Discharge Measurement in Small Hydropower Stations using Acoustic Doppler Current Profiler

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ABSTRACT

Discharge measurement is the most complicated and tedious exercise in the evaluation of the efficiency of hydro-electric power generating units, even in small hydropower (SHP) stations. For an accurate estimation of discharge in open channels and closed ducts, it is generally recommended to measure the flow velocity simultaneously at a number of points in the measuring section. One good method of simultaneous velocity measurement at a large number of points in an open channel is applying an acoustic Doppler current profiler (ADCP), which is non-intrusive since the velocity measurement is based on the reflection of an acoustic beam. The ADCP can be installed in either power channel or tail-race channel of the power station depending on flow and channel conditions, and on the convenience of mounting and using the ADCP. The paper reports the measurement of velocity profile in different flow sections using a horizontal- beam ADCP mounted on an I-section beam and moved up and down inside the flow section.

Generally the profiler is kept at four or five levels and velocity is measured along the width of the flow section. The accuracy of discharge evaluation depends on the cell size and the number of levels at which the velocity profile is measured by ADCP. The in-built program of ADCP calculates the average flow velocity at each level, and also computes the discharge based on the details of flow section provided to the profiler at the beginning of the measurement. However, such programs generally suffer from low accuracy because of in-built simplified assumptions. Discharge can be determined externally with a higher accuracy using the velocity profile data and applying an appropriate method of velocity area integration.

Velocity profile measurements carried out in 11 SHP stations using ADCP and discharge calculations using the velocity area integration method or velocity area-segment method as per IEC 60041are reported here. For two typical situations, namely, rectangular channel and trapezoidal channel, the mounting arrangement, the procedure of evaluation of discharge and discharge computed by ADCP have been discussed. The values of discharge obtained with horizontal-beam and vertical-beam ADCPs have also been compared with that obtained from multiple propeller current-meters for validation of the procedure followed.

Keywords: *Acoustic Doppler current profiler, ADCP, Discharge measurement, Hydropower, integration scheme, velocity area integration method.*

1. INTRODUCTION

Measurement of efficiency of a water turbine or a hydro-electric power generating unit in a power station requires an accurate measurement of discharge, which is the most difficult exercise in efficiency evaluation. The typical methods of open channel flow measurement like weirs and notches have low accuracy and are not preferred for the hydraulic efficiency measurement. The recent developments in flow measurement techniques and instruments have made it possible to improve the accuracy of discharge measurement in open channels by measuring the velocities at a matrix of locations in the flow section. The velocity matrix can be used to calculate the discharge by velocity area integration method or velocity area-segment method [IEC 60041]. This procedure has been used widely either by employing a number of current-meters fixed at different locations inside the flow measurement section or by a panel of current-meters moved horizontally/ vertically to cover the whole area of flow [ISO 748, 1997; Gandhi and Verma, 2007]. The current-meter measures the velocity at the point of insertion whereas an acoustic Doppler current profiler (ADCP) is comparatively non-intrusive instrument as it measures velocities from distance. However, ADCP is not recommended in IEC 60041, may be due to its development at a later stage. Consequently, no procedure has been standardized till date to measure the velocity profile with an ADCP and to evaluate the discharge from it. Simpson (2001) explained the operating principle of a Horizontal-beam ADCP and method of evaluation of discharge using its velocity profile data. Juan et al. (1996) discussed some examples where an ADCP has been used to determine the discharge. They have compared the velocity profile measured by ADCP with those determined from the available theories. Muste et al. (2004) observed that a moving-vessel ADCP estimated the river discharge successfully and they reported that the small and large turbulence scales are smoothed out by time averaging of a large number of data during ADCP measurements. They also discussed assumptions and error sources involved in ADCP measurements. Besides being non-intrusive at velocity measurement location, the ADCP has additional advantages over the current-meters in that it has no moving parts (and hence its calibration is very stable) and the pitch and roll of its sensors can be monitored online to ensure alignment of the sound beam with the flow section. ADCP measures velocity profile of a flow section and has been widely used in oceanographic and river flow applications.

In 2004, the Indian Institute of Technology, Roorkee assumed the responsibility of performance testing of small hydropower (SHP) stations in India. By now, its testing team has an experience of carrying out unit efficiency test in more than 30 stations of different types and involving generating units of different capacities. Discharge measurement in well defined open channels of SHP stations has been carried out in 11 SHP stations using horizontal-beam acoustic Doppler current profiler (ADCP). This paper gives some details of these stations and of the measurement with ADCP. Two representative case studies are given to explain the procedure followed for measurement and discharge calculation using horizontal-beam ADCP. For one case, a comparison of the results obtained with three methods of discharge measurement, viz. horizontal-beam ADCP, vertical-beam ADCP and propeller current meters (PCMs) is made for validation of ADCP method.

2. PRINCIPLE OF ADCP

The ADCP measures the flow velocity, in both magnitude and direction, of the particles suspended in the flowing water using Doppler effect. A piezoelectric transducer transmits an acoustic beam of ultrasonic frequency and listens to its echo. The instrument then calculates the velocity component of the reflecting particle along the direction of the sound beam from the difference of the frequencies of transmitted and reflected beams, i.e. the Doppler shift. A pair of transducers is generally used: one transducer sends and receives the sound beam on upstream side of the ADCP location, while the other one does the same on downstream side at an equal angle. By combining the two velocity components in the directions of the beams and taking the sound travel time into account, the instrument software calculates the flow velocity (both magnitude and direction) at certain distances from the instrument (Bradley, 1999). The beams can be sent by an ADCP either in a horizontal plane or in a vertical plane.

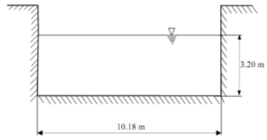
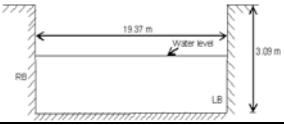
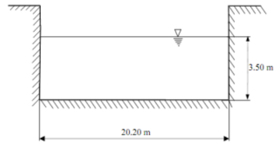
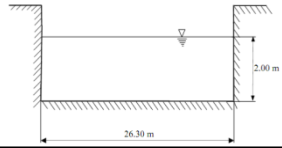
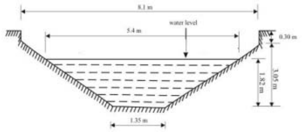
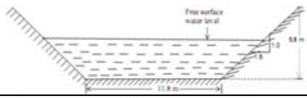
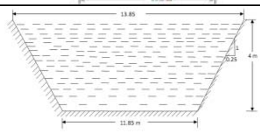
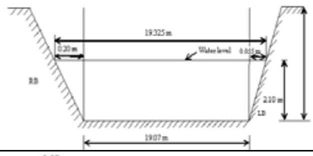
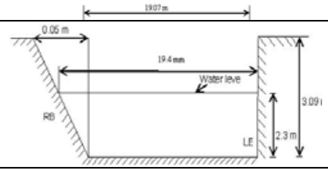
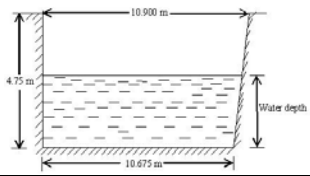
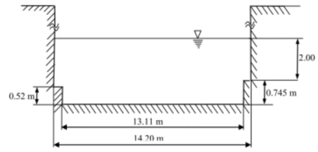
The horizontal-beam ADCP, used by IIT Roorkee Group, divides the width of the flow section into “cells” of a pre-selectable size. The ADCP is mounted on an I-section beam fixed along one wall of the open channel (power or tailrace channel) and can be moved up and down. It is positioned at several levels (typically 4 or 5) and velocity profile along the width of the measuring section is obtained at each level. The actual depth of water at each ADCP location is measured by an in-built immersible pressure sensor. The ADCP has internal software that calculates the discharge through the measuring section from the average velocity measured at each depth, the actual measured depth and the dimensions of the measuring section. The dimensional data are entered into the instrument before starting the velocity measurement.

The instrument can communicate with a desktop /laptop PC connected either by wires using RS-232/RS-485 protocol or by radio modems. The profile data can be downloaded on the PC for more accurate discharge calculation using external software. The IIT Group has developed a software based on velocity area integration that uses power-law relations for interpolating/ extrapolating the profile near the walls and bottom of the flow channel. The power-law velocity is used for the unmeasured part of the channel width, due to the blanking distance and mounting arrangement of ADCP. This procedure has been followed for rectangular channels. For the trapezoidal channels the width of measurement changes with the water depth and therefore velocity area-segment method is followed in this case using the area and velocity of each cell. The sum of discharges of all cells is used to determine the total discharge through the channel. Results of internal integration of ADCP have been used only for guidance during the test.

3. DETAILS OF ADCP APPLICATION

The discharge measurement location, the rated discharge and details of the measurement section for each of the 11 SHP stations referred above are given in Table 1. Important aspects of the velocity measurement carried out with ADCP in these stations are discussed in the following sections.

Table 1: Details of discharge measurement by ADCP in 11 SHP Stations

Sr. No.	Name of Hydro-electric power station and capacity	Location of ADCP	Rated discharge, m^3/s	Measurement section geometry	Measurement section details	Number of levels of ADCP data
1	Ranganatha-swamy 3 x 8.25 MW	Power channel	27.0	Rectangular		5
2	Lohgarh 2 x 1 MW	Power Channel	60.4	Rectangular		4
3	Chhayadevi 2 x 12 MW	Power channel	96.0	Rectangular		5
4	Neria 2 x 4.5 MW	Power channel	60.0	Rectangular		4
5	Bassi 4 x 15 MW	Power channel	24.2	Trapezoidal		3
6	Rani Avanti Bai 2 x 5 MW	Tailrace channel	86.3	Trapezoidal		1
7	Varahi Tailrace 3 x 7.5 MW	Tailrace channel	70.8	Trapezoidal		7
8	Killa 2x 0.875 MW	Power channel	46.0	Trapezoidal		4
9	Chakbhai 2 x 1 MW	Power channel	53.6	Trapezoidal		4
10	Sahoke 1 x 1 MW	Power channel	22.7	Trapezoidal		4
11	Mahatma Gandhi Tailrace 2 x 11 MW	Tailrace channel	35.4	Combination		3

4. ADCP MOUNTING ARRANGEMENT AND MEASUREMENT PROCEDURE

To measure the rate of water flow through the power plant in open channel, an ADCP can be mounted at one sidewall of the channel of any shape, namely, rectangular, trapezoidal or combination of rectangular and trapezoidal shapes. The ADCP is mounted on an I-section beam such as to move it inside the flow section, and the velocity profile is obtained at multiple depths. At each depth, the velocity along the width of the channel is measured for every 5 seconds and the average reading of every 120 seconds is used to find the velocity profile. The average of three such velocity profiles at each depth is used to evaluate the discharge through the channel.

Typical arrangements for mounting the ADCP inside rectangular and trapezoidal channels are discussed below.

4.1 Open power channel of rectangular shape

In one power plant, namely Ranganathaswamy SHP Station (see Table 1), the water flow in the power channel at about 20 m upstream of the intake gates was quite steady. The channel is lined and its geometry is well defined. This was the best available location for the measurement of total discharge through the turbines using a horizontal-beam ADCP. At this location an I-section beam was fixed to the right sidewall of the channel, as shown in Fig. 1, and the ADCP was mounted on the rail such that it could be moved up and down along it and held at desired elevations in the channel for taking the measurements.

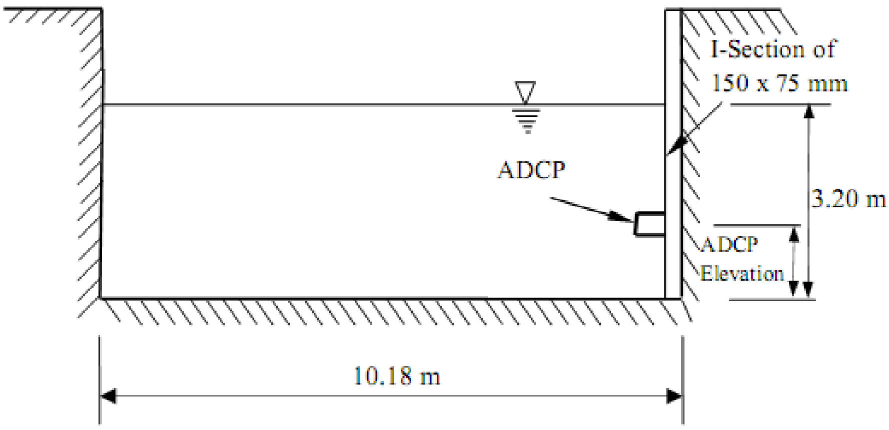


Fig. 1: Mounting rail for ADCP fixed to the right side wall of rectangular power channel of Ranganathaswamy SHP Station

During the efficiency test at 100% of rated load, the output of unit-1 was maintained as 8.25 MW. The flow profile was determined with the help of ADCP at five depths. A set of average velocity profiles measured at five depths is given in Table 2. This data was saved on a laptop computer and later used for calculating the absolute value of discharge. However for the efficiency test at 80% and 60% of the rated load, the profiles were taken only at 1.9 m depth from water surface (around 60% of total water depth) and the relative discharge value was obtained using index method at these part load conditions.

Table 2: Average velocity data obtained from ADCP in rectangular channel of Ranganathaswamy SHP station

Average flow velocity for each cell size of 0.5 m along the channel width starting from right sidewall, m/s																		
Depth, m	Unmeasured width	Distance of center of the measurement cell from right abutment, m																
	1.30	1.55	2.05	2.55	3.05	3.55	4.05	4.55	5.05	5.55	6.05	6.55	7.05	7.55	8.05	8.55	9.05	9.55
0.532	-	0.271	0.279	0.296	0.302	0.298	0.297	0.293	0.285	0.271	0.269	0.252	0.251	0.250	0.250	0.242	0.232	0.223
1.013	-	0.271	0.278	0.296	0.307	0.311	0.299	0.292	0.288	0.274	0.270	0.253	0.259	0.260	0.257	0.254	0.249	0.258
1.493	-	0.274	0.279	0.296	0.301	0.301	0.302	0.300	0.293	0.287	0.278	0.277	0.276	0.266	0.276	0.261	0.250	0.228
1.964	-	0.270	0.275	0.292	0.304	0.318	0.319	0.320	0.317	0.319	0.303	0.305	0.288	0.272	0.259	0.255	0.255	0.228
2.514	-	0.259	0.273	0.282	0.292	0.296	0.310	0.303	0.305	0.295	0.287	0.283	0.273	0.243	0.236	0.241	0.256	0.197

4.2 Power channel of trapezoidal shape

In Bassi Power Station (see Table 1), a horizontal-beam ADCP was mounted in the power channel, 845 m downstream of the intake point. At this location an I-section beam was fixed to the right side wall of the power channel of trapezoidal shape as shown in Fig. 2. The ADCP was mounted on the rail as discussed earlier. During discharge measurement process, ADCP readings were taken at four depths by moving it on the I-section beam. The velocity data from ADCP was directly saved on a laptop through a communication cable and later used for calculation of discharge.

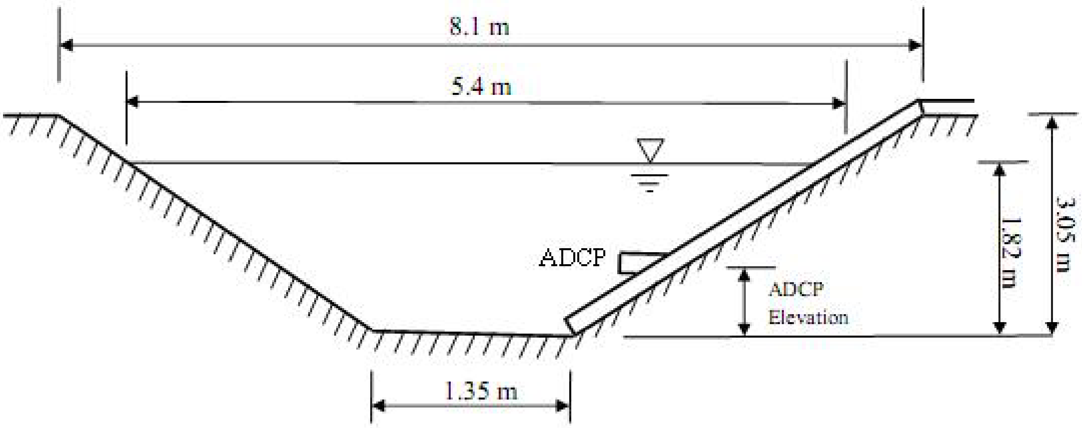


Fig. 2: Arrangement for ADCP Mounting in trapezoidal channel of Bassi Power Station

5. DISCHARGE CALCULATION

The horizontal-beam ADCP measures the velocity profile along the width of the channel and also the actual water depth at its orientation point. The profiler is accompanied by discharge computation software, which calculates the discharge by an index-velocity method. The index-velocity is the average velocity measured at the local area of the channel cross-section. The discharge is calculated by,

$$Q = AV \qquad \text{….. (1)}$$

where V= average channel velocity, m/s
A = wetted area of the channel cross-section, m^2

The average velocity is generally determined using a pre-defined nature of velocity profile and the geometry of the area can be input to the software in advance. However such method may have some error due to the following reasons:

(a) It estimates the average velocity based on the part of the channel width scanned by the profiler. Every profiler has a blanking distance which prevents it to measure velocity near the mounting wall. As the profiler is installed on the top flat surface of an I-section beam, the blanking distance can be as large as 1.3 m. Moreover, the bottom surface shear effect is neglected.
(b) The nature of velocity profile assumed in the software may not be true for the water flow through the channel.

In order to eliminate the above errors, following two methods have been used to calculate the discharge externally from the velocity data obtained from the ADCP:

(a) Velocity area integration method for rectangular measuring section
(b) Velocity area-segment method for other than rectangular measuring sections

5.1 Velocity area integration method

The average cell velocities measured with horizontal-beam ADCP are plotted along the water depth and a smooth curve through these points is drawn along each vertical, as illustrated in Fig. 3 (a). The curve is extended up to the free surface to estimate the free surface velocity. In addition, the velocity curve is extrapolated from the last measuring point to the bed (unmeasured zone) by calculating V_x from the power-law equation given below [IEC: 60041, 1991]:

$$V_x = V_a \left(\frac{x}{a} \right)^{\frac{1}{m}} \qquad \text{---------- (2)}$$

where V_x is the point velocity at a distance 'x' from the bed, and

V_a is the velocity at the last measuring point (at a distance **a** from the bed)

Generally the value of index 'm' lies between 2 and 7, but may vary over a wide range depending on the hydraulic resistance. The value m=2 applies to coarse beds or walls while m=10 is the characteristic of highly smooth metal surfaces.

The discharge through the measuring section is given by,

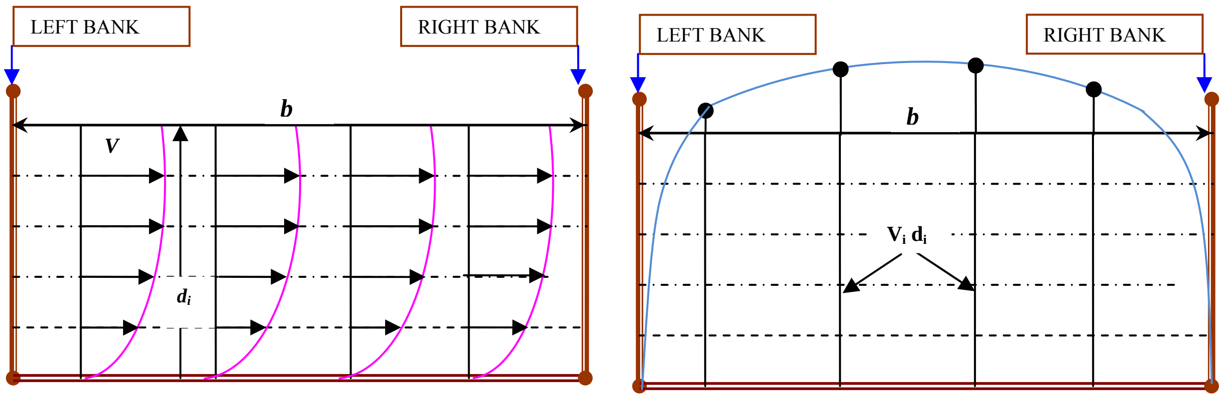
$Q = \int q \, .db,$ for mathematical integration

or $Q = \sum \overline{V_i} . d_i . \Delta b,$ for numerical integration ---------- (3)

where

Q is the total discharge in the open-channel, m^3/s
q is the unit-width discharge along a vertical line, m^2/s
db is the incremental width of the channel, m
$\overline{V_i}$ is the average velocity along the i^{th} vertical, m/s
d_i is the depth of water at the i^{th} vertical, m
Δb is the width of a vertical section, m

The average velocity $\overline{V_i}$ along each vertical is calculated from the average cell velocities V, see Fig. 3a. The unit-width discharge ($\overline{V_i}$.d_i) is plotted against the width, as shown in Fig. 3(b). This curve is extrapolated beyond the last measuring points upto the side walls using the power-law equation (2). Finally, the total discharge Q through the channel is determined by integrating the unit-width discharge curve with respect to the width of the channel as per equation (3).

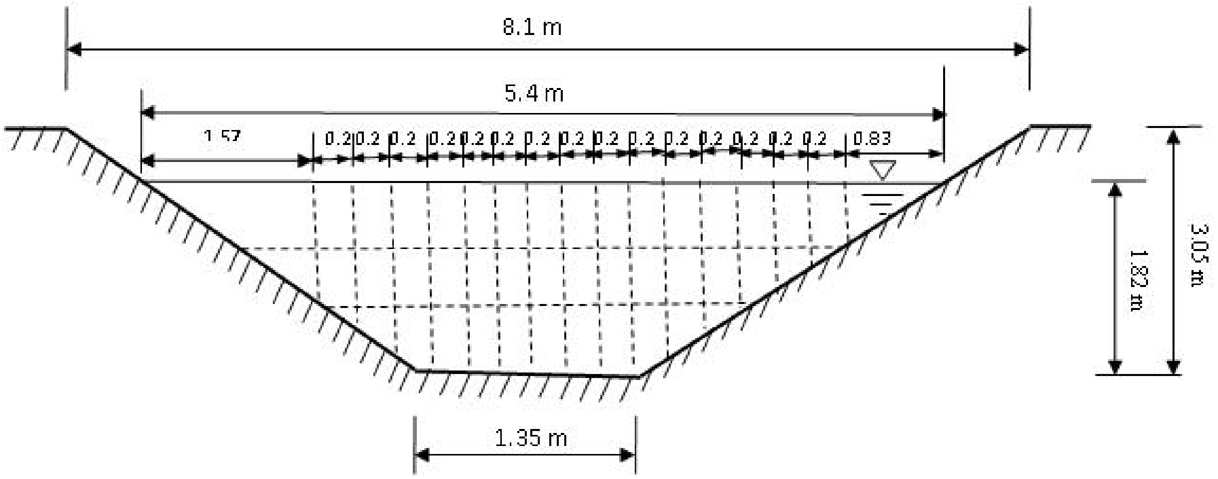


(a) Velocity profiles along the verticals **(b) Average velocity profile over channel width**

Fig. 3: Computation of discharge using velocity area integration method

5.2 Velocity area-segment method

This method can be used for other than rectangular-section channels, in which case the centres of the cells do not lie on a vertical. For example, in case of trapezoidal channel the channel width changes at each water depth and therefore the cell center position shifts. In such cases, the whole area is divided into a number of cells as shown in Fig. 4. The discharge is calculated for each cell as a product of its velocity and area. The discharge for the unmeasured width is calculated by extrapolating the velocity data near the walls using the power-law equation (2). These discharge values for each segment are added up to obtain the total discharge through the whole measuring section.



All dimensions in m

Fig. 4: Discretising the flow area for velocity area-segment method

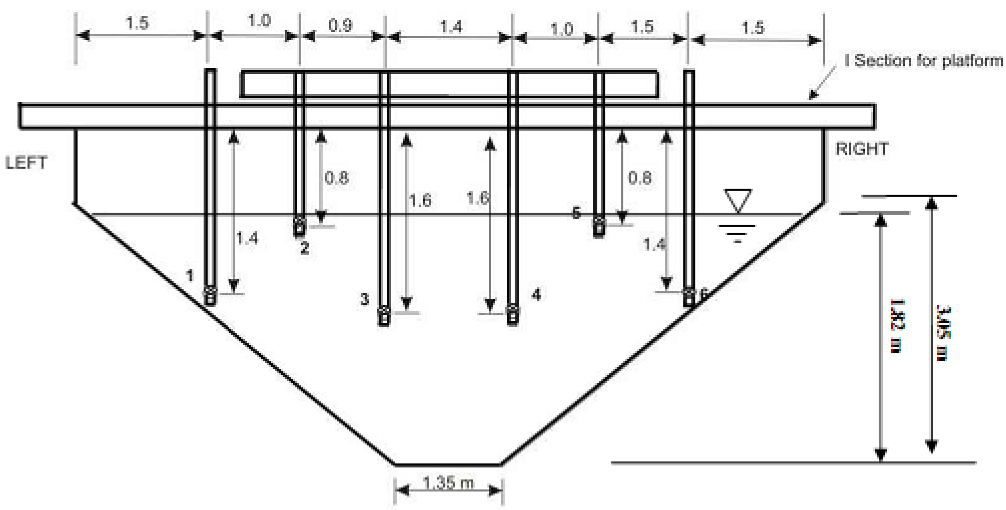
6. CASE STUDIES

The velocity profiles measured with ADCP in all the SHP stations listed in Table 1 were used to evaluate the discharge in each case as per above procedure. In the next section, the discharge values measured with two ADCPs are compared with the discharge measured with a matrix of current-meters in an open channel of trapezoidal shape. Then the discharge evaluation for two typical cases, namely, one rectangular channel and one trapezoidal channel, are discussed for illustration.

6.1 Comparison of discharge measured with two ADCPs and PCMs

Discharge through a trapezoidal power channel of Bassi hydropower station was determined by three methods, namely, panel of PCMs, horizontal-beam ADCP, and vertical-beam ADCP for cross verification. A summary of each method is discussed below:

(a) PCMs: Six PCMs were used for simultaneous measurement of flow velocity in the measurement section at 855 m downstream of the intake. As the channel is trapezoidal, the current-meters were placed at equidistance from the centerline of the channel. Two current meters were fitted near the banks on a fixed frame whereas four current meters were fitted on a movable frame, as shown in Fig. 4. The movable frame was traversed vertically to measure the velocities at five levels. This resulted in measurement of velocity at 22 current-meter locations in the channel.



(All dimensions are in m)

Fig. 5: Arrangements of Current-meters in fix and movable frame

(b) Vertical-beam ADCP: A vertical-beam ADCP of RD Instruments make (Rio Grande), with a specified accuracy of 0.25%, was used for determining the velocity profile in the channel at 840 m downstream of the intake and thence the discharge through the channel. The ADCP, mounted on a small boat, was moved from one bank to the other at the measuring section. A platform was made with the help of two I-section rails so as to guide the movement of the ADCP between these I-sections. The velocity data was acquired through communication with laptop using a radio modem.

(c) Horizontal-beam ADCP: A horizontal beam ADCP was mounted at 845 m downstream of the channel intake. A horizontal-beam ADCP of RD Instruments make (model 1200) with a specified accuracy of 0.5% was used at this location for determining the velocity profile. An I-section rail was fixed to the right side wall of the power channel and the ADCP was mounted on the rail such that it could be moved vertically up and down along the I-section. During the measurement process, the ADCP readings were taken at three different depths by moving it on the rail and then transferred to a laptop computer using RS-232 cable.

The discharge through the flow section was determined for a width of 2.8 m of the flow section at the middle of the channel scanned by vertical-beam ADCP and is compared with the discharge measured with PCMs, both using velocity area integration method. For comparison of discharge evaluated using the velocity measured with horizontal-beam ADCP and PCMs, the full area of flow section was considered, with maximum width at the top of the channel as 5.4 m (see Fig. 4). Velocity area-segment method was used. All the results along with estimated uncertainties are given in Table 3.

Table 3: Trapezoidal channel Discharge calculated by velocity area-segmentation method

Velocity measurement method	*Total velocity measurement points*	*Maximum width of the channel scanned by ADCP, m*	*Calculated discharge, m^3/s*	*Estimated uncertainty of discharge evaluation, %*
Panel of Current-meters	14	2.8	10.994	2.69
Vertical-beam ADCP	In-built program of the instrument with average of 18 readings	2.8	11.330	2.61
Panel of current-meters	14	5.4	14.990	2.69
Horizontal-beam ADCP	36	5.4	14.695	2.55

The discharge calculated from readings taken with PCMs and vertical–beam ADCP at the same time of measurement show a good match. The difference is approximately 3%, which is well within the total of the uncertainties of the two methods, that is 2.69% + 2.61% = 5.30%. Similarly, the discharge calculated with PCMs and horizontal-beam ADCP readings taken at the same time again match favorably. In this case, the difference is only about 2%, which is within the estimated uncertainty of either method.

6.2 Rectangular Channel

The velocity profiles obtained from the ADCP (see Table 2) were used for calculating the discharge through the rectangular shape power channel of Ranganathaswamy SHP station. Water was not available to run all three turbines installed in the power house and hence only one turbine was run at full load for measurement of the generating-unit efficiency. The measurement of average velocities over the flow section at five water depths took around 40 minutes and the load was maintained constant for this period to ensure steady state conditions. The average velocities measured at different points over the flow section, already given in Table 2, have been used to determine the partial unit-width discharge for each cell position. The depth of the water was also measured by placing a submersible pressure transmitter at either abutment of the channel. The average depth of water was determined as 2.72 m and the width of the channel was measured as 10.18 m. The unit-width discharge is plotted along the channel width as shown in Fig. 6, wherein the curve has been extended close to each wall using power law given by equation (2) with a power index 'm' value as 5. The discharge evaluated by this method is 8.270 m^3/s.

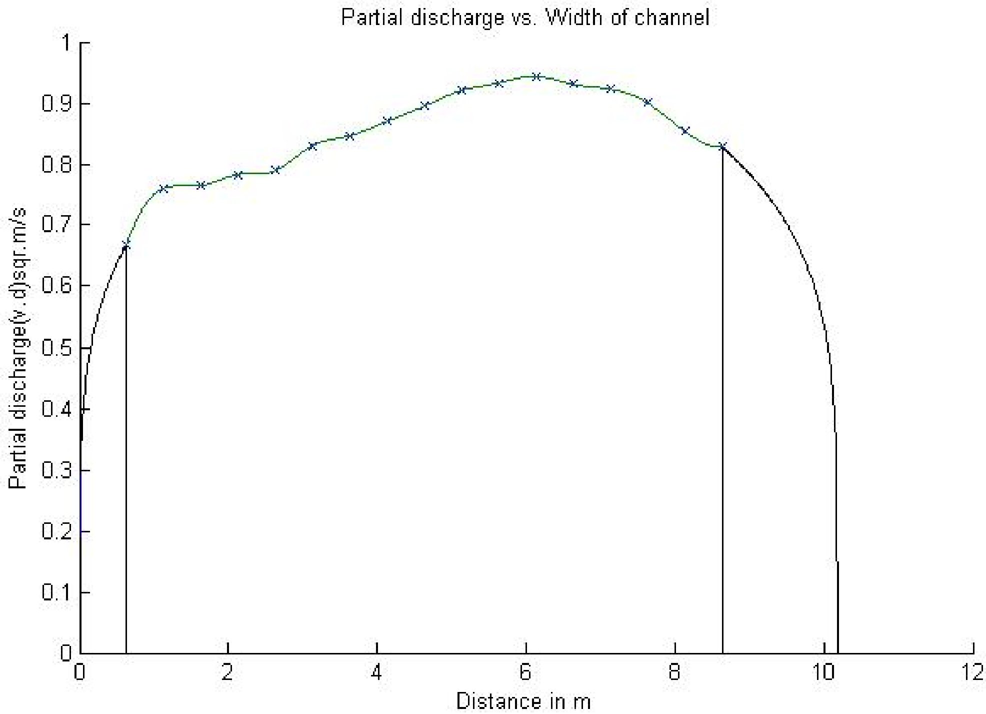


Fig. 6: Plot of unit-width discharge along channel width for Ranganathaswamy SHP station

6.3 Trapezoidal Channel

In Varahi Tailrace Power Plant, the water flow in the tailrace at few meters downstream of the draft tube exit was quite steady. The channel is lined and of trapezoidal shape (see Table 1). This was the best available location for the measurement of total discharge from the turbines. The horizontal-beam ADCP was used at this location for determining the flow profile and thence calculating the discharge in the channel. An I-section rail was fixed to the right sidewall of the tailrace for mounting the ADCP. During the efficiency test at the rated load, outputs of the three machines were maintained at 7.5 MW each. The flow profile was determined with the help of the ADCP at seven depths and the velocity profile readings were used for calculating the discharge through the channel by velocity area-segmentation method. Assuming that the three machines are identical and were running under identical conditions, one-third of the total discharge was taken as the discharge through each turbine, this was 20.91 m^3/s.

7. CONCLUSION

Based on the discharge measurement in 11 SHP stations using horizontal-beam ADCP, the following conclusions can be drawn:

(i) The horizontal-beam ADCP can be conveniently installed in an open channel and moved in the flow measurement section to determine the flow velocities at several water depths and thereby obtained the velocity profile in the section. Further, it can be installed in either the power channel or tail race channel depending on the conditions of channel and flow.

(ii) Software has been developed and successfully used for the evaluation of discharge from the velocity profile measured with ADCP in open channels. For rectangular channel, velocity area integration method is followed where as for trapezoidal channel the velocity area-segment method is more suitable.

(iii) The velocity profile in the unmeasured area between the bed/wall and the nearest measured point is determined by power law equation using suitable value of the power index based on the surface condition of the bed/wall. The free surface velocity is estimated by extrapolating the velocity profile along a vertical.

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