Optimal Design of Water Transmission System

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Abstract - *Water transmission network is used to convey the water from supply reservoir at water treatment plant to receiving reservoirs. If node of demand is highly elevated than the source node, pumping system serves as the best solution over gravity system. Water transmission by pumping system involves investments of huge amount of cost associated with design, maintenance and operations of various units of the system. The prime principle of the design of water transmission scheme is to improve the cost-effectiveness and performance. In this paper, optimal diameters and pumping head is worked out by flow path algorithm and dynamic programming. The two junction network with pumping was designed and analyzed using EPANET. The effect of pumping head on total cost of system was studied. The main aspect focus in this paper is to obtain optimal design and cost with ease for water transmission network involving pumping*

Key Words: **Dynamic programming, EPANET software, Flow path algorithm, Pumping, Water transmission network**

1. INTRODUCTION

Water transmission network is one of the foremost and principal parts of water supply scheme like a water treatment plant and water distribution network. This is used to transmit water from the supply source reservoir to receiving reservoirs. The gravity system, pumping system or combined system are three water transmission systems used for water transmission. Pumping system is likely to be used where the available head of supply node is lower than the receiving node. The huge investment of cost has been made over the maintenance, construction, and operation of water supply scheme. The water transmission with pumping system demands more funds due to pumps and other accessories associated with it as compared to gravity system. Thus any small saving in cost for water network leads to significant markdown over the total cost of scheme. The traditional methods generally used for design and analysis are proved to be tedious and uneconomical. The prime elemental objective of this paper is to design the water transmission network with pumping considering the careful analysis for cost investment with maintenance and operation. In this paper the optimal diameters for gravity main, pumping mains and optimal cost transmission network, are determined by using the method of the Lagrange's multipliers. Flow path algorithm and dynamic programming is developed in such a manner that optimum diameter with optimal cost of water transmission network could be worked out. The design equations for optimization had been developed by using Hazzen William's equation. Total design is then analyzed by using EPANET software. Variable costs with different heads were trailed out to get total optimal cost.

2. EQUATIONS USED FOR DESIGN AND ANALYSIS OF NETWORK

2.1 Equation for Diameter of Pumping Main

In the pumping main water is flow in pipe by creating the pressure head difference using pumping. Pumping main can also be termed as rising main. The diameter for pumping mains is calculated by using Eq. (1) [1]:

$$Dp = \left(\frac{51.98 \gamma L Q^{1.852}}{m C_H{}^{1.852}} \frac{K_T}{K_m} \right)^{\frac{1}{m+4.870}} \qquad (1)$$

$\frac{K_T}{K_m}$ =

Relative cost factor which depends on cost of pipe and cost of pumping and energy.

2.2 Hydraulic Equations

Hydraulic equations commonly used for design and analyses of water transmission network are as follows:

A. Darcy-Weisbach equation;
B. Hazen-Williams equation; and
C. Modified Hazen-Williams equation.

In this paper, the design and analysis was worked out by using the most popular Hazzen-Williams equation. This is empirical equation developed in 1902, and used for smooth flow. This equation is conventionally acceptable equation for design of water conveyance system as it is simple to use. Hazen-Williams equation with hydraulic mean depth, slope and velocity is given by [2]:

$$V = 0.849 C_H R^{0.63} S^{0.54} \qquad (2)$$

Where,
C_H = Hazen Williams constant; R = Hydraulic mean depth, m; and S = Slope of the energy line.
For the design and analysis, the value for constant C_H was taken as 130 for new cast iron (*CI*) pipe. (Manual, 1993)
The frictional head loss is considered as the major loss in pipe network which can be computed by Eq. (3):

$$h_f = \frac{10.678 L Q^{1.852}}{C_H^{\;1.852} D^{4.870}} \qquad (3)$$

h_f = Frictional head loss m; D = Pipe diameter, m; Q = Flow of water, m³/s; and L = Length of pipe, m.

3. COST FUNCTIONS

Cost function was developed for various components of water transmission network. The total cost of pumping system worked out by calculating cost function for each unit such as pipes and pumps. Cost functions for different components used in water transmission system are as follows;

3.1 Cost of Pipes

Pipe is the prime component of water supply scheme. Pipe involves the huge investment of cost as compare to other components.

Cast iron or ductile iron pipes are most preferable in pumping system. These pipes are durable, cost effective and resistant to high pressure and acid corrosion. It can sustain the large pressure which is developed in pumping system. *CI* Pipes are much easier for connections. Cost of pipe given by Eq. (4) [1,3]:

$$C_m = K_m L D^m \qquad (4)$$

Where, K_m *and* m = Cost parameter for pipes; L_i = Length of i^{th} pipe, m; and D_i = Diameter of i^{th} pipe, m. To determine the cost parameters for pipes, the cost data was taken from Schedule Rate (CSR) of Maharashtra Jeevan pradhikaran (MJP) for Amravati region [4]. The provision of valves is the prime requirement in water transmission network; it is used for operation and maintenance of pipe line by controlling over the flow. Therefore, the 10% of the total pipe cost was taken as cost for fixture and fastening of pipe. The Cost of CI pipes for different diameters were taken from schedule of rate and it was multiplied by capitalization factor calculated using Eq. (5) as follow [1,3]:

$$C_f = 1 + \frac{1-\alpha}{(1+r)^T - 1} + \frac{\beta}{\gamma} \qquad (5)$$

Where,

α = components salvage fraction;

β = the component maintenance fraction;

r = rate of discount or interest expressed as fraction, Rupees/year; and

T = components useful life, years. The value of K_m = 30106 and m = 1.407 was obtained by plotting graph as shown in Fig. (1).

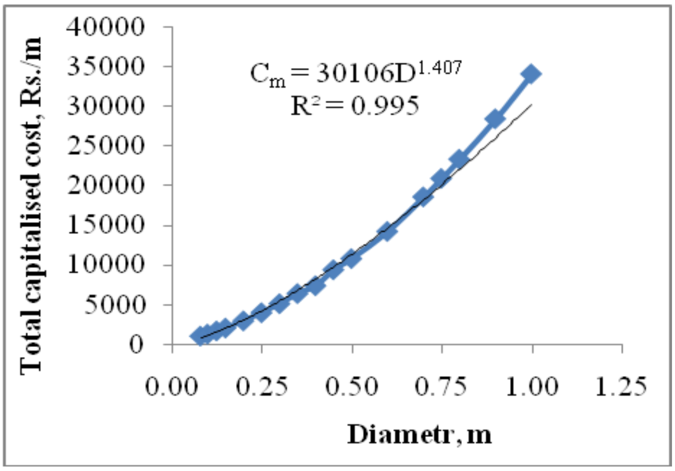

Fig.-1: Cost Variation of CI Pipe with Diameter

3.2 Cost of Pumping

In case of flat terrain or low head difference, it becomes necessary to provide some external energy to fulfill water demand in such condition pump is used. Pump and pumping house are the two major parts of pumping system. The cost function for pumping calculates the pump power which directly relates to cost of pump house. Cost of pumping plant is given by Eq. (6) [1,3]:

$$C_p = K_P P \qquad (6)$$

Where, K_P = Cost parameter of pump; and P = Power of pump, kW. The power required for pump is given in Eq. (7)[1]:

$$P = \frac{\rho g Q h_0}{1000\eta} \qquad (7)$$

Where,

η = Efficiency of pump; ρ = Mass density of fluid; and h_0 = Pumping head, m. The pump cost data was taken from CSR of MJP for Mechanical and Electrical 2016-17 for region of Amravati [5]. The value of cost parameter K_P = 18099 was obtained from Fig. (2).

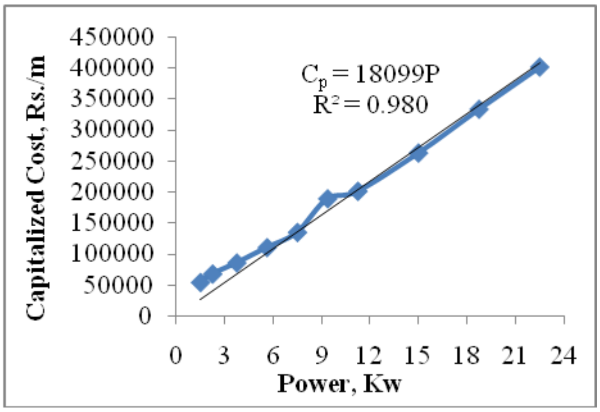

Fig.-2: Cost variation with power

Equation for power calculation including provision of stand by pump is given by Eqs. (8) and (9):[2]

$$P = \frac{(1+S_b)\rho g Q h_0}{1000\eta} \quad (8)$$

Where, S_b = Standby fraction.

$$P = K_P\left(\frac{(1+S_b)\rho g Q h_0}{1000\eta}\right) \quad (9)$$

3.3 Cost of Energy

The power over a year is given by Eq. (10) [2]:

$$P = \frac{F_A F_D \rho g Q h_0}{1000\eta} \quad (10)$$

F_A = Annual averaging factor; and F_D = Daily averaging factor for the discharge.
The total cost of energy required annually given by Eq. (11) [2]:

$$C_e = \frac{8760 F_A F_D R_e \rho g Q h_0}{1000\eta} \quad (11)$$

Re= Electricity rate, Rs./kWH,

4. PROCEDURE FOR DESIGN AND ANALYSIS OF WATER TRANSMISSION LINE WITH PUMPING

4.1 Design Procedure

1. Calculate the diameter for pumping main using Eq. (1);
2. Calculate the optimal diameter of pipe for gravity main using method of Lagrange's multiplier with considering different available flow paths;
3. Find h_f (frictional head loss) using Eq. (3);
4. Find out the H_j (junction head) by subtracting h_f from respective previous head;
5. Calculate the diameter of branch pipe which is linked with junction H_j using Equation (3);
6. Next diameters of pipe after next junction was worked out using Steps 2-5; and
7. Calculate Cost of pipe and cost of pumping units using cost functions.

4.2 Analysis using EPANET Software

The software EPANET is used for analysis of water network. The process for analysis of water transmission network is described as follows;

1. Draw the network and add the objects junctions, reservoirs and pipes *etc.;*
2. Assigning properties by selecting object;
3. Analyzed the network by selecting on Run analysis; If run analysis status shows successful then drafted network model is right
4. If run analysis show unsuccessful status (not ok) then check out the network for each objects with assigned properties and by Correcting it then further go for run analysis.
5. View the result of analysis.

5. ILLUSTRATIVE EXAMPLE

5.1 Water Transmission Network

The five reservoirs with two junctions water transmission network shown in Fig. (3).

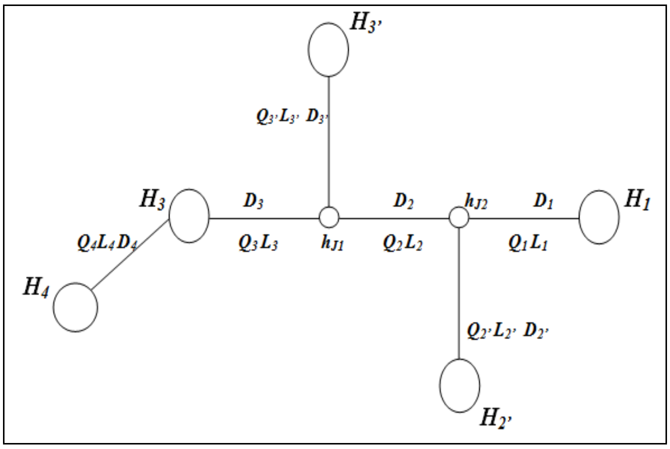

Fig-3: Two Junction Five Reservoir System

The different notations are assigned to elaborate developed network. In which H_4, H_3, $H_{3'}$, $H_{2'}$, and H_1 represented the heads or elevations of reservoirs assigned as 4, 3, 3', 2' and 1, respectively. H_4 is assign for elevation of source node from which water is pump to H_3. From H_3 water is then supply completely by gravity to $H_{3'}$, $H_{2'}$ and H_1. The head at junctions is assigned by h_{J1} and h_{J2}. The design data for same network is shown in Table (1).

Table 1: Design Data for Water Transmission Network

Pipe / Reservoir	*H*, m	*L*, m	*Q*, m³/s
4	60	50	0.80
3	80	6500	0.80
3'	70	3000	0.65
2	-	4500	0.15
2'	65	2500	0.10
1	60	3800	0.55

5.2 Design Procedure

Design procedure for two junction water transmission networks with pumping is as follow;

1. Diameter for pumping main/rising is calculated using Equation (1);
2. Diameter (D_3) for pipe 3 is calculated by equation derived using flow path algorithm and method of Lagrange's multiplier;
3. Head loss due to friction (h_{f3}) is calculated using Equation (3) and use diameter D_3 calculated in Step 2;
4. Calculate the h_{j2} by subtracting hf3 from H3.

5. Calculate the diameter D_3' which is linked with junction h_{j2} using Equation (3);
6. To calculate pipe diameter D_2, D_2' and D_1 for pipe 2, 2'and 1 adopt the same procedure as explain in Step (2), (3), (4) and (5);
7. After calculating diameter Cost of pipe and cost of pumping calculated using equations mention in cost function; and
8. Optimum cost of complete system is works out by increasing head H_3 with one meter.

5.3 Analysis using EPANET Software

Network was analyzed using EPANET software as follow [6]:

1. Add the object that is reservoirs, junction and linked it by pipe;
2. Assigned the head to all reservoirs by selecting object;
3. Assigned the length and diameter to pipe; and
4. Analyzed network by using tool run analysis.
5. View the result and check the design flow.

Fig. (4) shows the developed model of water transmission network using EPANET software after assigning object and its properties.

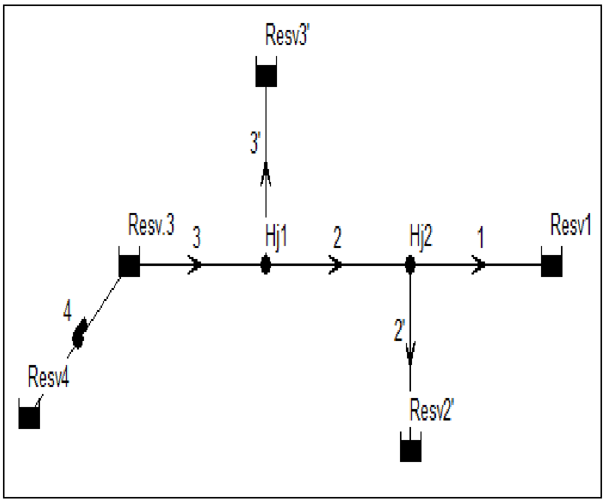

Fig. - 4: Drafted water transmission network in EPANET

6. RESULTS AND DISCUSSION

Results are obtained by designed and analysis of two junction water transmission network with pumping are as follow:

To get optimum cost, the pumping head (H_3) elevated. And then for each head the sets of pipe diameters obtained for is shown in Table 2.

Table 2: Design Diameters with Different Head

Head, m	D4, m	D3, m	D3', m	D2, m	D2', m	D1, m
80	0.91	0.950	0.550	0.850	0.475	0.750
81	0.91	0.925	0.550	0.850	0.475	0.750
82	0.91	0.900	0.550	0.850	0.475	0.750
83	0.91	0.900	0.500	0.825	0.475	0.750
84	0.91	0.900	0.475	0.825	0.425	0.725
85	0.91	0.875	0.500	0.825	0.450	0.750
86	0.91	0.875	0.475	0.800	0.450	0.750
87	0.91	0.875	0.450	0.800	0.425	0.725
88	0.91	0.850	0.475	0.800	0.450	0.725
89	0.91	0.850	0.450	0.775	0.450	0.750
90	0.91	0.850	0.450	0.775	0.425	0.725
91	0.91	0.825	0.450	0.775	0.450	0.750
92	0.91	0.825	0.450	0.775	0.425	0.725
93	0.91	0.825	0.425	0.775	0.400	0.700
94	0.91	0.825	0.425	0.750	0.400	0.725
95	0.91	0.825	0.400	0.750	0.400	0.700

The water transmission model was developed in EPANET by using set of diameters obtained for each pipe. Then the same network was analysed for design flow. The results obtained after the analysis of designed water transmission network using EPANET software is shown in Fig. (5).

Network Table - Nodes

Node ID	Elevation m	Demand LPS	Head m	Pressure m
Junc Hj1	0	0.00	72.70	72.70
Junc Hj2	0	0.00	66.76	66.76
Resvr Resv.3	80	849.14	80.00	0.00
Resvr Resv3'	70	150.62	70.00	0.00
Resvr Resv2'	65	101.50	65.00	0.00
Resvr Resv1	60	556.52	60.00	0.00
Resvr Resv4	60	-1657.77	60.00	0.00

Fig.-5: Analysis Results by EPANET Software

Developed results of analysis give a check over the obtained designed values by optimization technique. The cost was calculated for different head. The total cost of complete system with pumping includes the pipe cost and pumping cost. The cost of pipe was calculated for different sets of diameters obtained for variable head. Similarly the pumping cost was calculated for required power and energy by using cost function parameter. Fig. (6) shows the variation of total cost of water transmission system with head.

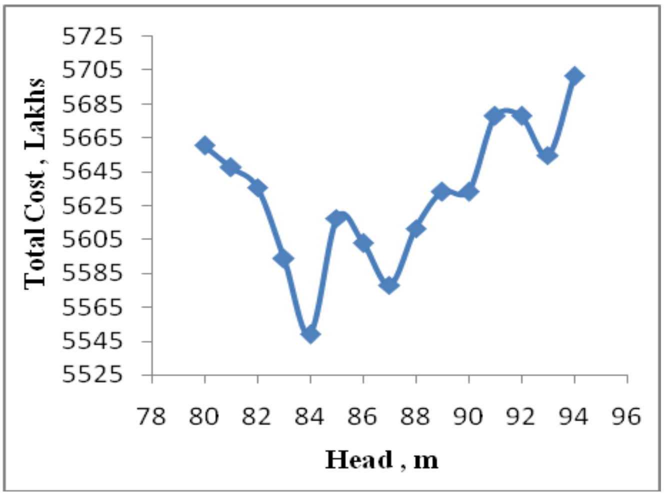

Fig. - 6: Total cost variation with head

Fig. (6) Indicates the fluctuation of total cost with head, in which total optimal cost for water transmission network after taking trails for different head was found to be less at head of 84.0 m and the optimal cost was found to be 5549.006 Lakhs.

7. CONCLUSION

The optimization is cost efficient method of design for water transmission network with pumping. The design parameter which was optimized for pumping system of water transmission shows a remarkable markdown in the overall cost. The developed model in EPANET software was analyzed for design flow and results compared with analytical design was found to be within permissible limits. The design model of water transmission system with variable head will help to choose the network with optimal cost.

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