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EXPERIMENTS OF ARCHIMEDES SCREW TURBINE ON MAIN LINE LOWER AT FALL RD 19+850

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By

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ABSTRACT

A hydropower scheme is planned on Main Line Lower canal at fall RD 19+850 in district Hafizabad. The proposed installed capacity of the plant is 200 kw comprises of 5 units of 40 KW each of Archimedes Screw Turbines. The plant design discharge of 642.72 m3/s is considered based on average annual monthly flows of last ten years which is available 65% of the time. The average annual daily flow is 634.54 m3/s. The plant factor is 50.45 %. The canal flows during different seasons vary widely and in dry season, the flow is lower than one third of designed flow. The fall site has very low head below three meter. The use of conventional turbines is a very costly proposition. Archimedes screw turbines are proposed in the existing bays of the fall for energy generation and are capable of operating between 15% to 110% of designed flow. The daily discharge data of Main Line Lower for the duration of last ten years from 1 January 2012 to 30 December 2022 has been analyzed. Flow duration curve indicates that canal runs 50% of the time with discharge exceeding 19.82 m3 /s and available with discharge 35.39 m3 /s for about 5% of the time. Experiments are planned to test the performance of screw turbine by using single bay of the fall for hydropower generation. This paper highlights the details of the experiments which is useful for humanity specially for hydropower professionals.

Keywords: Archimedes Screw turbine, small hydropower, Small Medium Enterprise

1.0 Introduction

The electricity is the main economic driver of Pakistan. The hydroelectric power generation is the green renewable resource being given priority worldwide to prevent the planet from fossils fuels. Punjab Government has attracted private investment to tap the hydel potential on falls of canals, barrages and streams in Punjab province. To develop falls sites for hydropower generation, Punjab Government has approved Captive Guidelines for development of the small hydropower projects in Captive mode.

The Energy Department Government of the Punjab permitted the private sponsor for development of the hydropower site at RD 19+850 on Main Line Lower (MLL) in district Hafizabad in captive mode as per Punjab Government cabinet approved Captive Guidelines. Main Line Lower is an irrigation canal. The canal flows during different seasons vary widely and in dry season, the flow is lower than one third of designed flow. The project site has very low head below 3 meter. All these parameters made use of conventional turbines a very costly proposition. Screw turbines are capable of operating between 15% to 110% of designed flow. Also, unlike conventional turbines the civil work depth required for screw turbines would have been same as that of existing canals. Archimedean screw turbine technology is most suitable for the site.

The daily discharge data of Main Line Lower for the duration of last ten years from 1 January 2012 to 30 December 2022 has been analyzed. The full supply canal design

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flow is 2670 cusecs. However, flow data indicates that the canal has never exceeded discharge of 1800 cusecs. The discharge in the canal has passed maximum 1800 cusecs between January 2, 2019 to January 11, 2019 only for 10 days. Flow duration curve (FDC) is developed using average 10 daily discharge data in order to estimate the availability of water for power generation. Flow Duration curve indicates that canal runs 50% of the time with discharge exceeding 19.82 m3 /s (700 cusecs) and available with discharge 35.39 m3 /s (1250 cusecs) for about 5% of the time. For the Project, plant design discharge of 642.72 m3/s is considered based on average annual monthly flows of last ten years which is available 65% of the time. The average annual daily flow is 634.54 m3/s. The proposed installed capacity of the plant is 200 KW which comprises of 5 units of 40 KW each of Archimedes Screw Turbines. The plant factor is 50.45 %.

The advantage of the Archimedean Screw turbine is simplified civil engineering works and foundations. Because screws don't have draft tubes. The depth of concrete works on the downstream side of the screw is relatively shallow, which reduces construction costs. The civil works are also relatively simple, the main part being the load-bearing foundations underneath the upper and lower bearings. The fall structure RD 19+850 has been remodeled in the recent past. The new skew DR bridge is constructed upstream about 300 feet from the fall. The existing remodeled fall structure is used for power generation, which is the most suitable layout option for the project involving minor civil works. The different study options have been considered for power generation including construction of power plant in the diversion canal on the right side of existing fall in bye pass arrangement as an alternate layout. The existing structure health is safe and can bear the additional load with good factor of safety. The stability analyses have been performed. The site layout using existing fall at RD 19+850 is preferable solution for power generation and economically viable under low head available at the site.

The developer planned to inject 100% equity to construct the plant and Small Medium Enterprise (SME) to use generated energy within the one year. The developer took full responsibility to take care of canal regime and its sustainable operation of the canal during and after construction. The developer bears all damages consequential due to power plant, if any and rectify immediately. It is ensured that the main canal operation shall not be disturbed and maintained as per requirements of Punjab Irrigation Department (PID). No significant environmental or social issue is likely to be involved during construction and operational phase of the Project. The environment department has issued no objection certificate. PID allowed to test the turbine in the one of the existing bays of the fall structure using screw turbine to assess its performance. This paper presents the details of experiments at project site located at RD 19+850 on Main Line Lower in District Hafizabad. The pilot test site having coordinates 32°03'41.55"N & 73°42'50.53"E is shown in **Figure-1**.

2.0 Material

Archimedes screw turbine (AST) is water turbine that converts the potential energy of water on an upstream level into work. It works is driven by the weight of water, similar to water wheel, and can be considered as a quasi-static pressure machine. Archimedes screw generators operate in a wide range of flows 0.01 m^3/s to 14.5 m^3/s and heads from 0.1 m to 10 m, including low heads and moderate flow rates that are not ideal for traditional turbines and not occupied by high performance technologies. Its efficiencies vary from 70 to 83%. Water transiting the screw from high to low

elevation generates a torque on the helical plane surfaces, causing the screw to rotate. The Archimedes screw generator consists of a rotor in the shape of an Archimedean screw which rotates in a semicircular trough. Water flows into the screw and its weight presses down onto the blades of the turbine, which in turn forces the turbine to turn. Water flows freely off the end of the screw into the canal or river. The upper end of the screw is connected to a generator through a gearbox. The Archimedes screw is theoretically a reversible hydraulic machine.

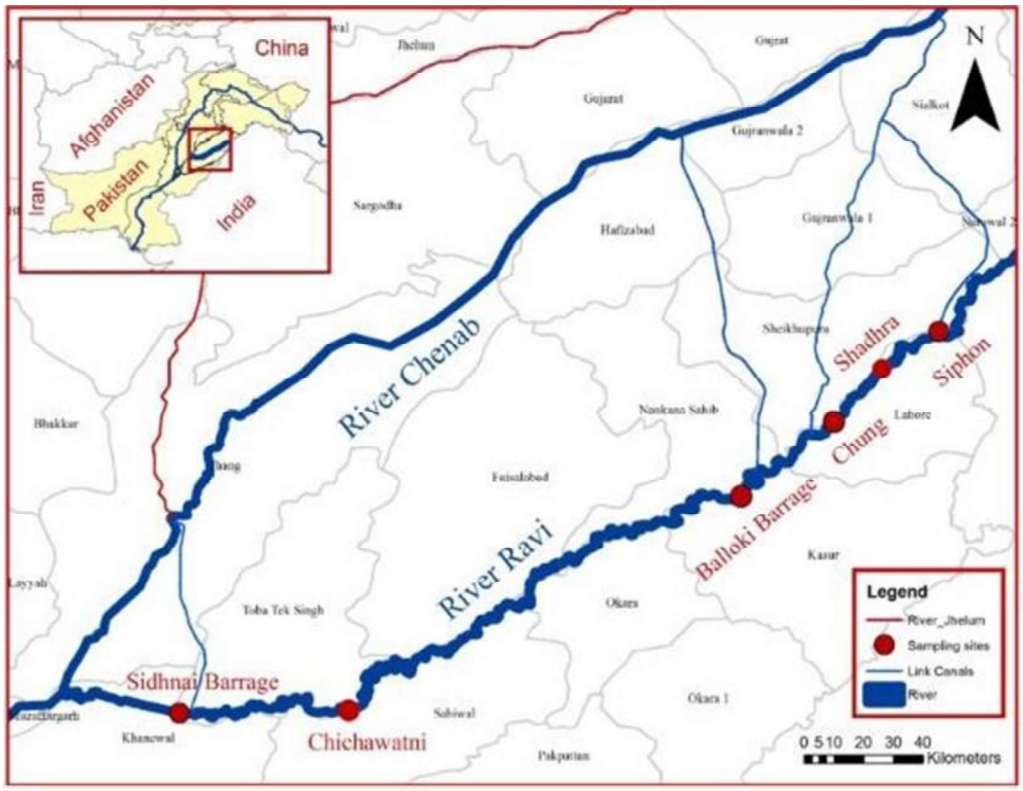


Figure-1: Map of Pakistan showing Project site

The Archimedes Screw is becoming the most commercially successful of the contemporary low head hydropower machines. Dozens of units have been installed in recent times, the main manufacturers being ANDRITZ Atro GmbH (formerly Ritz-Atro GmbH), REHART Group, GESS-CZ, Mann Power Consulting Ltd. The maximum flow rate through an Archimedean screw is determined by the screw diameter. The smallest screws are just 1 meter diameter and can pass 250 liters / second, then they increase in 250 mm steps all of the way up to 5 meters in diameter with a maximum flow rate of around 14.5 m^3 /s.

2.1 Design parameters

The design parameters of an AST are usually the head H and the discharge Q that are available at the installation site. Regarding the head, a few considerations are necessary. Due to the geometry of the turbine, it can be considered that the areas of the inlet and outlet sections are roughly equal, hence the mean velocities of the water through these sections are also roughly equal. The flow through the entire turbine has a free surface, which allows us to consider that the static pressures at turbine inlet and outlet equal the atmospheric pressure. Then, the turbine head can be estimated as $H = z_1 - z_2$, where z_1 and z_2 are the heights of the free surface at turbine inlet and outlet, respectively, measured from a conveniently chosen reference plane.

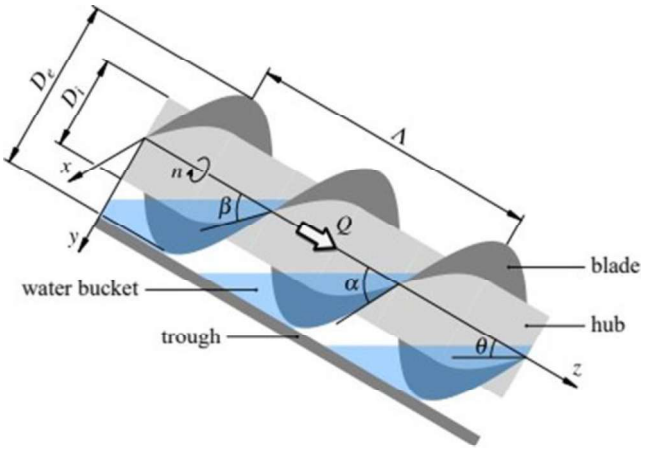


Figure-2: Side view and main dimensions of an Archimedean screw

2.2 Blade geometry

The inner and outer edges of the runner blades are sinusoids having the same phase and period, but different amplitudes. The amplitudes of the two curves equal the inner radius and the outer radius, respectively. Given the pitch, Λ, and the number of blades, N, the distance between two successive blades equals Λ/N.

2.3 Installation angle

From the economical point of view, a value of the installation angle as high as possible is preferred, since a larger installation angle leads to a shorter screw, hence to lower manufacturing costs. From the point of view of the turbine efficiency and power extracted, experimental studies shows the maximum power can be obtained for installation angles that are roughly between 30° and 35°. For the site, a value of 36^0 is considered.

2.4 Screw length

The length of the screw, L, depends on turbine height and installation angle according to the following relationship, $L = (z_1 - z_2) / \sin\theta = H / \sin\theta$, for the project when the installation angle is of 30◦, the length of the screw equals twice the turbine head is taken.

2.5 Number of blades (flights)

A larger number of blades increases the screw weight and, consequently, the loads on the shaft and bearings, the friction losses inside the bearings, and the costs of manufacturing, transporting, and installing the turbine. The optimal number of blades of an AST is taken as N = 3 for the site.

2.6 Outer diameter

The choice of the outer diameter of an Archimedean screw, De, is strongly related to the turbine speed that the value of the speed in rpm does not exceed the upper threshold. $n = 50 / D_2/3$, The turbine speed is chosen so that the flow rate absorbed by the runner during a full rotation equals the discharge. Assuming that N buckets get filled with water during a full rotation, the following relationship can be derived $n = 60 Q / N V_b$, where V_b is the volume of a bucket.

A serious problem that arises when designing an AST is the calculation of the volume V_b. Normally, this volume strongly depends on the turbine discharge and on how the blade pitch and the turbine speed are chosen. When the blade pitch and the turbine

speed are chosen as proposed before, the bucket volume is bounded by five surfaces: (i) the free surface of the water in the bucket, that builds the installation angle θ with the turbine axis, (ii) the wetted surface of the downstream blade, (iii) the wetted sufrace of the upstream blade, which is, however, very small, (iv) the wetted inner surface of the trough, and (v) the wetted outer surface of the hub.

Outer diameter can be expressed as, $De = (18.63\ KQ / N(1-\delta 3))^{3/7}$

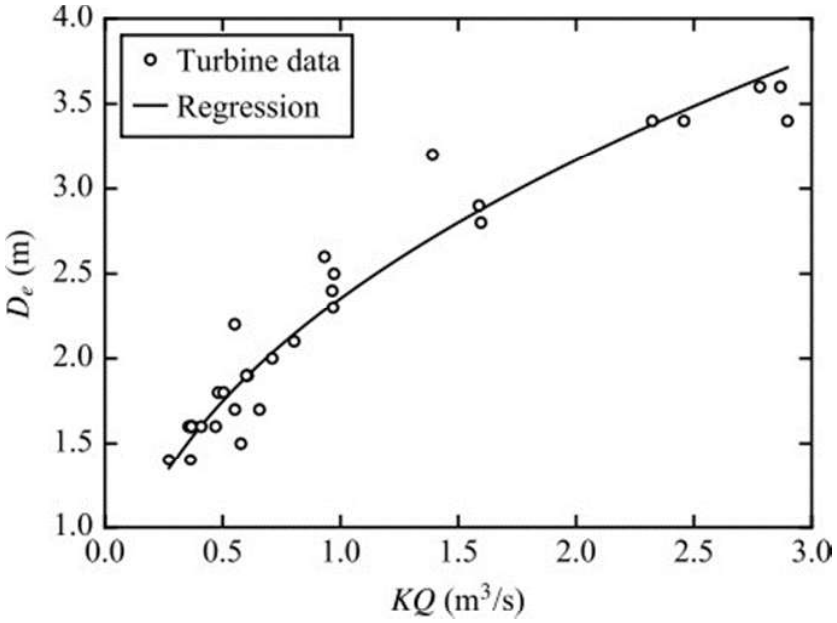


Figure-3: Outer diameters of ASTs depend on the product between turbine slope and discharge and corresponding regression curve

2.7 Turbine speed

The turbine speed is calculated by the equation,

$n = (931.4\ KQ) / (NDe^3\ (1-\delta\ ^3))$,

The speed calculated with the previous formula must be lower than the upper threshold $n_{lim} = 50 / De^{2/3}$

2.8 Turbine efficiency

The AST turbine-generator units have efficiencies ranging roughly from 60% to 76%. Since these efficiencies are of complete units, that include not only the AST, but also the electrical generator and the speed increasing gear box, it can be expected for a well designed AST to have a total efficiency η of about 70–75%.

2.9 Shaft power

After estimating the total efficiency, the shaft power of an AST, i.e. the power delivered, is evaluated with the formula used for turbines:

$P_s = 9.81\ \eta\ Q\ H$ in Kw

2.10 Design Procedure

The considerations presented above allow the formulation of a simple design procedure for ASTs. This procedure is described in form of a flowchart in **Figure 4**. Once the turbine head and discharge are known, the design procedure is straightforward and allows to calculate step by step all parameters detailed as above.

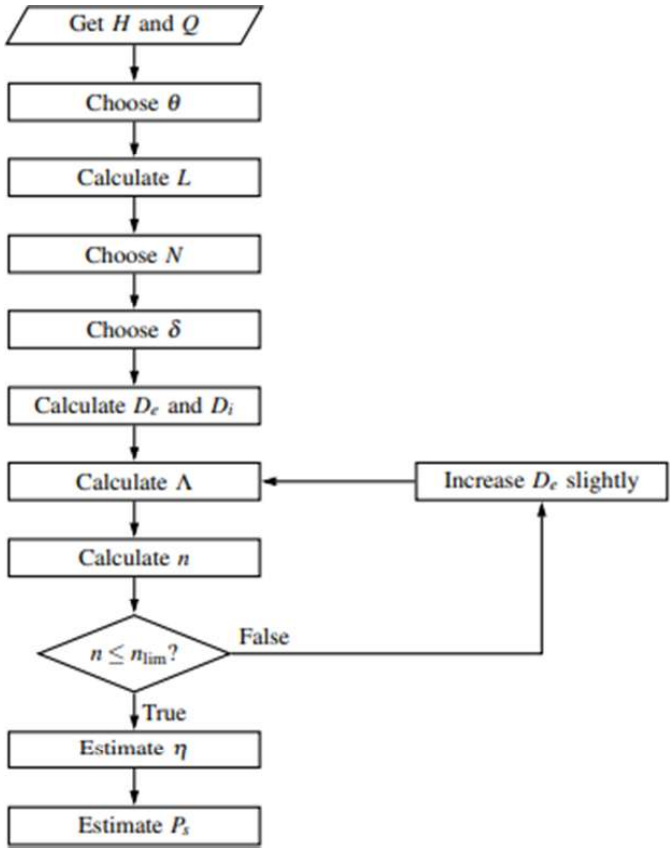


Figure-4: Design procedure for Archimedes screw turbine

3.0 Salient Features of Screw Turbine

The salient features are indicated in the **Table1** below. **Figure 5** shows the parameters of the Archimedes Screw turbines considered for the experiment.

Table-1: Screw Turbine at fall RD 19+850 Main line Lower

No	Parameters	Units	Measurements
A	**Canal system**		
	Canal		Main line Lower
	Location		RD 19+850
	District		Hafizabad
	Coordinates		32° 03' 41.55" N & 73°42' 50.53" E
B	**Design parameters**		
	Canal Design Discharge, Q	m^3/s	75.59 (2670 ft^3/s)
	Plant Design Discharge	m^3/s	18.30 (642.72 ft^3/s)
	Gross head, H'	M	1.55 (5.1 ft)
	Net Head, H	M	1.35 (4.43 ft)
	Power, P	KW	200
	Annual Energy	KWh	883915.5
	Plant Factor	%	50.45
C	**Hydro Mechanical**		
	Technology		Archimedes Screw Turbine
	No of units	No	5

No	Parameters	Units	Measurements
	Discharge per unit	m^3/s	3.64
	Capacity/ Power per unit	Kw	40
	Turbine efficiency	%	80
	Angle, a	Degrees	22
	Screw Length, L	M	4.15
	Number of blades, N	No	3
	Outer Diameter, De	M	2.591
	Inner Diameter, Di	M	1.399
	Turbine speed, n	Rpm	31
	Blade pitch, p	M	0.8636
	Volume of Bucket	m^3	2.747

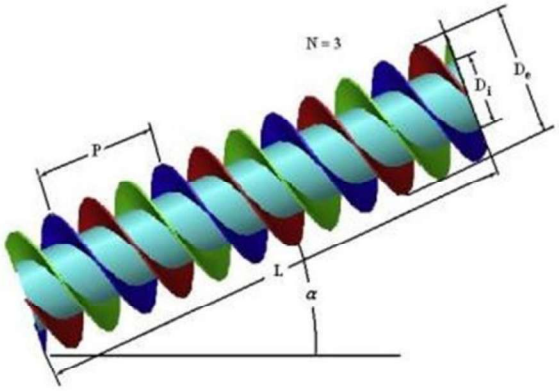


Figure-5: Parameters of Screw Turbine

4.0 Hydrology

4.1 Flow Data Analysis

The daily discharge data of Main Line Lower at RD 0+000 was studied for the duration of last ten years from 1 January 2012 to 30 December 2022 and accordingly the flow data analysis has been carried out for fall at RD 19+850. The longitudinal section of Main Line Lower and Structure drawing of fall cum bridge was also reviewed. The upstream canal design discharge at fall RD 19+850 is 2670 cusecs. The data series indicates that the canal has never attained this discharge. The maximum discharge passed in the upstream section is 1800 cusecs from 1I January 2019 to 19 January 2019 (only ten days). Ten daily discharge data indicates that maximum 10 daily average discharge is 1245 in the first ten daily of January and minimum ten daily average discharge is 220 cusecs with the exception of last ten daily of January and first ten daily of February. The canal remains closed for annual maintenance from 15 January to 15 February each year.

4.2 Flow Duration Curve

Flow duration curve (FDC) is developed using average 10 daily discharge data in order to estimate the availability of water for power generation. Flow Duration curve is shown as Figure 6 indicates that canal runs 50% of the time with discharge exceeding 19.82 m^3 /s (700 cusecs) and available with discharge 35.39 m^3 /s (1250 cusecs) for about 5% of the time. The discharge of 1250,1100, 900, 850, 780 & 700 m^3/s are available for duration of 5%, 10%, 20%, 30%, 40% & 50% of the time respectively during the year.

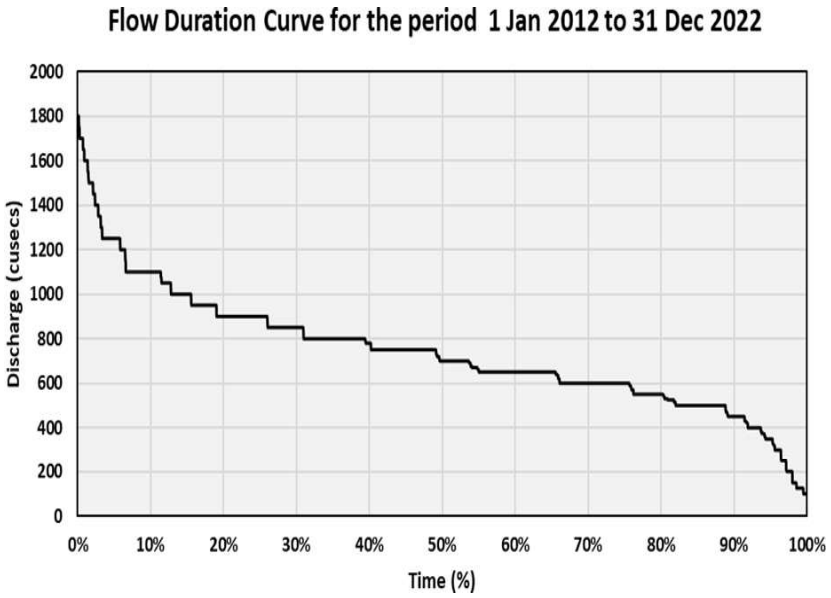


Figure-6: Flow Duration Curve

4.3 Availability of Flows for Power Generation

Average 10-Daily discharge data and the maximum monthly discharge data is analyzed based on daily discharge data for the last ten years from 1 January 2012 to 30 December 2022. The average 10-daily discharge is shown as Figure 7. The average monthly discharge analysis indicates June, July, August and September are the months of high flows.

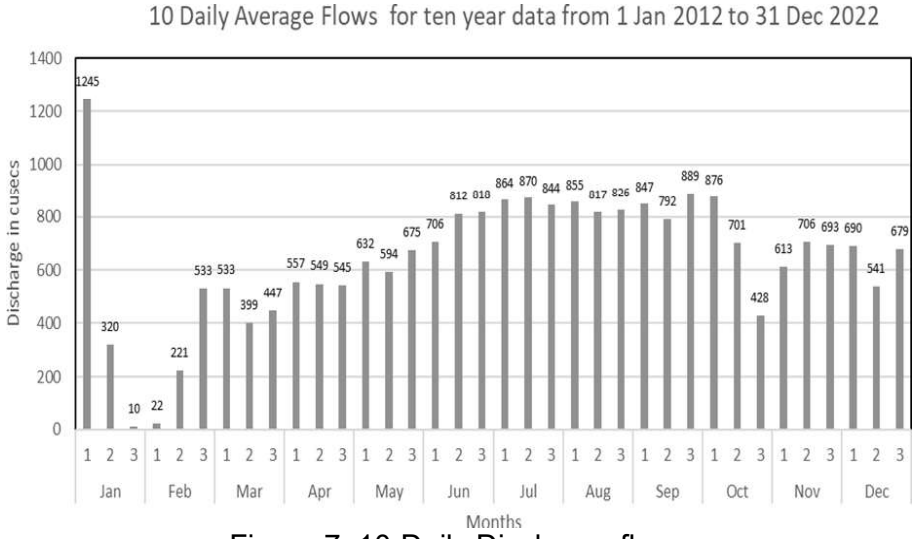


Figure-7: 10-Daily Discharge flows

4.4 Gross Head

The head has been estimated from difference of upstream and downstream water levels of the fall RD 19+850. At different discharges, the head is worked accordingly and is shown in the **Table-2.** At design discharge of 2670 ft^3/s, the upstream water level is taken as 695.63 and maximum downstream water level is taken as 693.15. The crest level of fall is 691.74. The head over crest is 3.89 feet.

Table-2: U/s and D/s water levels at Fall RD 19+850

Discharge (ft^3/s)	U/s Water level in feet	D/s Water level feet	Gross head in feet	Gross head in meter	Head on crest in feet
2670	695.63	693.15	2.48	0.755	3.89
1800	695.06	691.38	3.68	1.121	3.32
1245	694.33	690.1	4.23	1.289	2.59
859	693.76	689.025	4.74	1.444	2.02
643	693.40	688.3	5.10	1.55	1.66

5.0 Prototype Tests of Screw Turbine at Fall RD 19+850

An ungated and old existing fall structure at RD 19+850 has 7 bays and old a village road bridge over it. A new skew DR Bridge exists upstream about 500 feet which is in use. The old bridge over the fall is not in use and obsolete. A fall of about 4.53 feet is available at this location. **Photo 1** shows the fall structure at RD 19+850. The main components of the project involve to using existing fall structure, E & M equipment installed on the one of the 5 no fall bays. The existing top arch bridge slab removed in central bay and 5 no. pre cast metal operating deck slab placed on the existing piers. Further, no civil works is involved. No land for power plant is required and only land for SME is required. The project is planned to be completed in 12 months from the beginning of construction to commissioning of the project. This pilot test planned to perform on central bay of the fall to test the performance of the screw turbine.

Several factors such as the availability of water, the head and flow rate of the water, the cost of equipment, and the cost of construction and maintenance and energy estimates affect the tests of the screw turbine. The size and cost of water conveyance structures and electromechanical equipment required for this site depends largely on the flow rate. The project site at Rd 19+850 has high flows and low head. The Archimedes Screw turbine consists of a rotating screw supported within a trough by bearings at each end, with a gearbox and generator situated in the control house. The water is lowered within cells which form between the blades and the trough. A screw turbine is locally manufactured for low head at this site keeping in view the range of heads between 1 m to 2 m with designed flow rates between 1 m to 10 m^3/s and for inclination angle, 22^0 from the horizontal. The screw turbine rotors showed the efficiencies between 60 to 74%, making it an interesting alternative for turbines in low head hydropower applications.

The main parts of screw turbine used as hydro generator are shown below between **Figures-7 to 11.** The actual screw is below the upper bearing. The helical screw or 'flights' are made from rolled flat steel plate that is then welded to a central steel core. The screws have three flights, or three separate helices winding around the central core. The turbine screw rotates at around 26 rpm, so the top of the screw connects to a gearbox to increase the rotational speed to between 750 and 1500 rpm to make it compatible with standard generators. The screw turbine is set at an angle of 22^0 from horizontal, which is the optimum for the most cost-effective installations.

A significant advantage of this screw turbine is their debris tolerance. Due to the relatively large dimensions of the screw's flights and slow rotational speed, relatively

large debris can pass through unhindered and without damaging the screw and certainly all small debris such as leaves passed through without any problems at all.

The screw turbine is simplified civil engineering works and foundations. Because screws don't have draft tubes or discharge sumps, it means that the depth of any concrete works on the downstream-side of the screw is relatively shallow, which reduces construction costs. The civil works are also relatively simple, the main part being the load-bearing foundations underneath the upper and lower bearings.

6. Conclusions and Recommendations

The unique features of prototype test at fall 18+950 using Screw turbine are presented in the paper. Based on the above, following conclusions are drawn.

Layout with power house on existing fall has significant advantage. Such layouts plans are free of diversion, associated canal closures and construction of power house, as a critical task.

- A screw turbine is locally manufactured for low head at this site keeping in view the range of heads between 1 m to 2 m with designed flow rates between 1 m to 10 m^3/s for single bay and for inclination angle, 22^0 from the horizontal. The screw turbine rotors showed the efficiencies between 60 to 74%, making it an interesting alternative for turbines in low head hydropower applications.
- The turbine screw rotates at around 26 rpm, so the top of the screw connects to a gearbox to increase the rotational speed to between 750 and 1500 rpm to make it compatible with standard generators. The screw turbine is set at an angle of 22^0 from horizontal, which is the optimum for the most cost-effective installations.
- Based on the performance of the prototype test, the screw turbines shall be installed in the remaining four bays of the falls.

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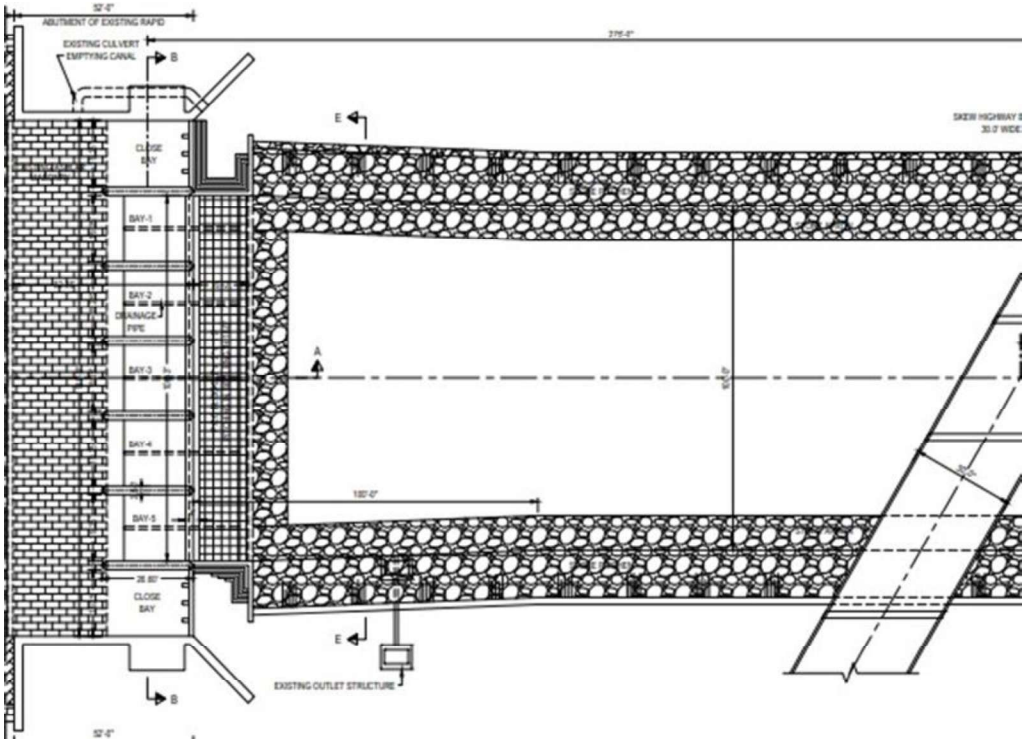


Figure-8: Plan of existing fall RD 19+850 of Main Line Lower

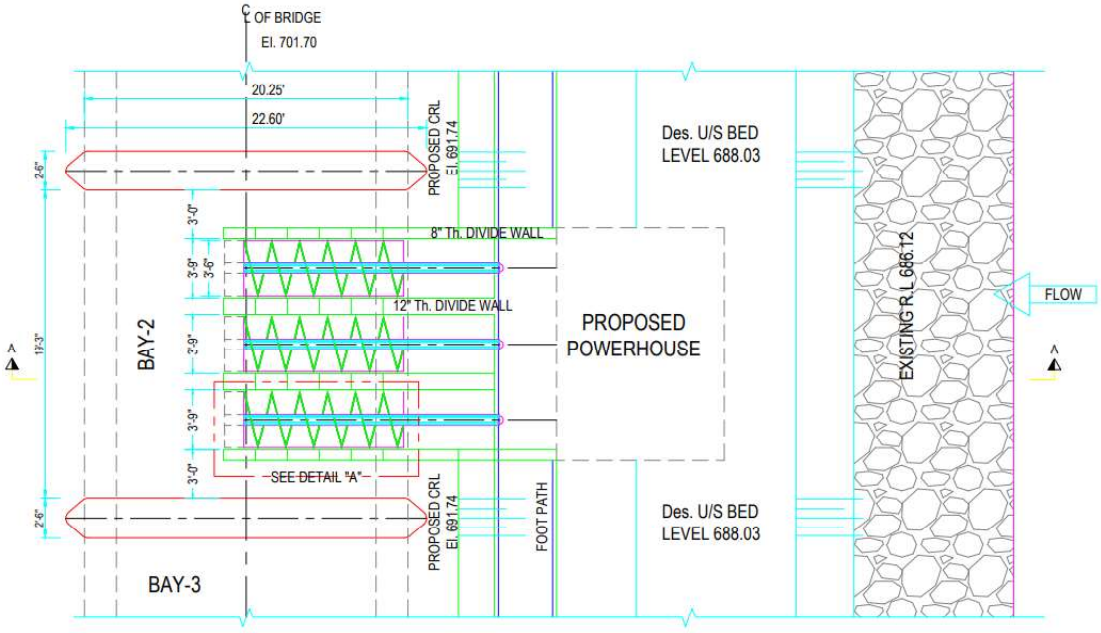


Figure-9: Part Plan of fall RD 19+850 showing arrangement of Screw Turbine

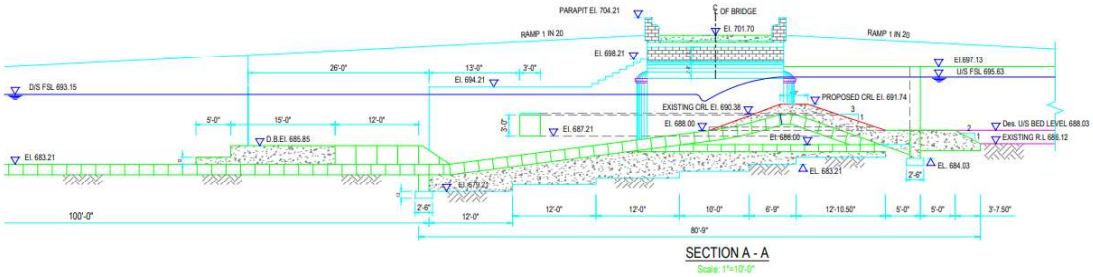


Figure-10: Longitudinal Section of Fall RD 19+850

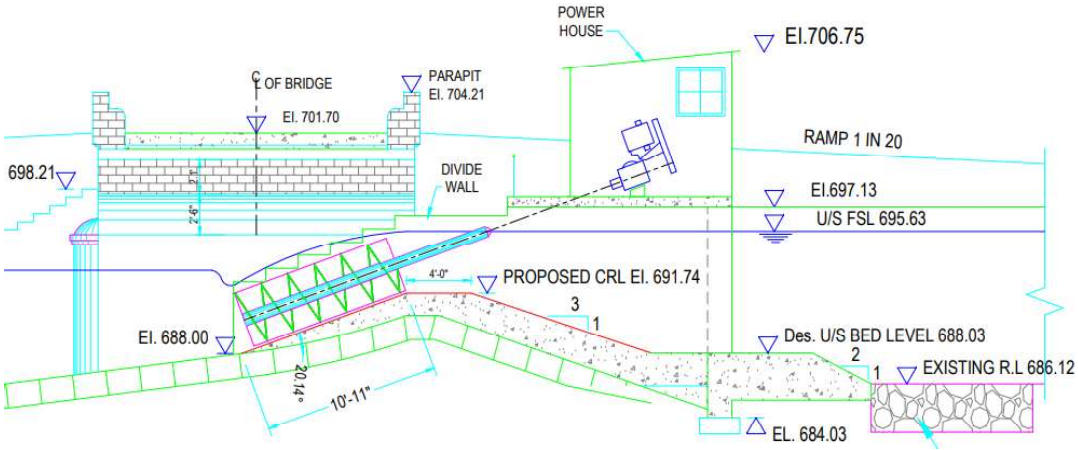


Figure-11: Section of fall RD 19+850 showing Screw Turbine



Photo-1: Downstream view of fall RD 19+850