Optimal Design of Complete Gravity Sewerage Network using Flow Path Algorithm

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Abstract -*A network of pipes that carry sewage from colony/society to a sewage treatment plant or discharge point for its proper disposal is called as sewerage system. Sewers have to be laid deep enough to receive all the flows, as gravity sewers are meant to transport waste water through sewers laid below ground surface. The sewerage network is designed considering constraints such as branch depth, minimum and maximum depths and velocities, discrete diameter, head loss etc. Sewerage system requires large amount of investment for their construction and maintenance. Therefore, it is necessary to find a cost-effective solution that reduces capital investment as well as ensures good system performance under the given criteria and constraints. This paper deals with the optimal design of a small sewerage network using flow path algorithm and dynamic programming. The proposed method is very simple, yields result in less time, and the computations can be performed in Excel sheet.*

Key Words: **Dynamic programming, Flow path algorithm, Optimization, Sewerage network, Sewerage system**

1.INTRODUCTION

A set of sewer channels collecting discharges at their nodal points and emptying the same into another set of sewer lines is called as sewerage network. Eventually, the sewerage network is ceased at the outfall. Sewage collection, treatment and disposal systems are embraced to ensure that the sewage released from colony/society is appropriately collected, transported and treated without causing any environmental problems. Sewers must be designed of appropriate size and planned skillfully so that it is prevented from overflow and succeeding damages to properties, and health.

In any society, sewerage networks are important part of infrastructures, and investment required for construction and maintenance of such large scale networks is huge. Therefore, it is mandatory to provide low cost sewers as any saving in the cost of these networks may result in considerable reduction in the total construction cost. Thus, the aim of optimal design is to find a cost effective solution that reduces capital investment as well as ensures good system performance under given criteria and constraints.

In this paper, with the help of Manning equation as hydraulic model the optimal design of sewerage network has been carried out using flow path algorithm and dynamic programming. The design processes have been explained and compared considering a small 7-link 3-junction sewerage network and the results obtained have been presented.

2. HYDRAULIC EQUATIONS

The Manning equation is the most popular and reliable hydraulic model in practice around the world due to its simplicity. Manning equation is:

$$V = \frac{1}{N} R^{\frac{2}{3}} S^{\frac{1}{2}} \quad (1)$$

Where, V = Flow velocity, m/s; N = Manning's coefficient of roughness. The value of manning coefficient of roughness for concrete sewers is 0.013 to 0.015[1]; R = Hydraulic radius, m; and S = sewer pipe slope.
The continuity equation is given by:

$$Q = AV \quad (2)$$

Where, Q = Sewage flow, m^3/s; and A = Cross-sectional area of flow, m^2.

$$A = \frac{\Pi D^2}{4} \quad (3)$$

The method comprises of designing the sewers as circular concrete sections with sewer running partially full. The formulae used for the design of sewer flowing partially full are as follows:
The central angle θ in terms of the relative depth of flow k_d is given by:

$$\theta = 2\cos^{-1}(1-2k_d) \quad (4)$$

The area ratio k_a:

$$k_a = \left(\frac{\theta - \sin\theta}{2\pi}\right) \quad (5)$$

The velocity ratio k_v:

$$k_v = \left(\frac{\theta - \sin\theta}{2\pi}\right)^{\frac{2}{3}} \quad (6)$$

The discharge ratio k_q:

$$k_q = \left(\frac{\theta - \sin\theta}{2\pi}\right)\left(\frac{\theta - \sin\theta}{2\pi}\right)^{\frac{2}{3}} \quad (7)$$

For a given sewage flow, the design of a sewer can be obtained if the self-cleaning velocity and design relative depth are known, and these can be obtained only when the diameter is known, using Eqs. (1) to (7):

3. COST FUNCTIONS

For the optimal design of sewerage network, it is necessary to describe the cost function of the various components of a sewerage network. The main components are sewer pipes, manholes and excavation.

3.1. Cost of sewer pipes

The capitalized cost of the sewer C_m can be demonstrated as [2]:

$$C_m = K_m L D^m \quad (8)$$

Where, k_m and m = Cost parameters of pipe; L = Length of pipe, m; and D = Diameter of sewer, m. The cost of RCC pipe for different diameters was taken [3] and the cost parameters found were k_m = 7015.3 Rs. per m, and m = 1.3992.

3.2. Cost of excavation

The total cost of excavation is the summation of sheeting cost and shoring cost of sewer trenches and earthwork. Assuming sides of excavation trench to be vertical, the capitalized cost of earthwork for sewer C_{er} can be written as [2]:

$$C_{er} = \frac{1}{2} L_w (d_u + d_d) C_e + \frac{1}{6} L_w (d_u{}^2 + d_u d_d + d_d{}^2) C_r \quad (9)$$

Where, C_{er} = cost of capital earthwork; c_e = ground level unit earthwork cost, Rs./m³; c_r = per unit depth increase in unit earthwork cost, Rs./m⁴; d_u and d_d = invert depth at upstream and downstream nodes, respectively, m; and w = width of sewer trench, m.

The surface area of side walls of excavation trenches influences the cost of sheeting and shoring of sewer trenches. The capital cost C_{es} can be demonstrated as:

$$C_{es} = \frac{1}{2} L (d_u + d_d) C_s + \frac{1}{3} L (d_u{}^2 + d_u d_d + d_d{}^2) C_{rs} \quad (10)$$

Where, c_s = unit capital cost of sheeting and shoring at ground level, Rs./m²; and c_{rs} = increase in unit sheeting and shoring cost per unit depth, Rs./m³. Merging Equations (9) and (10), and rearranging the terms, the total capital cost of excavation C_e is given by:

$$C_e = k_e L (d_u + d_d) \quad (11)$$

Where, k_e = earthwork cost coefficient given by

$$C_{es} = \frac{1}{2} w c_e + \frac{1}{6} w \left(\frac{d_u{}^2 + d_u d_d + d_d{}^2}{d_u + d_d} \right) C_r + \frac{1}{3} c_e \left(\frac{d_u{}^2 + d_u d_d + d_d{}^2}{d_u + d_d} \right) C_{rs} \quad (12)$$

Costs of earthwork, and sheeting and shoring were taken [3]. The cost parameters for excavation found were c_e = 155.43 Rs./m³; c_r = 12.422., Rs./m⁴; c_s = 196.12 Rs./m²; and c_{rs} = 23.648 Rs./m³.

3.3. Cost of manhole

The cost of a manhole is based on the depth of manhole. The capitalized cost of the manhole C_h can be demonstrated as:

$$C_h = k_h d_h + b_h \quad (13)$$

Where, k_h and b_h = Manhole cost coefficients; d_h = Depth of manhole, m. The cost of manhole for different depths was taken [3]. The cost parameters found were k_h = 15253 Rs./m; and b_h = -8111.3 Rs.

3.4. Total cost

The total cost C_T of a sewer line is the addition of the cost of prime components of the line together, and is given by:

$$C_T = C_m + C_e + C_h \quad (14)$$

4. DESIGN CONSTRAINTS

To carry peak or design sewage flow, sewerage network is designed at a relative depth along with other design constraints such as self-cleaning velocity, scouring velocity, outfall depth, minimum cover, branch depth, invert progression constraint *etc.*

4.1. Self-cleaning velocity

The variation of self-cleaning velocity with respect to diameter of pipes as given in Table 1[4]

Table - 1: Self-cleansing Velocity

Diameter, m	Self-cleaning velocity, m/s
0.150-0.250	1.00
0.300-0.600	0.75
> 0.600	0.60

4.2. Scouring velocity

To ensure that there should not be any damage or scouring of the pipe material, flow velocity is restricted to a maximum permissible velocity as given in Table 2 [4]

Table - 2: Souring Velocity

Sewer material	Souring velocity, m/s
Cast iron	3.5-4.5
Stoneware	3.0-4.5
Concrete	2.5-3.0
Brick	1.5-2.5

4.3. Relative depth

The relative depth k_d should not exceed 0.75, and it varies with the diameter of pipes as given in Table 3 [4]

Table - 3: Relative Depth

Sewer diameter, m	Relative depth
0.150-0.250	0.50
0.300-0.500	0.60
0.550-1.200	0.70
> 1.200	0.75

5. CONSTRAINT SATISFACTION

The main aim is to find the optimal cost solution of a sewer line subjected to the pertinent design criteria, hydraulic relationships and design constraints. It is mandatory to satisfy all the pertinent constraints for the link as well as for the nodes of the sewerage network. A sewer should have a minimum cover depth h_{min}, which is generally taken to be between 1.0 m and 2.0 m [2]. The minimum depth at a node is $D+h_{min}$.

6. DESIGN PROCEDURE

Following steps are used to design a sewerage network:

1. Determine feasible set of diameters; head loss and slope for each diameter of all links;
2. Determine cost of all sewer links individually considering cost parameters;
3. Design all the lines coming at junction manhole and selecting the main line with minimum cost;
4. Extend the main line with minimum cost and greater downstream invert depth up to next junction point;
5. Select the branch lines with minimum cost option to join the main line and check their downstream invert depth at junction; and
6. Repeat Steps 1-5 till outlet is reached.

With the help of maximum and minimum velocities and design relative depths, set of feasible diameters can be determined from Eqs (1) to (6). Assuming that, diameters for each sewer link with an increment of 50mm are available which gives feasible set of diameters. Relaxing relative depth $k_d$on the lower side can give few more options if there is scarcity of available options. Relaxation was extended till decrease in head loss is less than 20 mm. Determine k_v and $k_q$for each diameter using Eqs (5) and (6), respectively. The flow and velocity at full flowing condition can be determined using flow and velocity at the partially full flowing condition. The slope for each option of a link and thereby head loss should be determined using the Manning equation.

Minimum soil cover and link diameter governs the upstream invert of first sewer; its downstream invert depends on the upstream invert, head loss and ground levels. Design all the single link sewer lines. Determine the cost of each line using Eqs (8) to (14) for the obtained set of feasible diameters. Select the least cost options and options above it for further calculations. Design can be further extended with greater downstream invert depth up to next junction point after checking the downstream invert depth for all selected options. Select the least cost options and neglect the options below it from the extended design and check its downstream invert depth with respect to other selected options at previous junction point. Continue the design of the sewer line as main sewer line if the extended line has greater downstream depth at previous junction point; otherwise redesign the same using the least cost option with greater downstream depth.

This process is continued till the extended sewer line option satisfies the downstream depth criteria at the junction point. Further, select optimal solutions in the same way from the extended design and proceed using the design process to the next junction [5]. Similarly, determine the total cost of all the links coming at the next junction point and select the least cost options from all the designed lines at that junction point and neglect the options below least cost for further design. Check the downstream invert depth of all the selected options and further extend the design with greater downstream invert depth up to next junction point.

The process is continued till outfall is reached and the main sewer line with optimal cost is obtained, and the remaining lines are considered as branch lines. Check the downstream invert depth of all the least cost options of the branch lines and join the branch line to the main line at the junction point. The optimal design of sewerage network can be obtained by combining the least cost solution from all the steps.

7. ILLUSTRATIVE DESIGN EXAMPLE

The process of optimal design of sewerage network is illustrated using a 7-link, 3-junction sewerage network as shown in Fig. 1. The nomenclature system adopted for the network is four level for each option of pipe here the first number indicates the line number, the second indicates the pipe number, and the third indicates the option number of feasible diameter for the pipe. The location of the system outlet or sink for the sewerage network is at the downstream end of pipe 1-4. The required design data for the 7-link 3-junction sewerage network are given in Table 4.

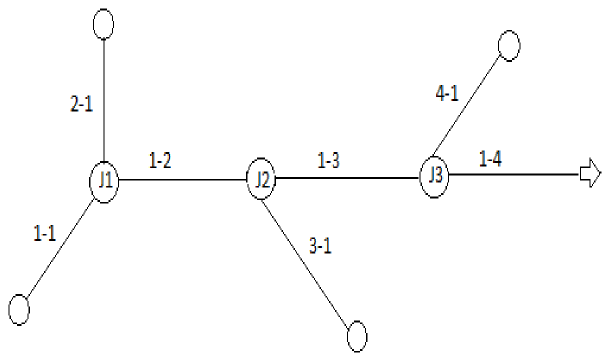

Fig -1: Description of sewerage network

Table -4: Design Data for 7-link Sewerage Network

Pipe	Q, m^3/s	Z_1, m	Z_2, m	L, m
1-1	0.06	170.0	169.5	65
1-2	0.20	169.5	169.2	85
1-3	0.30	169.2	168.9	85
1-4	0.07	168.9	168.7	70
2-1	0.05	168.9	169.5	55
3-1	0.07	169.3	169.2	60
4-1	0.04	169.0	168.9	50

8. RESULTS AND DISCUSSION

Feasible set of diameters their corresponding head loss calculatedfor each linkis given in Table 5.

Table -5: Set of Feasible Diameters and Head Loss

Pipe	Set of feasible diameters (head loss), m
1-1	0.450 (0.105), 0.400 (0.160), 0.350 (0.325), 0.300 (0.740), 0.250 (3.525)
1-2	0.750 (0.055),0.700 (0.08),0.650 (0.115), 0.600 (0.175), 0.550 (0.275), 0.500 (0.705), 0.450 (1.235), 0.400 (2.315)
1-3	900 (0.045), 0.850 (0.065), 800 (0.085), 0.750 (0.120), 0.700 (0.170), 0.650 (0.255), 0.600 (0.390), 0.550 (0.615), 0.500 (1.585), 0.450 (2.780)
1-4	0.400 (0.235), 0.350 (0.480), 0.300 (1.085), 0.250 (5.170)
2-1	0.550 (0.035), 0.500 (0.055), 0.450 (0.170), 0.400 (0.345), 0.350 (0.345), 0.300 (0.785), 0.250 (1.150)
3-1	0.550 (0.040), 0.500 (0.065), 0.450 (0.110), 0.400 (0.200), 0.350 (0.410), 0.300 (0.930), 0.250 (4.430)
4-1	0.300 (0.255), 0.250 (0.670), 0.200 (3.965)

Consider the sewer pipe 1-1 as a starting point. Slope and head loss for each diameter of link 1-1 were determined; invert depths and total costs for each option were calculated. Similarly, the invert depths and total cost for each option of all lines 1-2, 1-3, 1-4, 2-1, 3-1, 4-1 were determined.

Pipe option having the least cost and the options above it were selected from all links and considered for further double line calculations. All selected options of link 1-1 combined with all selected pipe options of link 1-2 ensuring that the upstream invert depth of link 1-2 is less than or equal to the downstream invert depth of link 1-1 at the junction J_1. Similarly, link 2-1 combined with link 1-2, link 3-1 combined with link 1-3, link 4-1 combined with link 1-4. Different sets were obtained by combining various options of these links on the basis of downstream invert depths of all the links at their respective junctions J_1, J_2, J_3. The optimal cost pipe options of double line calculations are given in Table 6.

Table - 6: Optimal Cost Pipe Options of Double Line

Sets	Total cost, Lakh Rs.
(1-1-4)+(1-2-8)	4.7503
(2-1-5)+(1-2-8)	4.5540
(3-1-5)+(1-3-9)	5.3825
(4-1-1)+(1-4-3)	3.0526

In the similar way, three lines (1-1+1-2+1-3), (2-1+1-2+1-3), (3-1+1-3+1-4)), and four lines ((1-1+1-2+1-3+1-4), (2-1+1-2+1-3+1-4)) cost calculations were done by selecting the options up to the least cost and checking the downstream invert depths of the links at their respective junctions.

Comparing all the costs, it was found that line (2-1-5)+(1-2-5)+(1-3-8)+(1-4-3) gives the optimal solution with optimal cost 10.7492 lakhs Rs. (Fig. 2), which was considered as the main line, and other lines were considered as the branch lines. The optimal cost options for the main line, and the calculations with its downstream invert depths at all junctions are given in Table 7.

As (2-1-1)+(1-2-5)+(1-3-8)+(1-4-3) line is main line of sewerage network and the other links are branch lines. Branch line 1-1, 3-1, 4-1 are combined with the main line by considering the invert downstream depths at the respective junction points and least cost option.

Table - 7: Optimal cost pipe options of four line with downstream invert depths at junctions

Sets	Total cost, lakh Rs.	Depth at J_1, m	Depth at J_2, m	Depth at J_3, m
(1-1-3)+(1-2-5)+(1-3-8)+(1-4-3)	11.004	1.575	1.550	1.865
(2-1-5)+(1-2-5)+(1-3-8)+(1-4-3)	10.749	1.595	1.570	1.885

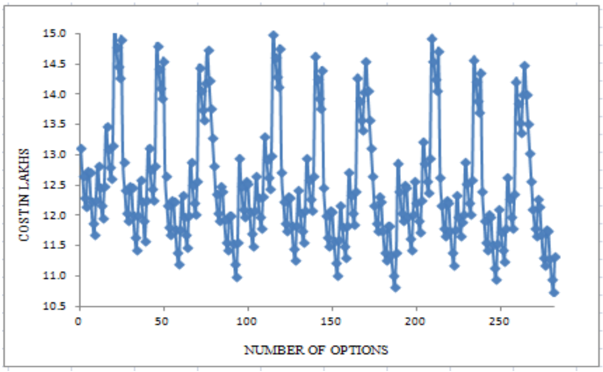

Chart - 1: Cost variation of main line

The total cost of sewer line was calculated. The cost effective grouping of options of branch lines with the main line was done such that the terminal depth of all the branch line meeting at the junction is less than or equal to the invert depth of the main line at the junctions.

The optimal solution for the illustrated sewerage network is the pipe set (1-1-4) + (2-1-5) + (1-2-5) + (3-1-4) + (1-3-8) + (4-1-2) + (1-4-3) having cost Rs. 15.1413 lakhs.

Final optimal solution of 7-link, 3-junction sewerage network is as shown in Fig.2 with the respective upstream invert depth and downstream invert depth of the main and branch lines.

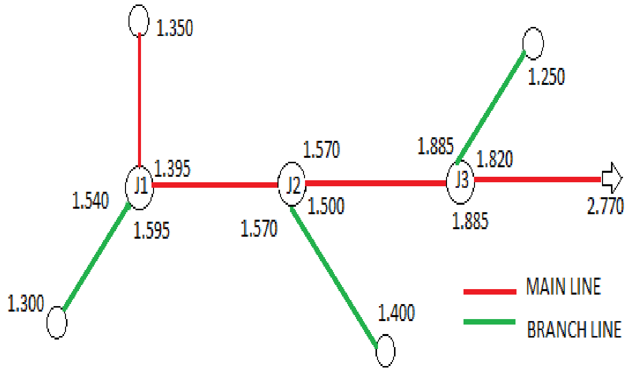

Fig - 2: Final solution with invert depths

It can be seen that the total number of options becomes very large as the size of the sewerage network increases, and it becomes very difficult to carry out design process. In order to reduce this problem, there is a need to apply certain rejection criteria so as to reduce the number of options without reduction in the quality of solutions.

9. CONCLUSIONS

Following conclusions can be drawn from the study:

1. The optimal solution for the design can be easily obtained using flow path algorithm and dynamic programming.
2. Substantial savings in the design of sewerage networks can be obtained as compared to the conventional design.
3. The number of options of diameters can further be reduced by designing each link individually and neglecting the options having more invert depths than the optimal option. Thus, computational efforts for finding the optimal solution for a network can further be reduced.

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