Evaluation of Methodologies for Determination of Economical Pipe Diameter of Water Pumping Mains

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Abstract - Pipes represent a large proportion of capital invested in water pumping system undertakings and proper sizing of the pumping main play an important role in the overall design of any water supply system. Therefore, determination of pipe diameter for pumping mains shall have to be judiciously selected not only from the point of view of its hydraulic performance but also from the point of view of its installation and operation costs necessary to ensure the required function and performance throughout its designed lifetime. It should also be designed to reduce pumping costs through economical combination of pipe diameters, pumping head and pump requirements. It is therefore, the purpose of this paper to analyse the methodologies commonly used for optimization and determination of economical pipe diameter of a simple water pumping main taking Metti Town Water Sypply system as a case study area with the expectation that the knowledge of the interdependence of the variables involved might produce a better understanding of the problem and, perhaps, lead to better designs.

Key Words: Water supply system, Water pumping main, Optimization, Economical pipe diameter, Water pumping head

1. INTRODUCTION

The essential design objectives for pumping mains are assessing hydraulic capacity under various flow conditions, facilitating best management practices in the operation of the pumping system, and providing for the buried infrastructure's long-term physical resiliency. It therefore requires the appropirate dimensioning of pipe diameter in addition to the selection of materials that provide the highest efficiency. The appropriate dimensioning depends on the determination of water flow velocity, flow rate, pipe diameter and head loss in the pumping main. Since flow rate is a parameter determined in the project demand analysis, three parameters remain to be defined. However, there are only two equations available for this task, the mass and energy conservation equations, which are functions of flow rate and pipe diameter, meaning the dimensioning is a hydraulically undetermined problem.

Pipe network optimization problems can be classified in numerous ways. The two most meaningful classifications concern whether the flow distribution is initially fixed (fixed versus variable flow pattern), and whether the system's energy is provided by gravity or pumping (gravity versus pumped systems).

In gravity systems, the least costly piping system will dissipate all excessive head thus keeping pipe size, and hence cost, to a minimum. In pumped systems, the available head is not fixed but can be altered by changing pump head with the associated changes in energy and pumping equipment costs.

2. MATERIALS AND METHODS

2.1. Methods Used for Determination of Economical Diameter

In history, different reserchers have come to pipe optimization models that rely on some technique from the field of operations and researchs to find optimal solutions. In order to apply the solution technique, however it is necessary to simplify the field problem to make it fit the solution technique and was impossible to incorporate reliability considerations into design in an unarbitrary and computationally efficient manner. These methodologies have traditionally been guided by rule of thumb that includes different hydraulic factors such as flow velocities, water pressure and flow conditions for different combination of pipe diameters.

Now a days, the economical pipe size for pumping main can be computed using either computer aided rigorous pipe optimization analysis or by adopting empirical formula proposed by various scholars.

2.2. Methods Using Empirical Equations

Several authors have published formulae and nomographs for the estimation of the economic pipe diameter, Genereaux (1937), Peters and Timmerhaus (1968) (1991), Nolte (1978) and Capps (1995). Dupuit (1854) proposed that the economic pipe diameter could be expressed by:

$$D = k\sqrt{Q}$$

Where: D is the economic pipe size; k is a parameter that depends, among others, on the costs of the material, transportation, manhour, electric power, and system operation and maintenance; and Q is the required flow rate. Dupuit suggested a value of 1.60 for k, based on the prices of coal, pipes, manpower and services at that time.
Other famous formulation which is dominantly practiced in Ethiopia for the calculation of the economic pipe diameter is

Lea's emperical formula (Garg, S. K.). Lea's equation is expressed as;

$$D = a\sqrt{Q}$$

Where; D is economical diameter in meters, a is coefficient ranging from 0.97 to 1.22 and Q is the amount of water to be pumped in cubic meter per second. This relation gives optimum flow velocity varying between 0.8 to 1.35 meter per second.

2.3. Rigorous Economic Analysis

In rigorous economic analysis, the total cost of pipe and pumping are worked out at different assumed velocities and a graph plotted between the annual cost and the size of the pipe. This analysis requires the flow in the pipe is known beforehand and finding the most economical combination of pumping capacity, pumping main diameter and pumping head to at the lowest annual cost.

For a given discharge of water to be pumped there are two options to be considered for the economical determination of the pipe diameter. In one hand it can be done through a pipe of large diameter at low velocity or in the other hand through a pipe of small diameter at high velocity. Using a large pump will unnecessarily add to the cost of the pipe and if the diameter of the pipe is kept low, the velocity of flow will have to be measured, which will increase frictional loss and will also require more power for pumping thereby increasing the cost of pumping.

An optimum pipe diameter shall be worked out which will provide an economical pumping of the required quantity of water. The economical diameter therefore, is the one which minimizes the total cost meaning, investment cost of pipes (placement and installation costs), cost of pump and energy cost of operation (operation and maintenance costs).

Therefore, the total cost of pumping main depends mainly on the cost of the pipe, the pump and construction of the pumping station, and the cost of the energy required for the pumps to work during the entire lifespan of the system.

3. METHODOLOGY

3.1. Case Study: Definition of Project Conditions

For the evaluation of the methods discussed above, Metti town water supply, sanitation and hyegine project pumping system located in Gambella Regional State, Ethiopia, is considered. The porject consists of pumping water to the 350m³ service reservoir with a design discharge of 20Lit/s from the well field. For the case study, the pipe material is selected to be Ductile Cast Iron (DCI) pipe.

The follwing data summarized in the table below is used for the analysis in which Q is the project flow in cubic meters per second, L is the cummulative length of pumping main in meters and H is static head of the systems in meters.

Table 1 Project parameters

Source	Q (Lit/sec)	L (m)	H (m)
Borehole (BH)	20	4863.58	183.75

The objective here is to determine what type of pipe size should be installed for minimum total annual cost. This can be achived either by using empirical approch or rigorous economic method meaning, calculate the total annual cost as a function of the summation of cost of pipe per year and cost of pumping per year.

For the determination of dynamic head of the pumping system, Hazen-Williams equaiton is adopted as follows;

$$h_f = 10.7 * \left(\frac{Q}{C}\right)^{1.85} * \left(\frac{L}{D^{4.87}}\right)$$

Where C is coefficient of roughness for DCI pipe (130), g is acceleration due to gravity (9.81m/s²) and D is the economical diameter of pumping main(m). Minor head losses due to valves and fittings is taken to be 5% of head loss due to friction.

Taking the calculated duty point of pumps; Pump discharge(Q) and total head (H_T) & assumed value of overall pump and motor efficiency η, the required pump and motor power is calculated using the following formula:-

$$P_p = \frac{\delta Q H_p}{\eta}$$

Where, δ is specific gravity of water (9.81KN/m³), Q is the design discharge to be pumped (m³/s), H_p is the total pumping head (m) and η is efficiency of the pump (0.65)

Assumptions

The following assumptions hold in the present approach for the economic pipe size analysis.

- ✓ For evaluation of cost of pipe and pumping, water flow velocity is taken to be in the range of 0.8m/s and 2m/s
- ✓ Acutal present prices of Ethiopian market is considered for the cost of pipe, pump, installation, operation and maintenance and energy.
- ✓ Electricity as a source of energy and its local prices are used in this paper for the evaluation of the cost of energy. The price of electricity is 0.5 Ethiopian Birr (ETB) per kWh for households and 0.816ETB per kWh for businesses which includes all components of the electricity bill such as the cost of power, distribution and taxes.

3.2. Economical Pipe Diameter Calculation

Based on the methods of analysis discussed in previous paragraphs the empirical formula proposed by two scholars and rigorous economic analysis using the annual cost of pipe and energy as the main factors is used for evaluation of determination of economical pipe diameter of the case project.

Empirical Analysis

In this analysis, inserting the values of design flow directly from the water demand analysis to the equation proposed and claculating for both upper and lower values of the costant is calculated. Then, market available pipe diameter size laying in the range of calculated higher and lower sizes is taken as to be the economical pipe diameter that will inreturn minimizes the total annual cost of the system. The flow velocity in the economical pipe diameter calculated shall also be calculated for its hydraulic feasibility.

Cost Functions of Rigorous Economic Analysis

The rigorous calculations in this research cover the cost of pipes, annual energy and maintenance. According to Prabhata K. Swamee and Ashok K. Sharma (2008), the above-mentioned types of costs cannot be simply added to find the overall cost or life-cycle cost. These costs have to be brought to the same units before they can be added. In net present value analysis method, the current value of the infrastructure can be calculated for the known infrastructure associated future costs using a suitable discount rate. The net present capital cost (P_{NC}) of a future expenditure can be derived as

$$C_{NP} = \frac{F}{(1+r)^T}$$

Where F is future cost, r is discount rate, and T is the analysis period.

Pipe Cost

It is understood that various pipe sizes are commercially availabe and the cost is calculated collecting price data of each pipe sizes. The cost of fixtures and appurtenances are assumed to be 10% of the cost of the pipeline. (Samra and Essery, 2003). The cost of completed pipeline, meaning transportation, excavation and installation cost is also calculated taking 5% of the cost of the pipeline.

Cost of Pump and Pumping Station

Different pump models usually have similar cost since the group and stage configurations depend on the variability of the demand and not on the pipe features. The cost of the pumping station is not of significance to be worked out as a separate function and therefore, is not considered in this paper.

Energy Cost

The cost of energy depends mainly on the variables such as the volume of water to be pumped, the total pumping head, the pump efficiency and also the velocity of flow adopted for the given project. The pumping head is dependent on the pipe size for the fact that the cost of energy decreases with increasing pipe size due to reduced headloss and, therefore, results in reduced pumping head and power consumption.

The annual recurring cost of energy consumed in maintaining the flow depends on the discharge pumped and the total pumping head H_T produced by the pump. An electrical cost could be calculated by multiplying the pump size equation with operation hours. The calculated pumping hour for the system is 8hrs/day or 2920hrs/yrar. Multiplying the power by the number of pumping hours in a year and the rate of electricity per kilowatt-hour, R_E, the annual cost of energy C_e consumed in maintaining the flow could be written as follows.

$$Cost_{energy} = \frac{2.92\rho g Q H_T R_E}{\eta}$$

4. RESULTS AND DISCUSSION

4.1. Dupit and Lea's Empirical Equation

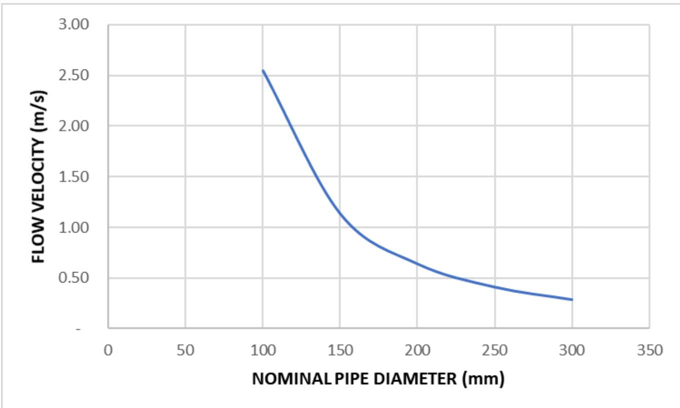
For design discharge of 20Lit/s, Lea's emirical equation gives the economic pipe size as 137.18mmm for lower coefficient value of 0.97 and 172.53mm for higher coefficient value of 1.22. Market available pipe size for calculated diameter sizes in between 137.18mm and 172.53mm is 150mm. Now, checking the velocity of flow through the pipe using continuity equation,

$$V = \frac{Q}{A} = \frac{0.020\, m^3/s}{0.01766 m^2} = 1.13m/s$$

Table 2: Pipe Diameters and Coresponding Flow Velocity (m/s)

Nominal Pipe Diameter (mm)	Velocity Through the Pipe (m/s)
100	**2.55**
150	**1.13**
200	**0.64**
250	**0.41**
300	**0.28**

Figure 1: Variation of Flow Velocity with Pipe Diameter



From the calculated result and the figure 1 above, it can clearly seen that the velocity of flow through 150mm diameter pipe size gives optimum value that meets the design fow velocity and therefore, pipe size of DN150mm can be selected to be the economical pipe diameter.

Using parameter k value as 1.60, the Dupit expression for economical pipe diameter D=k√Q results in the pipe size of 226.26mm. Taking market avilable diameter of 200mm and 250mm and checking the velocity of flow, pipe diameter results in 0.32 for 200mm 0.8m/s for 250mm pipe diameter.

4.2. Rigorous Economic Analysis

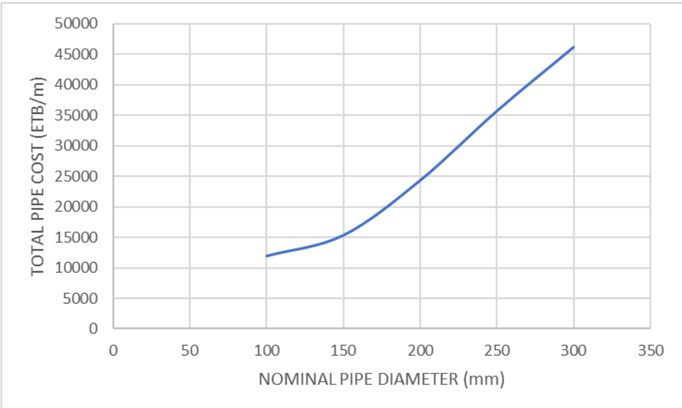
4.2.1. Pipe Size and Pipe Cost Relationship

It can be clearly seen from the table below that pipe cost increases with increase in pipe diameter.

Table 3: Pipe Diameters and their Corresponding Costs (Ethiopian Birr, ETB)

Nominal Pipe Size (mm)	Total Pipe Cost (ETB/Meters)
100	11,884
150	15,294
200	24,284
250	35,660
300	46,124

Figure 2: Variation of Pipe per meter Cost with Pipe Diameter

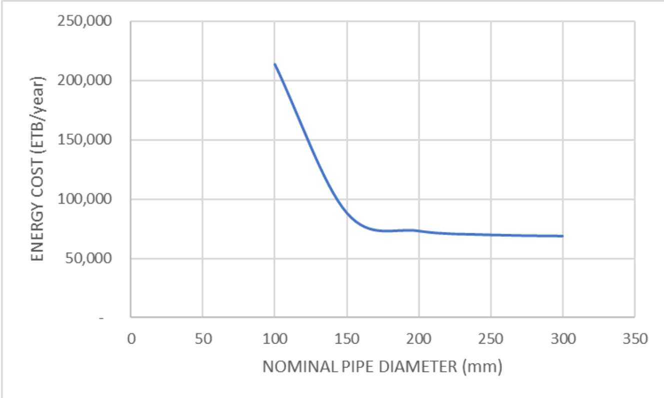


4.2.2. Annual Energy Cost and Piipe Size Relationship

Table 3: Pipe Diameters and Coresponding Annual Energy Cost (ETB/year)

Nominal Pipe Diameter (mm)	Csot of Energy (ETB/year)
100	213,718
150	88,246
200	73,004
250	69,702
300	68,713

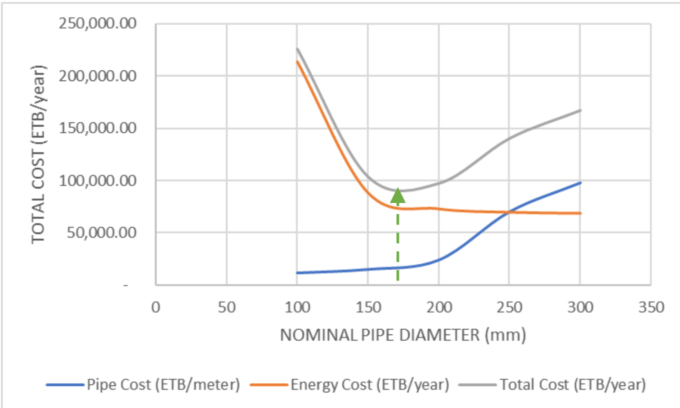
Figure 3: Variation of Annual Energy Cost with Pipe Diameter



4.2.3. Total Annual Cost and Piipe Size Relationship

From the annual pipeline cost and energy cost relationships, we have clearly seen when the larger the pipe diameter becomes, the greater will be the capital charges. In addition, the cost of energy goes down rapidly as the pipe size increases resulting in pressure drop.

Figure 4: Total Annual Cost Versus Nominal Pipe Diameter



The total cost is obtained by adding, the energy and piping cost functions which are computed for each pipe size for the design flow and taking derivative of the new combined function with respect to diameter. This combination will create the function representing the total annual cost of the pipeline. As shown in Figure 4 above, a curve drawn results in U-shape. The pipe diameter corresponding to this point at the bottom of the U-shaped curve is the pipe which gives minimum annual cost and the size at this point can be taken as the economical pipe diameter.

Therefore, it can be seen from the graph minimum annual total cost lays at coresponding pipe size of around 170mm. But this pipe size is not market available and has to be decided to be taken from either 150mm or 200mm checking for the validity of meeting the design flow velocity criteria.

5. CONCLUSION

The aim of this study was to reach the economical pipe diameter of the simple pumping main of Metti town water supply, sanitation and hyegine project using empirical equations and rigorous econmic analysis. The study shows both methodologies resulted in slightly similar values of economic pipe diameter.

The empirical equations preseneted by two scholars Dupit and Lea uses flow of water and constants to reach the economical pipe diameter checking for design flow velocity range. In rigorous economic analysis, the relationship between pipes and pumps creates many economic trade-offs to consider. While a smaller pipe has lower capital costs, the larger pump required to overcome the additional pressure losses will cost more (both in capital and long-term operating costs). Meanwhile, a larger pipe costs more upfront, but enables lower operating costs as the pump does not need to work as hard. Even with this simple example, it is clear that there is a point where a perfectly sized pump paired with a perfectly sized pipe can minimize system costs. This point can be seen visually in Figure 4. Each pump-pipe pair is informed by the essential design requirements, placing each potential component pair on equal technical footing.

In complex water pumping mains, the operating costs are made up of many complex functions. Likewise, cost functions for the fixed capital investment are very complex and also made up of several factors. Thus, the resultant total cost function may not be a simple curve, and it could be a polynomial function with many local minimums and one global optimal minimum total cost. One could understand why this problem could be impossible to complete by hand without using several risky assumptions.

Thus, it is essential for engineers to design the pumping mains with precise economic specifications. The work associated with operating a pump and the initial cost of pipe are interrelated by the diameter of the pipe. Therefore, designing a pipe with the appropriate diameter is crucial to the optimization of the pumping mainline.

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