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Optimal Design of Sewer Line with Tail End Pumping Station

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Abstract: The optimal design of sewer line have, so far, been restricted to complete gravity systems whereas in real life situations, intermediate or tail end pumping station becomes imperative, both from engineering and cost considerations. This paper deals with the development of an approachfor the optimization of sewer line with tail end pumping station. The work is divided into two parts. At the first part, gravity sewers are designed and at the later part, the sewer line is designedalong with the tail end pumping station. The dynamic programming (DP) technique is used as a tool for optimization throughout the sewer line design, along with Manning equation. The cost of pump considering the standbyfraction for pump and the energy cost are considered as cost function for pumping of wastewaterin addition to the cost function for sewer line design. The algorithm was developed for optimization of cost function of sewer line with tail end pumping station. The effectiveness of the algorithm was tested through an illustrated design example.

Keywords: Dynamic programming; sewage pumping; optimization; sewer design

I. Introduction

Sewage is required to be lifted up from a lower level to a higher level at various places in a sewerage system. Sewage may have to be lifted by pumps under the following circumstances:

i. The sewage from localized low lying pockets in a city has to be pumped, so as to throw it up into the city's sewer pipes flowing under gravity and running at higher elevations.

ii. When the ground is flat, the laying of sewers at their designed gradients may involve deeper and deeper excavations in the forward direction of flow. In such situation, it may advisable to lift the sewage at suitable intervals, and then to lay sewers at reasonable depth below the surface.

iii. For disposing of sewage of the basements of large commercial buildings, sewage may have to be pumped, as the street sewer may be higher than the level of basement floor.

iv. When the outfall sewer is lower than the level of the treatment plant, the sewage may have to be pumped up.

Therefore, taking into consideration the need of sewage pumping stations, the optimization algorithm wasdeveloped for cost trade-off analysis of sewer line with tail end pumping station.

1.1 Review of Literature

The researchers have recognized that the design of wastewater collection system is a sequential decision process. They have identified DP as an appropriate method for optimization of wastewater collection systems since the problem could be divided into a number of stages.

Kulkarni and Khanna (1985) presented a DP based optimization algorithm for cost trade-off analysis of 'pumped wastewater collection systems' to enable minimal cost designs of sewerage networks. Modified Hazen-Williams hydraulic equation model has been used in this DP based approach. This approach was applied to the efficient design of wastewater collection system at Khopoli, Maharashtra, India.

Gupta et al. (1983)used a modified Hazen-Williams hydraulic model under partial flow condition. They designed the optimization based approach for 'complete gravity wastewater collection system'. This optimization based approach used a modified DP method that is only suitable for medium sized sewerage networks and does not guarantee global optimality.

II. Hydraulic Model

Manning equation is used as the hydraulic model. Manning equation is given by:

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \qquad (1)$$

Where,

V = Velocity of flow, m/s;
R = Hydraulic radius, m;
η = Manning coefficient; and
S = Slope of sewer pipe.

The central angle θ in terms of relative depth of flow k_d is given by:

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

The area ratio k_a is given by:

$$k_a = \left(\frac{\theta - \sin\theta}{2\pi}\right) \qquad (3)$$

The velocity ratio k_v is given by:

$$k_v = \left(\frac{\theta - \sin\theta}{\theta}\right)^{2/3} \qquad (4)$$

The discharge ratio k_q is given by:

$$k_q = \left(\frac{\theta - \sin\theta}{2\pi}\right)\left(\frac{\theta - \sin\theta}{\theta}\right)^{2/3} \qquad (5)$$

III. Cost Model

The cost model was formulated by considering the cost of gravity sewer and cost of wastewater pumping. The cost for

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manhole and cost for standby pump were included in cost function of the system.

3.1 Cost of pipe

The capital cost of the sewer pipe, C_m is given by:

$$C_m = k_m L D^m \quad (6)$$

Where,

k_m, m = Cost parameters of pipe;
L = Length of pipe, m; and
D = Diameter of pipe, m.

The unit cost of cast iron (CI) pipes per unit length for various diameters wasobtained from Schedule of Rates (SOR), Maharashtra Jeevan Pradhikaran (MJP, 2013). Similarly, the cost of lying and joining of pipes per unit length were also obtained from SOR (MJP, 2013). The unit cost for specials was taken as 10% of unit cost of pipes. The initial cost of pipe for various diameters was obtained by adding these three components. Then, the capitalized cost of pipe for various diameters wascalculated by multiplying the total initial cost of pipes with capitalization factor. The cost parameters were obtained from the graph plotted between capitalized cost of pipes and diameters of pipes and the values of cost parameters werefound to be k_m = 27856 Rs./m,and m = 1.440.

3.2 Cost of Excavation

The cost of excavation of sewer trench includes the following components:

i. Cost of earthwork; and
ii. Cost of sheeting and shoring.

3.2.1Cost of earthwork

The cost of earthwork per unit volume is a function of depth of sewer and the type of earth strata available along the sewer line. If different strata are available for each link, the cost can be considered to be variable for each link. However, for the sake of simplicity in presentation of this work, the uniform layer of soil stratum was assumed throughout the entire length and depth of sewer line. The sides of excavation trench are assumed to be vertical. The capital cost of earthwork C_{ew} is given by:

$$C_{ew} = \frac{1}{2} L w (d_u + d_d) c_e + \frac{1}{6} L w \left(d_u^2 + d_u d_d + d_d^2\right) c_r \quad (7)$$

Where,

L = Length of excavation trench, m;
c_e = Unit excavation cost, Rs./m^3;
c_r = Increase in excavation cost,Rs./m^3/m;
d_u = Upstream depth of sewer, m;
d_d = Downstream depth of sewer, m; and
w = Width of excavation trench, m.

The capitalized cost of excavation was calculated by multiplying rates of excavation taken from SOR (MJP, 2013) with capitalization factor. The graph was plotted between capitalized cost of excavation per unit volume and average depth of excavation. From the graph, the values of c_e and c_r were found to be 142.3 Rs./m^3 and 10.16 Rs./m^3/m, respectively.

3.2.2 Cost of sheeting and shoring

The cost of sheeting and shoring of sewer trench depends upon the surface area of sidewalls of excavation trenches. The capital cost of sheeting and shoring of a sewer trench C_{es} is given by:

$$C_{es} = L(d_u + d_d) c_s + \frac{1}{3} L (d_u^2 + d_u d_d + d_d^2) c_{rs} \quad (8)$$

Where,

L = Length of excavation trench, m;
c_s = Unit capital cost of sheeting and shoring at ground level, Rs./m^2; and
c_{rs} = Increase in unit cost of sheeting and shoring per unit depth, Rs./m^2/m.

The capitalized cost of sheeting and shoring was calculated by multiplying cost of sheeting and shoring with capitalization factor. The graph between capitalized cost of sheeting and shoring and average depth of excavation was plotted. The values of c_s and c_{rs} were found to be 200.3 Rs./m^2 and 18.37 Rs./m^2/m, respectively.

Therefore, the total cost of excavation is the sum of the cost of earthwork and cost of sheeting and shoring. Adding the equations (7) and (8) and rearranging the terms, the total capital cost of excavation, C_e is given by:

$$C_e = k_e L (d_u + d_d) \quad (9)$$

Where,

k_e = Excavation cost coefficient, given by:

$$k_e = \frac{1}{2} w c_e + \frac{1}{6} w \left(\frac{d_u^2 + d_u d_d + d_d^2}{d_u + d_d}\right) c_r + c_s + \frac{1}{3} \left(\frac{d_u^2 + d_u d_d + d_u^2}{d_u + d_d}\right) c_{rs} \quad (10)$$

3.3 Cost of manhole

The cost of manhole is an insensitive function of diameter, and it solely depends on the depth of the manhole. The capital cost of the manhole, C_h can be expressed as:

$$C_h = k_h d + b_h \quad (11)$$

Where,

k_h, b_h = Manhole cost coefficient; and
d = Depth of manhole, m.

The capitalized cost of manhole was calculated by multiplying rates of manhole taken from SOR (MJP, 2013) with capitalization factor. From the graph plotted between the capitalized cost of manhole per unit depth and depth of manhole, the value of cost parameters were found to be k_h= 11359Rs./m, and b_h= -7247 Rs.

3.4 Cost of wastewater pumping

The cost of wastewater pumping is composed of cost for following components:

i. Cost of pumps; and

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ii. Cost of energy.

3.4.1Cost of pumps

The cost of pump depends on the power requirement of that pump. The power, P required to run the pump is given by:

$$P = \frac{\rho g Q h_o}{1000\eta} \quad (12)$$

Where,

P = Power required, kW;
ρ = Mass density of fluid, kg/m^3;
Q = Discharge of sewage to be pump, m^3/s;
h_o = Pumping head, m; and
η = Efficiency of pump.

Therefore, the cost of workingpumpC_{pw} is given by:

$$C_{pw} = k_p P \quad (13)$$

Where,

k_p = Cost parameter of pump.

But for reliability, actual capacity of wastewater pumping should be more than the required capacity of wastewater pumping. Therefore, the provision for standby pump is made. The cost of standby pumpC_{ps} is given by:

$$C_{ps} = S\, k_p P \quad (14)$$

Where,

S = Standby fraction for the pump.

Therefore, cost of pump, C_p is obtained by adding Equations (13) and (14) and can be given as:

$$C_p = k_p P + S k_p P \quad (15)$$

Using Equation (12) above equation can be written as:

$$C_p = k_p \left(\frac{\rho g Q h_o}{1000\eta}\right)(1 + S) \quad (16)$$

The cost of pump was obtained from SOR, Maharashtra Jeevan Pradhikaran for Electrical and Mechanical for Nagpur and Amravati region for the year 2012-13. The value of k_p was obtained by plotting the graph between pumping capacities and cost of pump. The value of k_p was found to be 19168 Rs./kW.

3.4.2Cost of energy

The annual recurring cost of energy consumed in wastewater pumping depends on the amount of wastewater pumped and the pumping head h_o produced by the pump. If Q= peak discharge of the wastewater pumped then, the effective discharge will be,$F_A F_D Q$

Where,

F_A = Annual averaging factor, and
F_D = Daily averaging factor.

The average power P in kW, required annually would be:

$$P = \frac{\rho g Q h_0 F_A F_D}{1000\eta} \quad (17)$$

Multiplying the power by number of hours in a year (8760 hours) and the rate of electricity per kW-hour, R_E; the annual cost of energy C_E required for wastewater pumping is given by:

$$C_E = \frac{8.76 \rho g Q h_o F_A F_D R_E}{\eta r} \quad (18)$$

The total cost of wastewater pumping can be obtained by adding Equations (16) and (18).

3.5 Total cost of sewer line

The total cost C_T of sewer line can be obtained by adding the cost of major components of the line together, and is given by:

$$C_T = C_m + C_e + C_h + C_p + C_E \quad (19)$$

IV Design Constraints

The self-cleaning velocity varies with the diameter of pipes as given in Table 1 (Swameeet al.1987).

Table 1: Adopted self-cleaning velocity

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

The maximum permissible velocity in the sewer lines depends upon the pipe material. The maximum velocity for cast iron pipe material was adopted as 3.5 to 4.5 m/s (Swameeet al. 1987).
The sewer lines are designed to flow partially full, so as to maintain free surface flow. Therefore, the relative depth was adopted referring to below Table 2 (Swameeet al. 1987).

Table 2: Relative depth

Sewer diameter, m	Relative depth
0.15-0.25	0.50
0.30-0.50	0.60
0.55-1.20	0.70
>1.20	0.75

V. Design Procedure

The optimal design of sewer line can be completed in the following major steps:

1. Determination of set of feasible diameter for each sewer link.
2. Determination of head loss for each diameter of sewer.
3. Determination of cost of sewer line considering the cost of pipe, cost of excavation and cost of manhole.
4. Determination of cost of wastewater pumping.

The minimum and maximum diameters can be obtained for a given flow using minimum velocity, maximum velocity and relative depths with the help of Equations (1) to (6). Assuming that the diameters are available at an increment of 50 mm, the set of feasible diameters can be obtained for each sewer link. If number of options is insufficient, a few more options can be obtained by relaxing relative depth on lower side. The head loss was calculated for each individual obtained diameter of sewer by Manning equation. The total cost of gravity sewer was calculated for every combination of two sewer links by taking into consideration cost of pipe, cost of excavation and cost of manholes. After finding out the total cost for gravity sewer, the cost of wastewater pumping was calculated. The total cost of sewer line was obtained by using Equation (19). The graph between the total cost of sewer line involving pumping and outfall depth of sewer was plotted and the optimal value of outfall depth of sewer was obtained for which the total cost of sewer line was minimum.

VI. Illustrative Design Example

The 2-link sewer line is considered as the design example. The input data required for designing the sewer line is given in Table 3.

Table 3: Design data for 2-link sewer line

Link	, m^3/s	, m	, m	L, m
1	0.070	158.0	157.9	70
2	0.200	157.9	157.8	80

6.1 Results and Discussion

The 2-link sewer line problem was solved by Manning equation and DP as a tool for optimization. The set of feasible diameters along with the corresponding head loss obtained for each sewer link is given in Table 4.

Table 4: Set of feasible diameter with head loss

Pipe	Set of feasible diameters (head loss), m
1	0.450 (0.115), 0.400 (0.180), 0.350 (0.365),0.300 (0.820), 0.250 (3.885)
2	0.600 (0.125), 0.550 (0.200), 0.500 (0.500), 0.450 (0.880), 0.400 (1.640), 0.350 (3.340)

The total cost of gravity sewer line was obtained for each individual combination of selected diameter of sewers.From Figures 1 and 2,the optimal cost of gravity sewer was found to be 12.93Rs. Lakh for option number 16 having outfall depth of sewer equal to 2.950 m. The optimal diameters of pipe 1 and 2 were found to be 0.400 m and 0.550 m, respectively.

The total cost of sewer line involving pumping was calculated for each combination of selected diameter of sewers. The total cost of sewer line involving pumping was calculated by adding total cost of gravity sewer and cost of sewage pumping. From Figs. 3 and 4, the optimal cost of sewer line involving pumping was found to be 286.32 Rs. Lakh for option number 6 having outfall depth of sewer equal to 1.730 m. The optimal diameters of pipe 1 and 2 were found to be 0.300 m and 0.450 m, respectively.

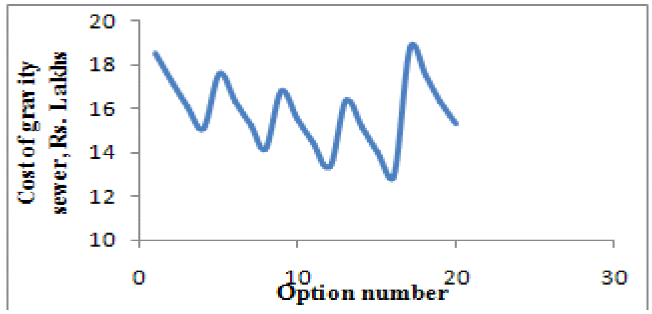

Fig. 1: Cost of gravity sewer vs option number

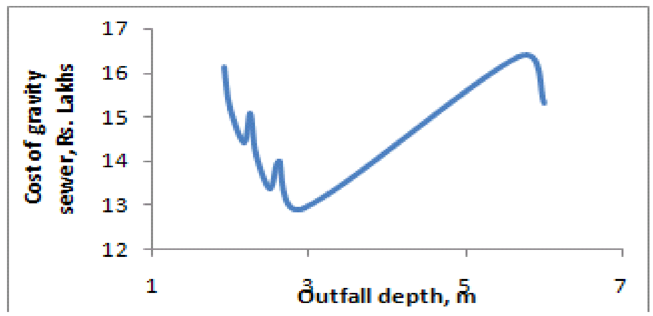

Fig. 2: Cost of gravity sewer vs outfalldepth

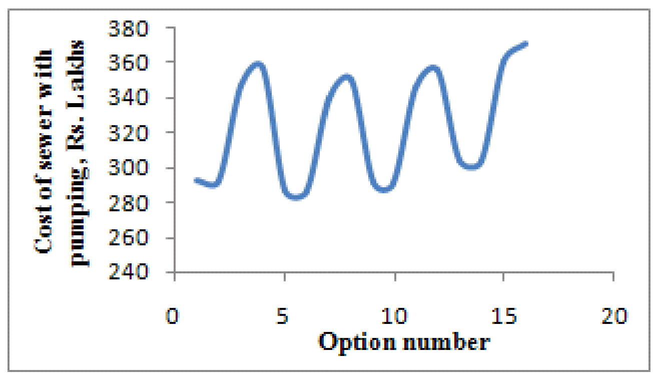

Fig. 3: Cost of pumping sewer vs option number

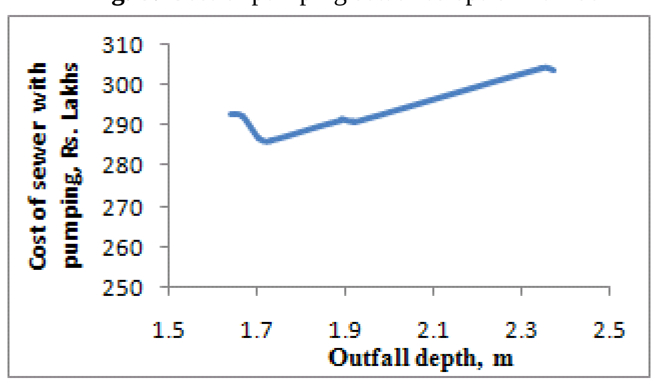

Fig. 4: Cost of pumping sewer vs outfall depth

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VII. Conclusions

The following conclusions can be drawn from the study carried in this work:

1. The cost of sewer line with pumping is lesser for options having lesser depths whereas the cost of gravity sewer is more when depths are either too less or too more.
2. The optimal solution with pumping is different in diameters as compared to that with gravity sewer.
3. The depth for which the total cost of gravity sewer line is the minimum, has more cost of sewer line involving pumping.
4. The total cost of gravity sewer line is more when the outfall depth of sewer is either less or more than that of the optimal solution.
5. The total cost of sewer line involving pumping initially decreases with the outfalldepth of sewer, and then it increases at higher rate as the outfall depth of sewer line increases.
6. The optimal solution can be obtained by using the dynamic programming. This process is easy for design of sewer line involving pumping.

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