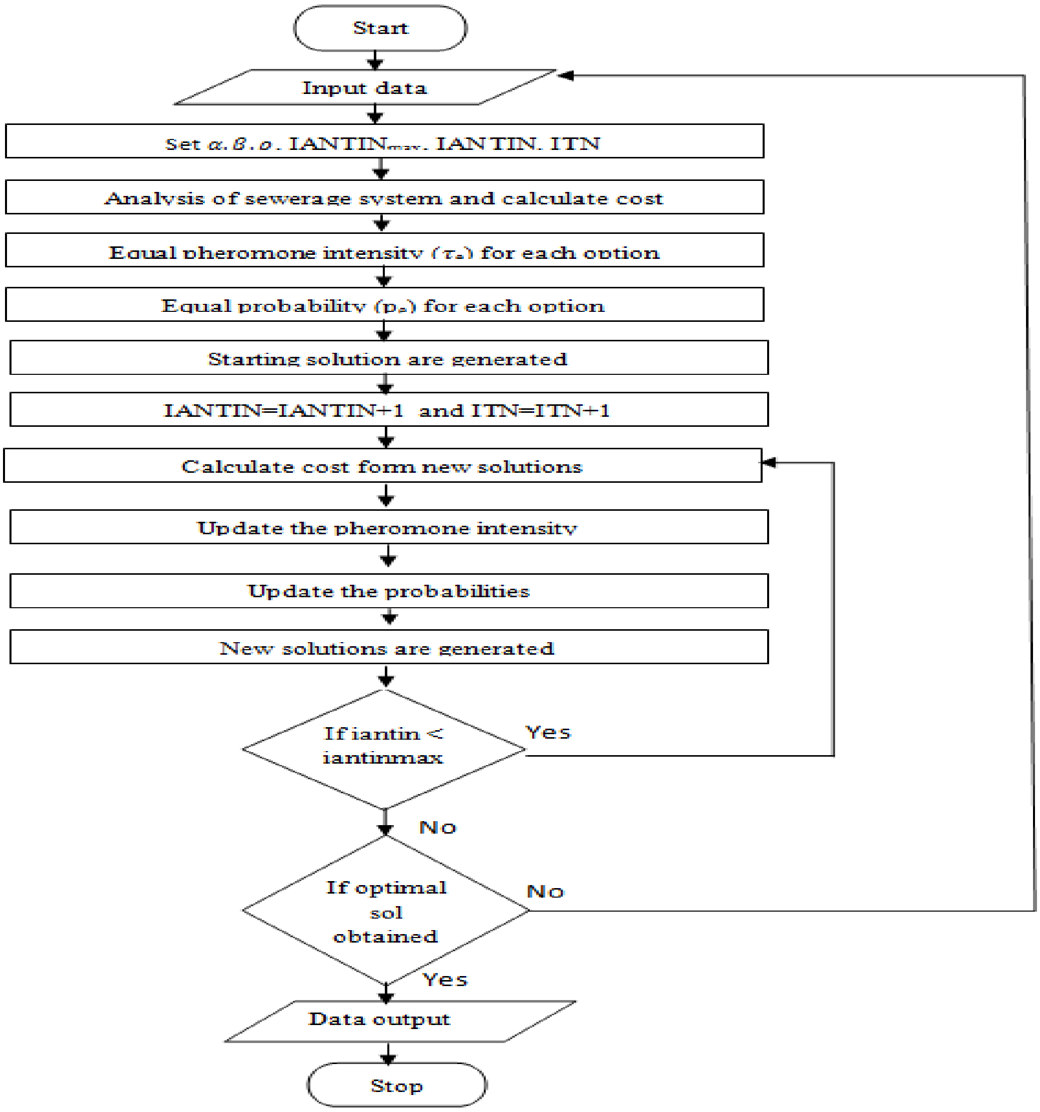

Figure 1: Flowchart for ACO

IV. RESULT AND DISCUSSION

In this paper, the ant colony optimization metaheuristic was applied to the problem of finding optimal pipe diameters and slopes for the conjunctive least-cost design and operation of a sewerage system network.

5 commercially available slopes and 18 slopes were considered to generate solutions. Hence a total possible diameter slope permutation were 90^{100} (approx. 2.656 X 10^{195}) and it is very difficult to find out the optimal pipe diameter and slopes from such a huge combinations if not using optimization technique (ACO).

A network of pipes having 100 links was considered in this case with input data of link no, upstream node, downstream node, length, discharge, upstream ground level, downstream ground level.

The program was developed in Fortran 2.1 compiler.

An initial number of 1000 ants (1000 combinations) were used for the each iteration. The total numbers of iterations done were 10. The total cost of the best solution obtained from the eighth iteration (out of 10niteration) was considered to be the Optimal Cost of the sewerage system and the pipe diameters and slopes obtained in the 8^{th} iteration were considered as the Optimal Pipe Diameters and slopes.

It took around 10/20 minutes of CPU time to reach to optimal solution using ACO method on a PC. The result exhibit a final optimal total cost of ₹4.6 Million with discrete diameter and slope.

The results indicate a cost reduction (around 0.13 Million) in optimal design due to reduction in both sewer size as well as in excavation. And the reduction in cost would be 2.89%

A summary of the results obtained in each iteration are presented in table 1

Table 1: Cost Summary for All Iterations

Iteration	No of ants	Cost of excavation (Millions Rupee)	Cost of manholes (Million Rupee)	Cost of sewer (Million Rupee)	Total cost (Million Rupee)
	1000	0.291	3.17	1.28	4.74
	1000	0.289	3.21	1.28	4.79
	1000	0.289	3.16	1.31	4.77
	1000	0.291	3.09	1.29	4.67
	1000	0.275	3.15	1.31	4.75
	1000	0.288	3.16	1.29	4.74
	1000	0.289	3.09	1.29	4.67
	1000	**0.288**	**3.03**	**1.28**	**4.60**
	1000	0.290	3.03	1.38	4.62
	1000	0.284	3.07	1.27	4.63

V. CONCLUSION

ACO is very promising technique as it can save a lot of time and the present work fulfills more than the objective of developing an efficient algorithm for optimal design of a gravity sewer system.

It is hoped that program shall find direct application in field problems of design of gravity sewer system. As the program developed for sewer system analysis uses the commercially available diameter and slopes. And it can handle discrete parameters of sewer system also.

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