COST ANALYSIS FOR DAM TOE SMALL HYDRO POWER PLANT

Ullas Dixit,
Research Scholar, Mechanical Engineering Department, Faculty of Engineering & Technology, Rama University, kanpur
dixitullas@gmail.com
Mr. Anurag Kumar,
Assistant professor, Mechanical engineering Department, Faculty of Engineering & Technology, Rama University, Kanpur Anurag.fet@ramauniversity.ac.in
Mr. Aditya Veer Gautam,
Assistant professor, Mechanical engineering Department, Faculty of Engineering & Technology, Rama University, Kanpur adityagautam.fet@ramauniversity.ac.in

ABSTRACT
The selection of the appropriate hydro turbine is critical for a hydropower site, as it depends on the site's specifications and affects civil engineering requirements. This study aims to optimize hydro turbine selection to minimize the overall plant cost for a typical dam toe site with 20 m head and 10,000 kW capacity. Three turbine types were compared: tubular propeller, tubular Kaplan, and vertical semi-Kaplan. Since the turbine type affects overall plant cost, the costs of the powerhouse, turbine, generator, and auxiliaries were analyzed for each option. The tubular propeller turbine contributed the lowest plant cost and is thus recommended for this site.

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INTRODUCTION

As small hydro power site are not identified as standard site, every site has different site parameters. Because of non-standardization of component of a SHP cost become critical issue. The exploitation of many hydro–energetic resources, especially those with low power water flows (less than 50 kW) [1-3], has over time become economically unfavourable. The increase in the availability of energy over recent decades has made it economically unviable to use plant configurations that exploit courses of water with low head and modest flow rates, with significant torrential characteristics. Today, the legislation covering energy is setting out ever clearer directives concerning the use of renewable resources in the place of those of high environmental impact. In the light of these changes, the possibility of using the largest number of hydro energetic resources available would appear to be of great interest.

The exploitation of hydro-energetic resources usually involves plant solutions using Pelton, Francis or Kaplan turbines, depending on the head and flow rates that are available. Literature exists describing the methods to evaluate the best plant configuration to adopt from the economic point of view. It should be noted that plants functioning with Pelton turbines are economically advantageous even with powers less than 5 kW, with Francis turbines the minimum powers are around 50kW, whereas the minimum powers that are economically interesting for Kaplan type turbines are greater than about 100 kW [4]. This means that, whereas it is possible to create low power plants with average specific energies and low flow rates, it is not possible to use Francis or Kaplan turbines in sites with the small head and low average flow rates.

COST INVOLVED IN SMALL HYDROPOWER

In dam toe schemes, the power house building is located at the toe of the dam and penstock is taken through the body of the dam. Basic components of such schemes are categorized into two parts: (i) civil works and (ii) electromechanical equipment. The major components of civil works consist of intake, penstock, power house building, and tail race channel [5-6]. The electromechanical components are turbines with governing system, generator with excitation system, electrical and mechanical auxiliary, and transformer and switchyard equipment.

Existing literature describe that the cost of components of civil works as well as that of electromechanical equipment mainly depends on the installed capacity and head of the scheme. The cost is divided in two part:-

INVESTMENT COST

It consists following:-

Civil works costs:

Consist of the construction and hydro-structural costs of the project, including a reservoir dam, the water penstock structure, the power house, the tailrace structure, the access road and any future unpredicted costs taken from the preliminary designs of a feasibility study.

Electro-mechanical equipment costs

Include turbines, generators, governors, gates, control systems, a power substation, electrical, and mechanical auxiliary equipment, etc.

Power transmission line costs

Include a power transmission line for delivering generated energy from the power plant to power transmission network. The transmission line cost depends on the location, type of existing system (overhead line or cable system), and the capacity of HPP as well as length of transmission lines, which have a very high effect on the project costs.

Indirect costs

Include Engineering and Design (E&D), Supervision and Administration (S&A), and inflation costs during the construction period.

E&D costs

These costs are affected by many parameters, such as type, size and location where the project is being constructed. The E&D costs are usually expressed as a percentage of construction costs, including civil and equipment costs, and the amount of this percent differs from one location to another. Recently, a case study on these HPPs has shown that this figure could range from 5% for small and medium sized projects, to 8%, for very large sized projects.

S&A costs

These costs include the purchase of land, management, inspection and supervision costs, and other miscellaneous costs in the region. Similar to the E&D costs, the S&A costs are expressed as a percentage of the construction costs.

Inflation costs during construction

To precisely calculate the investment cost of a project, it is necessary to take into account the inflation rate during the course of the project and adjust the investment cost with respect to the inflation rate. The inflation rate of future years should be determined by obtaining the average of previous years' inflation rate.

ANNUAL COST

In addition to investment costs, annual costs should be calculated to obtain the net benefit of a project. Annual costs include depreciation of equipment, Operating & Maintenance (O&M), and replacement and renovation costs.

depreciation of equipment

In the economical analysis of the project, depreciation and other factors affecting the equipment should be considered.

o & m costs

Include salary/wages of personnel, labour, insurance, tax, duties, landscape, and consumable materials. These costs are increased only by the annual inflation coefficient. A 5% inflation rate is used in the economical calculations. The costs which are related to the salary/wage and consumable materials make up one percent of annual investment costs, and insurance, tax, duties, charges, and unpredicted cases are also taken as one percent of annual investment costs. It should be noted that in order to calculate investment costs, the interest rate during construction should also be considered.

Replacement and renovation costs

The main parts of the HPP, such as generator windings, turbine runners and other parts will eventually need replacement and renovation. To estimate the costs for large and medium sized power plants, the percentage of renovation and replacement should be determined for different sections separately

PLANNING FOR COST OPTIMIZATION

Cost of any SHP project is depends upon site parameter which is vary from site to site. By analyzing different factors like hydraulic and electromechanical components causes to the rise in unit cost of power output. Among them some component are site specific like [7-8]:

- Flow characteristics
- Site selection and basic design
- Civil works
- Hydraulic turbine
- Power transmission system

While some cost are not site specific like:

- Mechanical and electrical control system
- Engineering and administrative charges

In hydropower projects, there are uncertainties on account of water availability that affect the availability of energy. Thus, there is an uncertainty in projection of the benefits from the project and the other uncertainty factor is the cost estimation. The cost of the project depends on location, construction period and variation in cost of materials, availability of construction equipment, and variation in labour cost. The project cost estimates are subject to a considerable degree of variation and fluctuation. The benefits also have a high degree of uncertainty.

Prior to 1991, small hydropower projects in India were only developed in the government sector as government departments were the licensee to generate, transmit, and distribute electrical energy [9]. From 1991 onward, power generation was opened to the private sector as well and government departments were streamlined as companies. Since then it has become the commercial sector and repayment of investments is of prime concern; therefore, financial analysis has been attempted to evaluate the schemes for evolving an optimum solution. In this context, financial analysis has been carried out to evaluate various layouts. An important part of establishing financial feasibility is the anticipated borrowing cost. The cost of capital is the return expected by potential investors and other market and economic costs. The costs are the sum of the real interest rate that compensates the lender for surrendering the use of funds, the purchasing power, the risk premium that compensates for expected inflation, the business and financial risk, and the market-ability risk associated with low liquidity of long-term debt.

BASIC COMPONENTS OF DAM TOE SCHEME

In dam toe schemes, the power house building is located at the toe of the dam and penstock is taken through the body of the dam. Basic components of such schemes are categorized into two parts: (i) civil works and (ii) electromechanical equipment. The major components of civil works consist of intake, penstock, power house building, and tail race channel [10]. The electromechanical components are turbines with governing system, generator with excitation system, electrical and mechanical auxiliary, and transformer and switchyard equipment. Following are the components:-

- INTAKE
- PENSTOCK

- POWERHOUSE
- TAILRACE
- TURBINE
- GENERATOR
- AUXILLIARY
- TRANSFORMER & SWITCHYARD

COST ANALYSIS OF DAM TOE SCHEME [6]

COST CALCULATION OF INTAKE

Typically, toe of dam projects are located below storage reservoirs that would effectively trap sediment entering the reservoir. Therefore sediment abrasion of turbine components would not be a problem with this type of development. These plants are often subject to large variation in head and flow and turbine selection must take this into account.

Dams and weirs are primarily intended to divert the river flow into the water conveyance system leading to the powerhouse. Dams also produce additional head and provide storage capacity. The choice of dam type depends largely on local topographical and geotechnical conditions. Basically cost of intake is the function of power and head, which is site specific.

Following correlation is used for cost calculation of intake:-

$$C_1 = 17940P^{-0.2366}H^{-0.0596} \quad (1.1)$$

Where, C_1= cost of intake per kW

P & H are power and head respectively.

Using Eqn. (1.1) variation in cost of intake with various head and power is calculated and results obtained are shown in Figure 1.1.

Now, considering capacity 2000 kW variation in cost of intake with respect to various head is shown in Fig. 1.1.

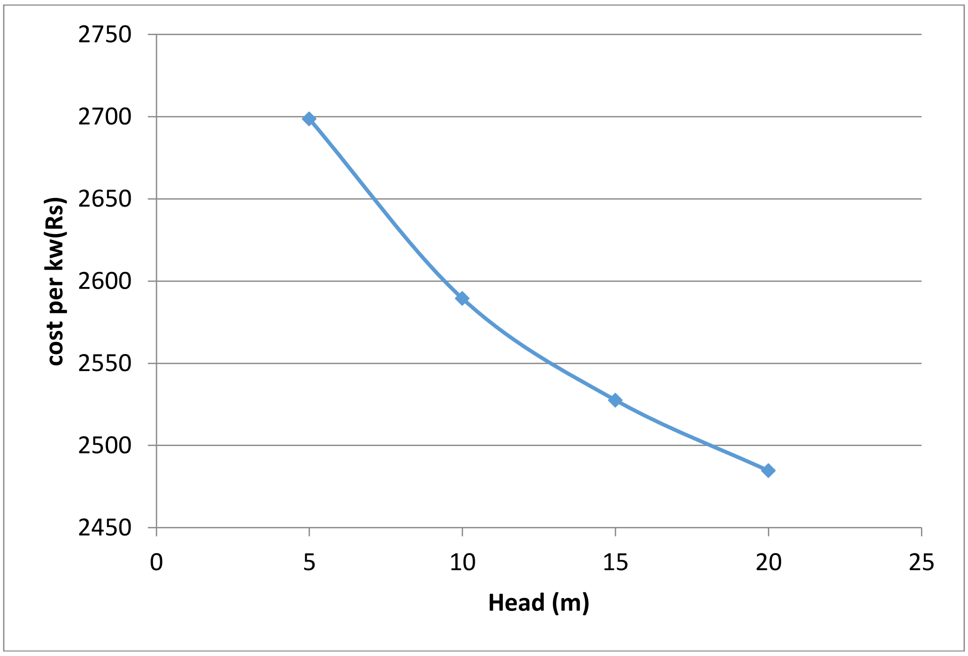

Fig 1.1 variation of cost of intake with respect to head (at Power = 2000 kW)

COST CALCULATION OF PENSTOCK

The penstocks made of mild steel constitute major expenses and hence to minimize its length, head race might be used. A stop valve must be provided at the entry to avoid the problems of water hammer. The optimum size of head race may be obtained by an analysis of construction and annual cost of the energy lost due to friction in the head race over the economic life span of the project.

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The correlation used for cost calculation of penstock as the function of head and power as:-

$$C_2 = 7875P^{-0.3806}H^{0.3804} \quad (1.2)$$

Where, C_2 = cost of penstock per kW

Using Eqn. (1.2) variation in cost of penstock with various head and power is calculated and results obtained are shown in Figure 1.2

Now, considering capacity 2000 kW variation in cost of penstock with respect to various head is shown in Fig. 1.2.

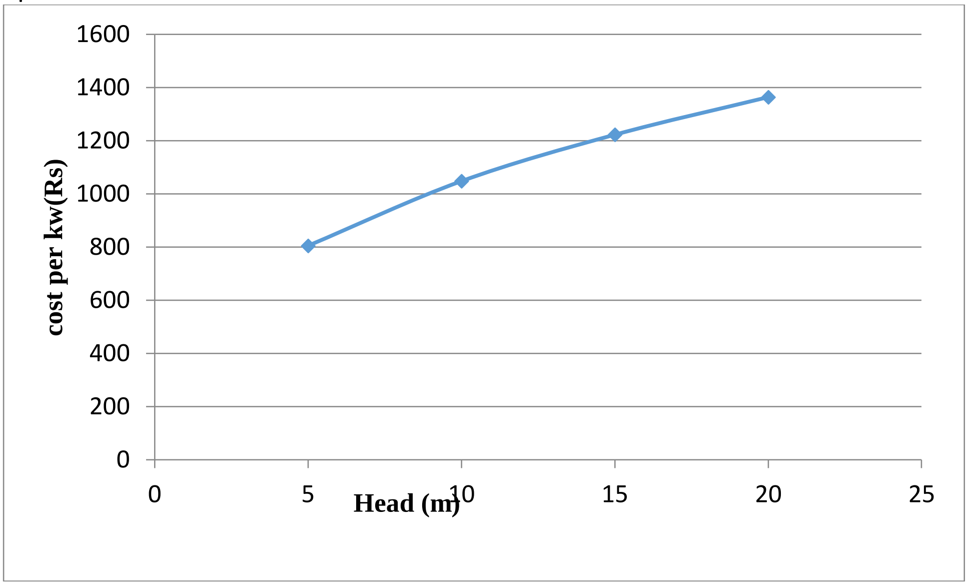

Fig 1.2 variation of cost of penstock with variable head and power (power is 2000kW)

COST CALCULATION FOR POWERHOUSE

If the powerhouse is founded on rock, the excavation work will remove the superficial weathered layer, leaving a sound rock foundation. If the powerhouse is to be located on fluvial terraces near the riverbanks that do not offer a good foundation then the ground must be reinforced.

It houses the turbine, generator and control panels. It should be as simple as possible. The significant parameters affecting the cost of power house i.e. super structures and substructures can be related to number, capacity and type of turbine and generators. The correlation used for calculation of cost of power house is varying according to types of turbine use.

CASE 1: when tubular propeller turbine is used

The correlation use for cost calculation of powerhouse for tubular turbine is given as:

$$C_3 = 91231P^{-0.2356}H^{-0.0588} \quad (1.3)$$

Where C_3 = cost per kW of powerhouse

Using Eqn. (1.2) variation in cost of powerhouse (when propeller tubular turbine is use) with various head and power is calculated and results obtained are shown in Figure 1.1.

Now, considering capacity 2000 kW variation in cost of powerhouse (for propeller tubular turbine) with respect to various head is shown in Fig. 1.1.

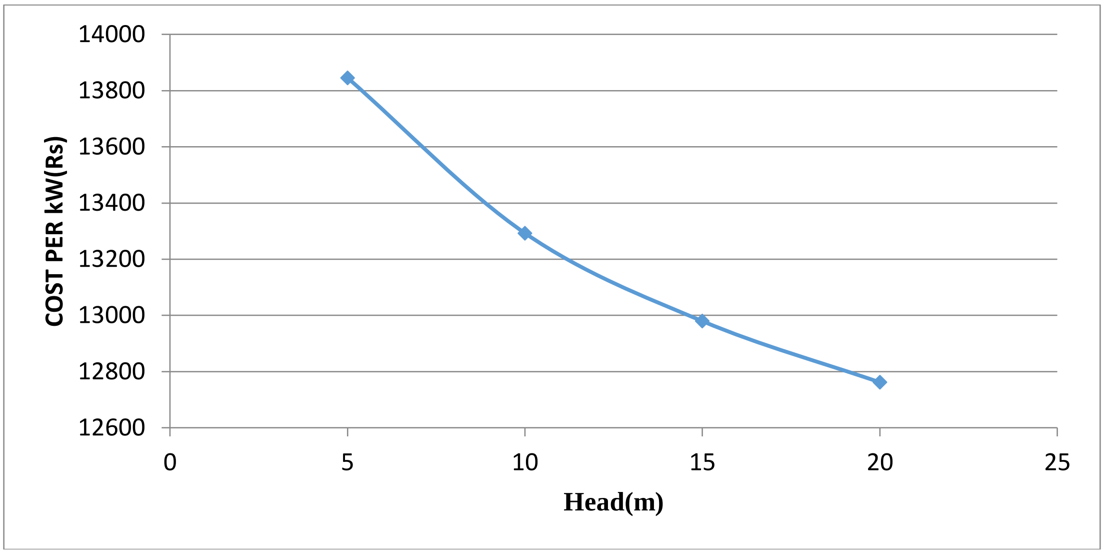

Fig 1.3 variation of cost of powerhouse at different head and power for propeller tubular (at P=2000kW)

CASE 2: **When tubular Kaplan turbine is used**

The correlation used for cost calculation of powerhouse is given as:

$$C_3 = 97764P^{-0.2356}H^{-0.0589} \qquad (1.4)$$

Where C_3 is cost per kW of powerhouse

Using Eqn. (1.4) variation in cost of powerhouse (for tubular Kaplan turbine) with various head and power is calculated and results obtained are shown in Figure 1.4

Now, considering capacity 2000 kW variation in cost of powerhouse (for tubular kaplan turbine) with respect to various head is shown in Fig. 1.4.

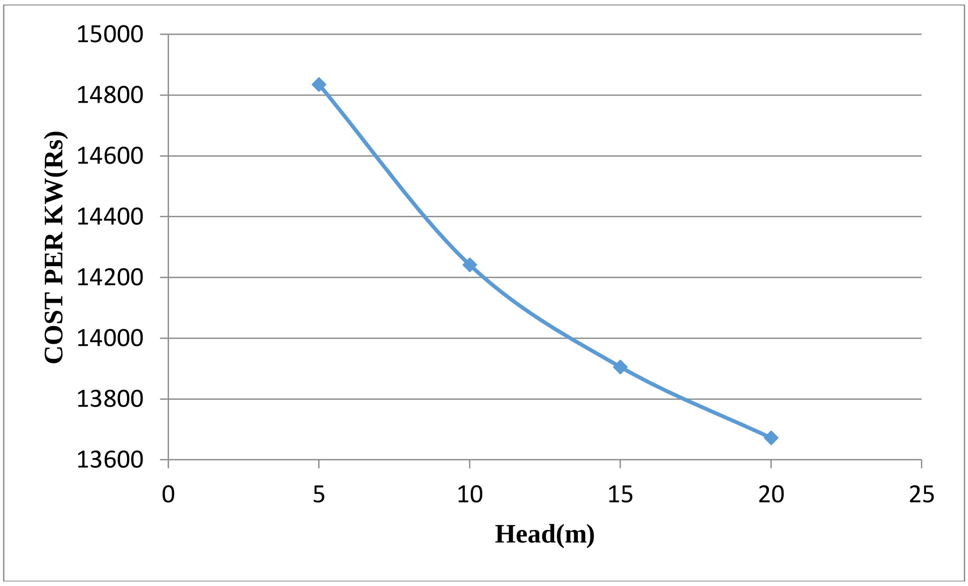

Fig 1.4 variation of cost of powerhouse with head and power when tubular Kaplan turbine is use (at P=2000kW)

CASE 3: when vertical semi-Kaplan turbine is used

The correlation used for determining cost of powerhouse when vertical semi-kaplan turbine is used is given as:

$$C_3 = 83406P^{-0.2353}H^{-0.0588} \quad (1.5)$$

Where C_3 =cost per kW of powerhouse

Using Eqn. (1.5) variation in cost of powerhouse (for semi- Kaplan turbine) with various head and power is calculated and results obtained are shown in Figure 1.5

Now, considering capacity 2000 kW variation in cost of powerhouse (for vertical semi-Kaplan turbine) with respect to various head is shown in Fig. 1.5.

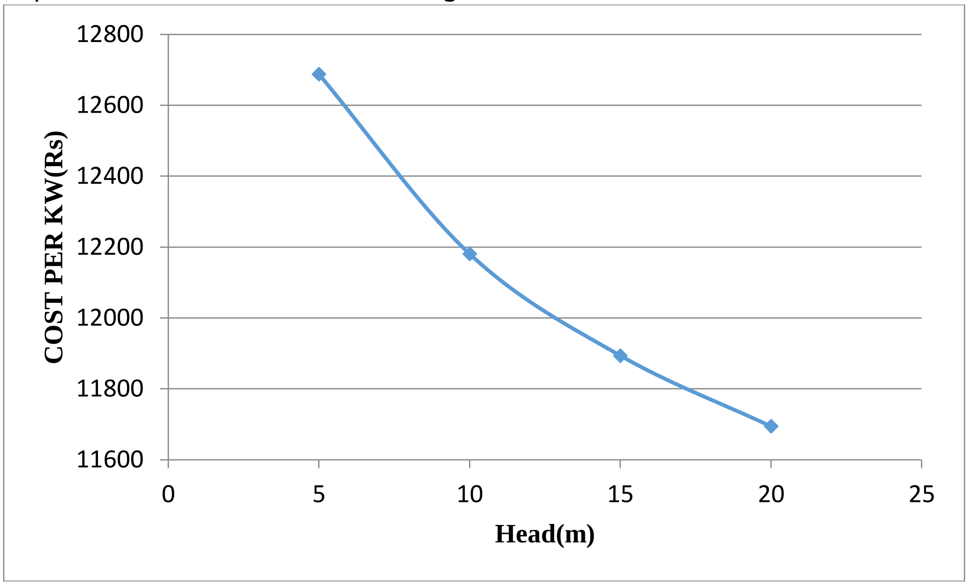

Fig 1.5 variation of cost of powerhouse for semi-Kaplan (at P=2000kW)

COST CALCULATION FOR TAILRACE

For discharging water after the generation of electricity in the power house, either a tail race channel or a tail race tunnel will be required. The design of tail race channel will follow the same principles as of any hydraulic channel.

The correlation used for calculating the cost of tailrace is given as:

$$C_4 = 28164P^{-0.376}H^{-0.6240} \quad (1.6)$$

Where C_4 = cost per KW of tailrace

Using Eqn. (1.6) variation in cost of tailrace with various head and power is calculated and results obtained are shown in Figure 1.6

Now, considering capacity 2000 kW variation in cost of tailrace with respect to various head is shown in Fig. 1.6.

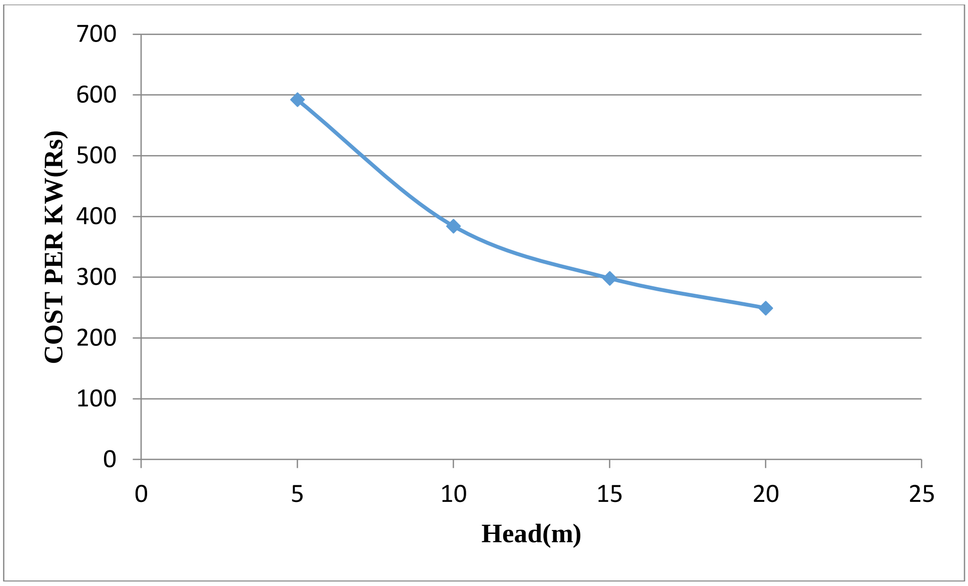

Fig 1.6 variation of cost of tailrace with head (for P=2000kW)

COST CALCULATION OF TURBINE

The electromechanical components are turbines with governing system, generator with excitation system, electrical and mechanical auxiliary, and transformer and switchyard equipment. Out of these, hydro turbine plays an important role that can be considered as the heart of a small hydropower station. The selection, type, and specification of other equipment in the SHP station are dependent on the hydro turbine. The selection of turbine is governed by head, discharge, capacity, speed, part load efficiency, number of units, and cavitation characteristics. The size of turbine is defined by its runner diameter.

CASE 1 when tubular propeller turbine is used

The correlation used for cost calculation of this type of turbine is given as:

$$C_5 = 61153P^{-0.1961}H^{-0.2111} \quad (1.7)$$

Where C_5 = cost per kW of propeller tubular turbine

Using Eqn. (1.7) variation in cost of tubular propeller turbine with various head and power is calculated and results obtained are shown in Figure 1.7

Now, considering capacity 2000 kW variation in cost of propeller tubular turbine with respect to various head is shown in Fig. 1.7.

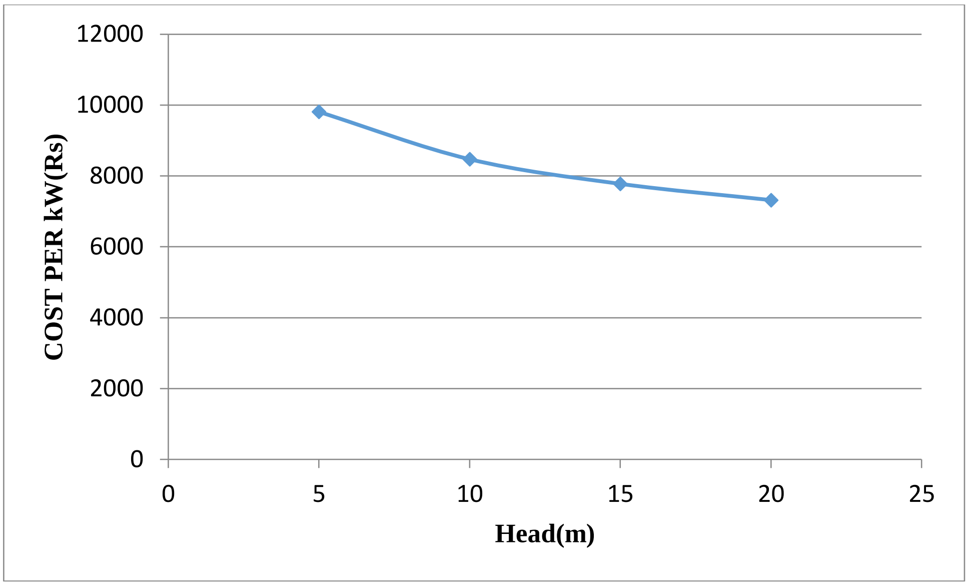

Fig 1.7 variation of cost of propeller tubular turbine with head (at P=2000KW)

CASE 2 when Kaplan tubular turbine is used

The correlation used for cost calculation of Kaplan tubular turbine is given as:

$$C_5 = 70170P^{-0.1853}H^{-0.2053} \quad (1.8)$$

Where C_5= cost per kW of Kaplan tubular turbine

Using Eqn. (1.8) variation in cost of tubular Kaplan turbine with various head and power is calculated and results obtained are shown in Figure 1.8

Now, considering capacity 2000 kW variation in cost of tubular Kaplan turbine with respect to various head is shown in Fig. 1.8.

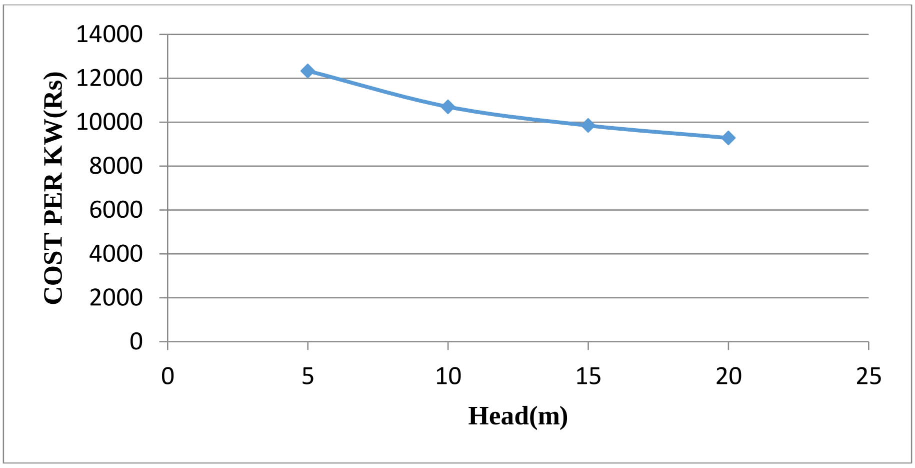

Fig 1.8 variation in cost of tubular Kaplan turbine with head (P=2000KW)

CASE 3 when vertical semi-Kaplan turbine is used

In order to determine cost of this type of turbine, the correlation used is given as:

$$C_5 = 62902P^{-0.1853}H^{-0.2092} \quad (1.9)$$

Where C_5= cost per kW of vertical semi-Kaplan turbine

Using Eqn. (1.9) variation in cost of vertical semi-Kaplan turbine with various head and power is calculated and results obtained are shown in Figure 1.9

Now, considering capacity 2000 kW variation in cost of vertical semi-Kaplan turbine with respect to various head is shown in Fig. 1.9.

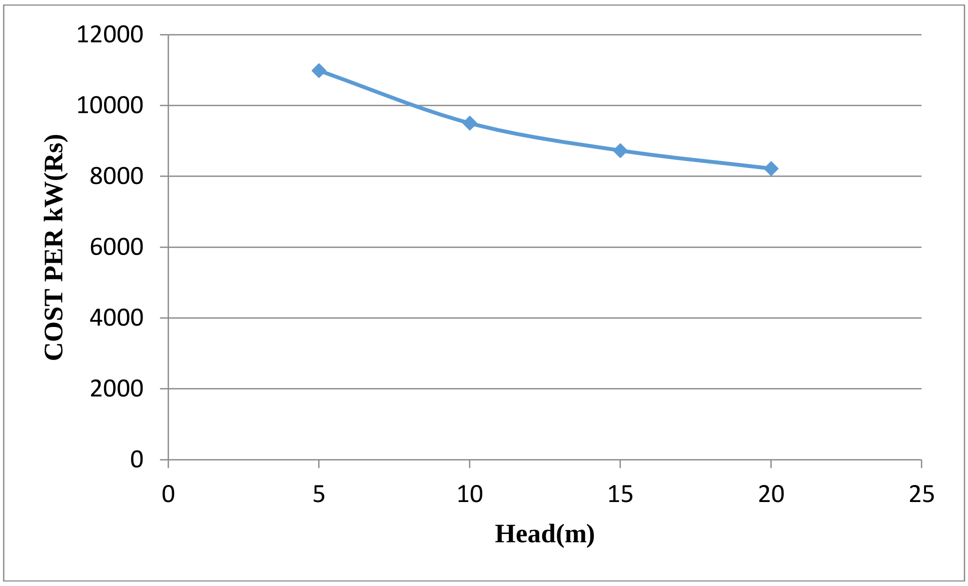

Fig 1.9 variation of cost of turbine with head for vertical semi-Kaplan (at P=2000kW)

COST CALCULATION OF GENERATOR & EXCITATION SYSTEM

Generators transform mechanical energy into electrical energy. Although most early hydroelectric systems were of the direct current variety to match early commercial electrical systems, nowadays only three-phase alternating current generators are used in normal practice. Depending on the characteristics of the network supplied, the producer can choose between:

a. Synchronous generator
b. Asynchronous generator

The cost of generator & excitation system varies with types of turbine so further we have three case:

CASE 1 cost of generator and & excitation system when propeller tubular turbine is used

The correlation use for cost calculation of generator & excitation system when propeller tubular turbine is use is given as:

$$C_6 = 78661P^{-0.1855}H^{-0.2083} \quad (1.10)$$

Where C_6= cost per kW of generator & excitation system

Using Eqn. (1.10) variation in cost of generator & excitation system (for propeller tubular turbine) with various head and power is calculated and results obtained are shown in Figure 1.10

Now, considering capacity 2000 kW variation in cost of generator & excitation system (for propeller tubular turbine) with respect to various head is shown in Fig. 1.10.

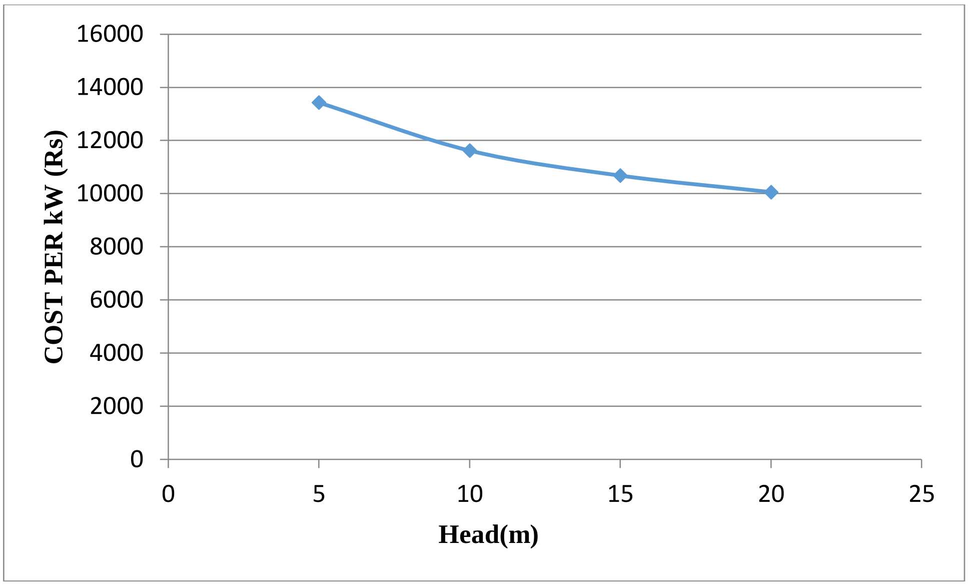

Fig 1.10 variation in cost of generator & excitation system for propeller tubular turbine (at P=2000kW)

CASE 2 cost of generator and & excitation system when tubular Kaplan turbine used

The correlation use for cost calculation of generator & excitation system when propeller tubular turbine is use is given as:

$$C_6 = 81881P^{-0.1858}H^{-0.2095} \qquad (1.11)$$

Where C_6= cost per KW of generator & excitation system

Using Eqn. (1.11) variation in cost of generator & excitation system (for tubular Kaplan turbine) with various head and power is calculated and results obtained are shown in Figure 1.11

Now, considering capacity 2000 kW variation in cost of generator & excitation system (for tubular Kaplan turbine) with respect to various head is shown in Fig. 1.11.

CASE 3 cost of generator and & excitation system when vertical semi- Kaplan turbine used

The correlation use for cost calculation of generator & excitation system when vertical semi-Kaplan turbine is use is given as:

$$C_6 = 83091P^{-0.1827}H^{-0.2097} \qquad (1.12)$$

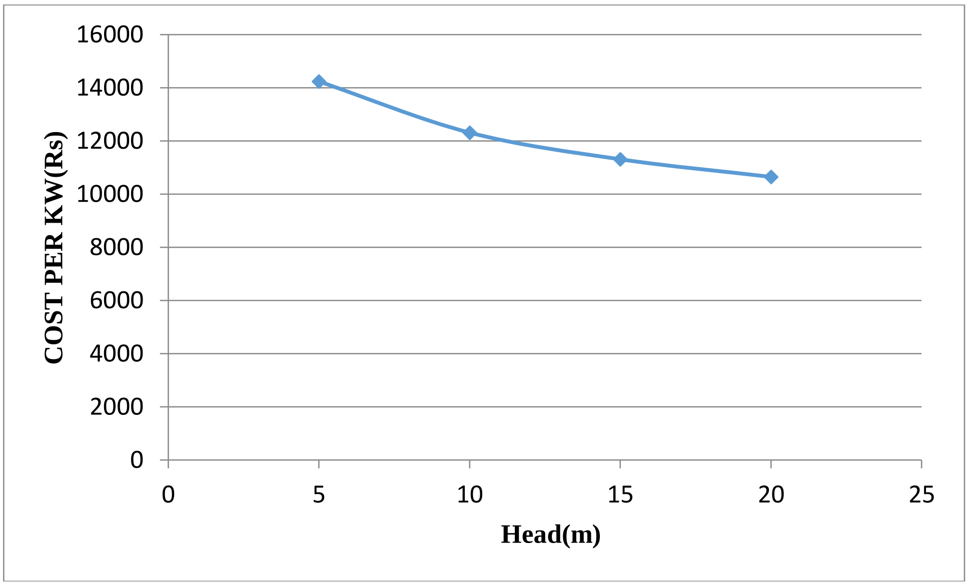

Fig 1.11 variation in cost of generator & excitation system for Kaplan tubular (P=2000kW)

Where C_6= cost per kW of generator & excitation system

Using Eqn. (1.12) variation in cost of generator & excitation system (for vertical semi-Kaplan turbine) with various head and power is calculated and results obtained are shown in Figure 1.12

Now, considering capacity 2000 kW variation in cost of generator & excitation system (for vertical semi-Kaplan turbine) with respect to various head is shown in Fig. 1.12.

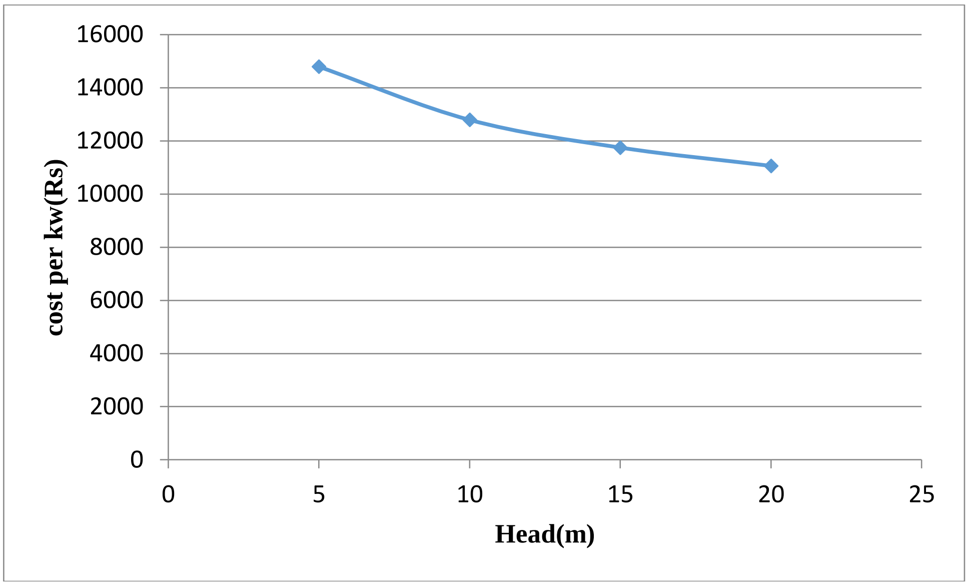

Fig 1.12 variation in cost of generator & excitation system when vertical semi-Kaplan turbine is use (at P=2000kW)

COST CALCULATION OF AUXILIARY

In small hydropower it also involves some auxiliary in for operation & maintenance. Operation of Auxiliaries and other system installed in power station like:-

- Turbine Governor Oil Pressure Unit
- Cooling water system
- Drainage & Dewatering system
- AVR & excitation system
- Generator neutral grounding system
- Station compressors
- Station illumination & emergency lighting
- Station D.C. control system
- Generator fire extinguishing system
- EOT cranes

So in order to calculate the cost involve in auxiliary, which is also varies according to the selection of turbine is further classified in three cases:

CASE 1 cost of auxiliary when propeller tubular turbine is used

In this case correlation used for cost calculation is given as:

$$C_7 = 38328P^{-0.1902}H^{-0.2134} \qquad (1.13)$$

Where C_7 = cost per kW of auxiliary

Using Eqn. (1.13) variation in cost of auxiliary (for propeller tubular turbine) with various head and power is calculated and results obtained are shown in Figure 1.13

Now, considering capacity 2000 kW variation in cost of auxiliary (for propeller tubular turbine) with respect to various head is shown in Fig. 1.13.

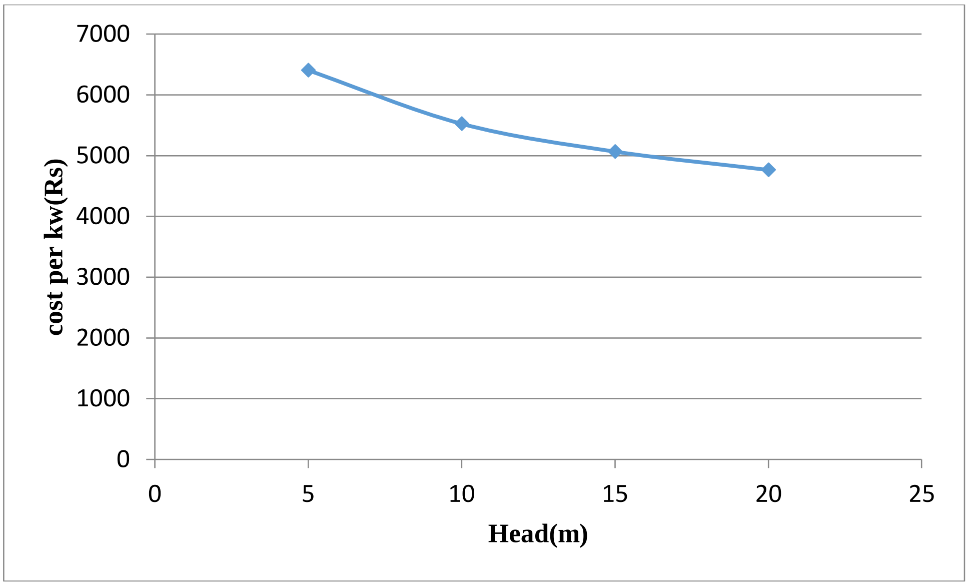

Fig 1.13 variation of cost of auxiliary with head for propeller tubular turbine (P=2000kW)

CASE 2 cost of auxiliary when Kaplan tubular turbine is used

In this case correlation used for cost calculation is given as:

$$C_7 = 41982P^{-0.187}H^{-0.2099} \quad (1.14)$$

Where C_7 = cost per KW of auxiliary

Using Eqn. (1.14) variation in cost of auxiliary (for tubular Kaplan turbine) with various head and power is calculated and results obtained are shown in Figure 1.14

Now, considering capacity 2000 kW variation in cost of auxiliary (for tubular Kaplan turbine) with respect to various head is shown in Fig. 1.14.

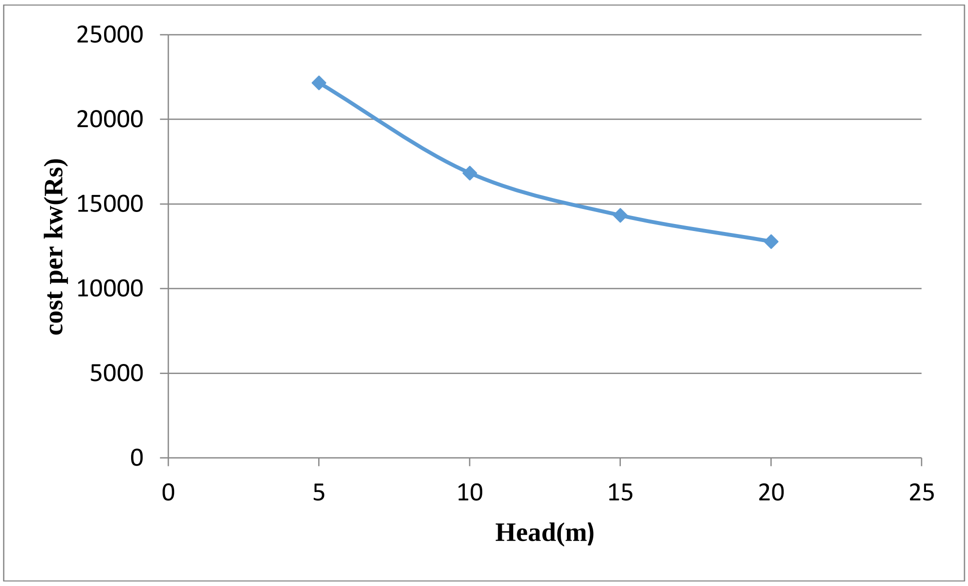

Fig 1.14 variation of cost of auxiliary with head when tubular Kaplan turbine is use (P=2000kW)

CASE 3 cost of auxiliary when vertical semi-Kaplan turbine is used

In this case correlation used for cost calculation is given as:

$$C_7 = 42332P^{-0.1859}H^{-0.2084} \quad (1.15)$$

Where C_7 = cost per kW of auxiliary

Using Eqn. (1.15) variation in cost of auxiliary (for vertical semi- Kaplan turbine) with various head and power is calculated and results obtained are shown in Figure 1.15.

Now, considering capacity 2000 kW variation in cost of auxiliary (for vertical semi-Kaplan turbine) with respect to various head is shown in Fig. 1.15.

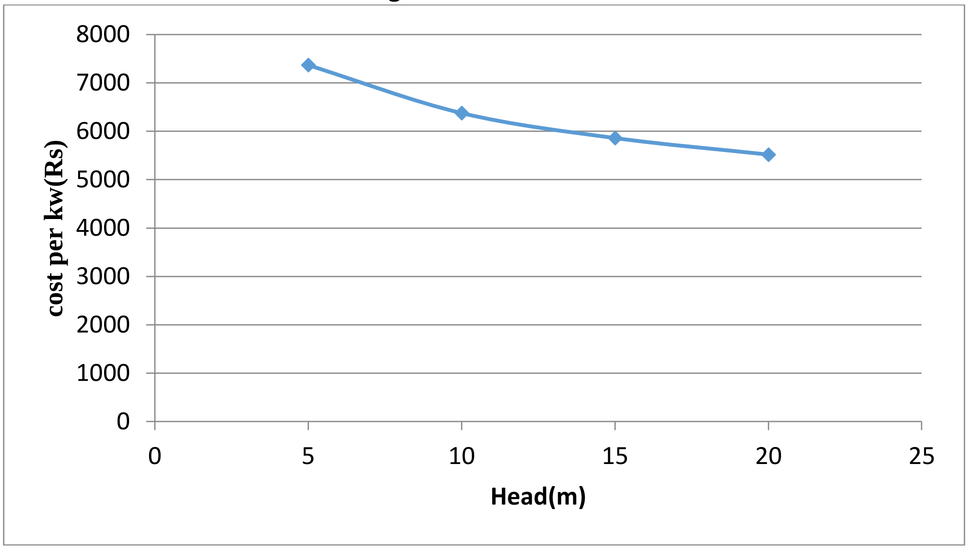

Fig 1.15 variation in cost of auxiliary with head when vertical semi-Kaplan turbine is use (P =2000kW)

COST CALCULATION FOR TRANSFORMER AND SWITCHYARD EQUIPMENT

In many countries the electricity supply regulations place a statutory obligation on the electric utilities to maintain the safety and quality of electricity supply within defined limits. The independent producer must operate his plant in such a way that the utility is able to fulfil its obligations. Therefore various associated electrical devices are required inside the powerhouse for the safety and protection of the equipment.

Switchgear must be installed to control the generators and to interface them with the grid or with an isolated load. It must provide protection for the generators, main transformer and station service transformer.

The correlation use for the cost calculation of transformer & switchyard is find out as:

$$C_8 = 18739P^{-0.1803}H^{-0.2075} \qquad (1.16)$$

Where C_8 = cost per kW of transformer & switchyard

Using Eqn. (1.16) variation in cost of transformer & switchyard with various head and power is calculated and results obtained are shown in Figure 1.16

Now, considering capacity 2000 kW variation in cost of transformer & switchyard with respect to various head is shown in Fig. 1.16.

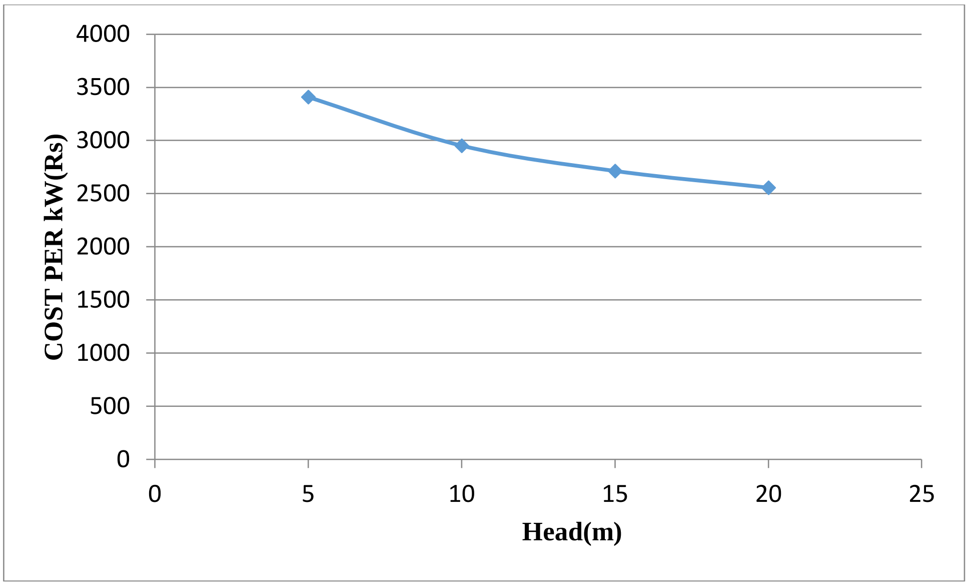

Fig 1.16 variation in cost of transformer & switchyard with head (power is 2000kW)

CONCLUSION

For the typical dam toe site having head 20m and capacity 10000kW cost of different components of civil works and electro-mechanical equipments for low head dam toe SHP using different turbines has been calculated and optimal selection of hydro turbine has been suggested. From the study it has been found that.

(1) For the considered site cost of SHP plant per kW (in Rs) is 33560,35059 and 36863when tubular propeller turbine, vertical semi-Kaplan and tubular Kaplan turbine is used respectively.

(2) Cost of such a considered typical low head dam toe based SHP would be minimum when propeller tubular turbine is in used.

(3) Cost of such a considered typical low head dam toe based SHP would be maximum when tubular Kaplan turbine is used.

Therefore for the considered low head dam toe based SHP propeller tubular would be economical to be implemented based on site conditions.

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