Comparative Discharge Measurement in Small Hydro Power Plants using different Methods

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Abstract

Discharge measurement has been carried out at two small hydro power (SHP) stations in India using different methods and compared their discharge and uncertainty. At Radhanagri SHP (2x5MW) at Radhanagri in District Kolhapur of, Maharashtra (India), horizontal- beam acoustic doppler current profiler (H-ADCP) in the tailrace channel and an ultrasonic transit- time flowmeter (UTTF) on the penstock were used for discharge measurement. At the second power station Nira-Deoghar SHP (2x3.5MW) Nigudhar in District Pune of Maharashtra state (India), a sharp-crested weir in the tailrace channel and an ultrasonic transit- time flowmeter (UTTF) on the penstock were used. Results from two different methods at each station are found very close, though discharge values with the weir and ADCP were found higher than the values obtained by UTTF method.

1. Introduction

Discharge measurement in hydro power station is an essential component of efficiency measurement. Various methods and instruments are used for the measurement of discharge e.g ultrasonic transit time flow meter and magnetic flow meter, acoustic Doppler current profiler, velocity- area method and flow measuring structures etc. However, use of such instruments is expensive, difficult, needs highly trained personnel and requires measurement of a number of parameters. Alternate Hydro Energy Centre (AHEC), Indian Institute of Technology Roorkee (IITR) have carried out performance testing of around 220 small hydro power (SHP) stations all over India where discharge measurement at each hydro power station has also been carried out. Among the SHP stations where efficiency measurement have been carried out, Radhanagri SHP (2x5MW) and Nira–Deoghar SHP(2x3.55MW) are in the district Kolhapur and Pune of Maharashtra, India respectively. Broad parameters of these SHP stations are given in Table 1.

Table1: Parameters of Radhanagri (2x5MW) and Nira- Deoghar (2x3.5 MW) power stations

Parameters	Radhanagri SHP	Nira–Deoghar SHP
No. of unit x Capacity (MW)	2 x 5	2 x 3.5
Unit Rated Discharge (m^3/s)	21.283	12
Rated Head (m)	28	28
Turbine type	Vertical Francis	Vertical Kaplan

2. Radhanagri SHP

At Radhanagri SHP H-ADCP and ultrasonic transit time flow meter have been used for measuring the discharge.

2.1. Discharge Measurement by H-ADCP

A horizontal-beam acoustic Doppler current profiler (H-ADCP) was installed in the tailrace, about 100 m downstream of the draft tube gates. The H-ADCP of RD Instruments make, model 1200kHz, with an accuracy of 0.5%, was used for determining the flow profile and to evaluate the discharge in the channel at different loads. A steel I-section (75x150mm) was fixed to the right side wall of the channel and the H-ADCP was mounted on the channel such that it could be slide up and down at desired depths in the channel. For discharge measurement, flow velocity was measured in a matrix of 4 x 29 points in the measurement section at 100% load. The discharge was calculated from these measurements by the velocity area integration method recommended in IEC-60041 using a software developed by IIT Roorkee. At other loads the velocity profile was measured at one depth (0.6 of water depth) and the discharge was calculated by indexing method. The discharge measurement section is a rectangular section with 15.5 m width and water depth of 1.35 m where the H-ADCP was installed. A photograph of installation is shown in fig 1.

Figure 1: ADCP Transducer sliding on the vertical I-section installed at tairace right side wall for discharge measurement at Radhanagri SHP

Velocity data at different depths and distances from right bank at different loads are given in Table 2 and Table 3:

Table 2: Velocity measured by H-ADCP at 100% load at Radhanagri SHP

Depth from free water surface (m)	0.2	0.45	0.65	0.9
Distance from right bank (m)	Average velocity from H-ADCP (m/s)			
0.95	0.2630	0.3699	0.2983	0.2327
1.45	0.3360	0.4107	0.3177	0.2327
1.95	0.4747	0.4705	0.3444	0.2169
2.45	0.5712	0.5657	0.4321	0.2111
2.95	0.6263	0.6834	0.4876	0.3037
3.45	0.6947	0.7762	0.6651	0.4065
3.95	0.8588	0.9002	0.8017	0.5410
4.45	1.0018	0.9926	0.9104	0.6585
4.95	1.0940	1.1061	0.9744	0.7114
5.45	1.1833	1.2154	1.0391	0.7800

5.95	1.2923	1.2723	1.1914	0.8515
6.45	1.3870	1.3683	1.3045	0.9221
6.95	1.3823	1.4464	1.3675	0.9821
7.45	1.3465	1.5258	1.4208	1.0591
7.95	1.3890	1.5610	1.4779	1.1367
8.45	1.4170	1.5690	1.4986	1.2021
8.95	1.4015	1.5244	1.5021	1.2544
9.45	1.3260	1.4933	1.4784	1.3027
9.95	1.2312	1.4570	1.4640	1.3239
10.45	1.1815	1.3520	1.4514	1.3219
10.95	1.1392	1.2903	1.4151	1.3098
11.45	1.1043	1.3288	1.3831	1.3041
11.95	1.0538	1.2866	1.3398	1.3091
12.45	1.0220	1.2483	1.3189	1.2731
12.95	1.0043	1.2197	1.2984	1.2361
13.45	0.9347	1.1922	1.2685	1.1815
13.95	0.9025	1.1084	1.1618	1.1106
14.45	0.6567	0.7541	0.7674	0.6414
14.95	0.0578	0.0853	0.0958	0.0828

Table 3: Velocity measured by H-ADCP at 60%, 80% and 110% load at Radhanagri SHP

Load (%)	60	80	110
Depth from free water surface (m)	0.65	0.65	0.65
Distance from right bank (m)	Average velocity from H-ADCP (m/s)		
0.95	0.9040	0.3018	0.3345
1.45	0.9107	0.3436	0.3302
1.95	0.9435	0.4109	0.3775
2.45	1.0079	0.4895	0.4450
2.95	1.0760	0.6010	0.5389
3.45	1.1484	0.6972	0.6321
3.95	1.1919	0.7698	0.7464
4.45	1.2266	0.8435	0.8332
4.95	1.2594	0.9319	0.8990
5.45	1.2690	1.0278	0.9585
5.95	1.2442	1.1153	1.0176
6.45	1.2163	1.1879	1.0993
6.95	1.1656	1.2516	1.1954
7.45	1.1090	1.3050	1.2498
7.95	1.0319	1.3495	1.2790
8.45	0.9511	1.3668	1.3300
8.95	0.8527	1.3622	1.3534
9.45	0.7385	1.3338	1.3298
9.95	0.6225	1.2978	1.3173
10.45	0.5160	1.2556	1.3008
10.95	0.4220	1.1917	1.2871
11.45	0.3338	1.1215	1.2682
11.95	0.2632	1.0224	1.2459
12.45	0.1958	0.9255	1.2100
12.95	0.1629	0.8336	1.1606
13.45	0.1642	0.7187	1.1004
13.95	0.1575	0.5868	1.0311
14.45	0.0870	0.3566	0.6476
14.95	0.1098	0.0737	0.1619

Computed discharge using H-ADCP are given in Table 4. Velocity-area integration method has been used for computing discharge at 100% load where relative discharge from velocity profile readings were taken at four depths. For the remaining loads, indexing method was used as the profile readings were taken at one depth only.

Table 4: Discharge measured by H-ADCP at Radhanagri SHP station

Load (%)	Water depth (m) in measuring section	Discharge (m3/s)
100	1.35	17.962
80	1.30	14.804
60	1.15	11.530
110	1.65	19.912

2.2 Discharge Measured by UTTF at Radhanagri SHP station

UTTF is normally used to measure water velocity due to its simple installation, no moving part, nonintrusive and non-obstructive measurements and it can be applied to different sizes of pipes. It consists of two transducers, which are an upstream transducer and a downstream transducer, and it measures water velocity using the difference of transit time between the sound signal traveling along and opposite to the flow direction. UTTF operates well, with clean and no particles in fluid, water, clear liquids and viscous liquids. However, many factors affect velocity measurement of ultrasonic flow meter, type of fluids, sound speed in fluid, flow characteristics, pipe characteristics (roughness, type of materials, coating and diameter) straight length of pipe before and after flow meter, and installation of upstream and downstream transducers. Shorter length of straight pipe leads to increase the error in measurement.

Intrusive type UTTFs are more accurate and which are included in IEC standards [IEC 60041(1991) and IEC 62006(2010)]. However drilling of the penstock is required and it is expensive for SHP station owners for carrying out such exercise for small hydro power plants.

A small length of the exposed penstock (2.5m dia.) just before main inlet valve (MIV) was selected for installing the UTTF at Radhanagri (2x5MW) SHP station. A UTTF of GE sensing make (model D-868) was used at the station. The pair of transducers of this flowmeter was fixed in direct mode as short length of the penstock did not permit fixing in reflection mode (Fig 2.). Readings of the UTTF, averaged over 120/60 seconds period by the instrument, were taken at regular intervals over the duration of 15 minute at each load. Average values of the readings were used to calculate turbine efficiency and are given in Table 5.

Figure 2: Ultrasonic Transit Time Flowmeter installed on penstock for Discharge Measurement

Table5: Discharge measured by UTTF at Radhanagri SHP station

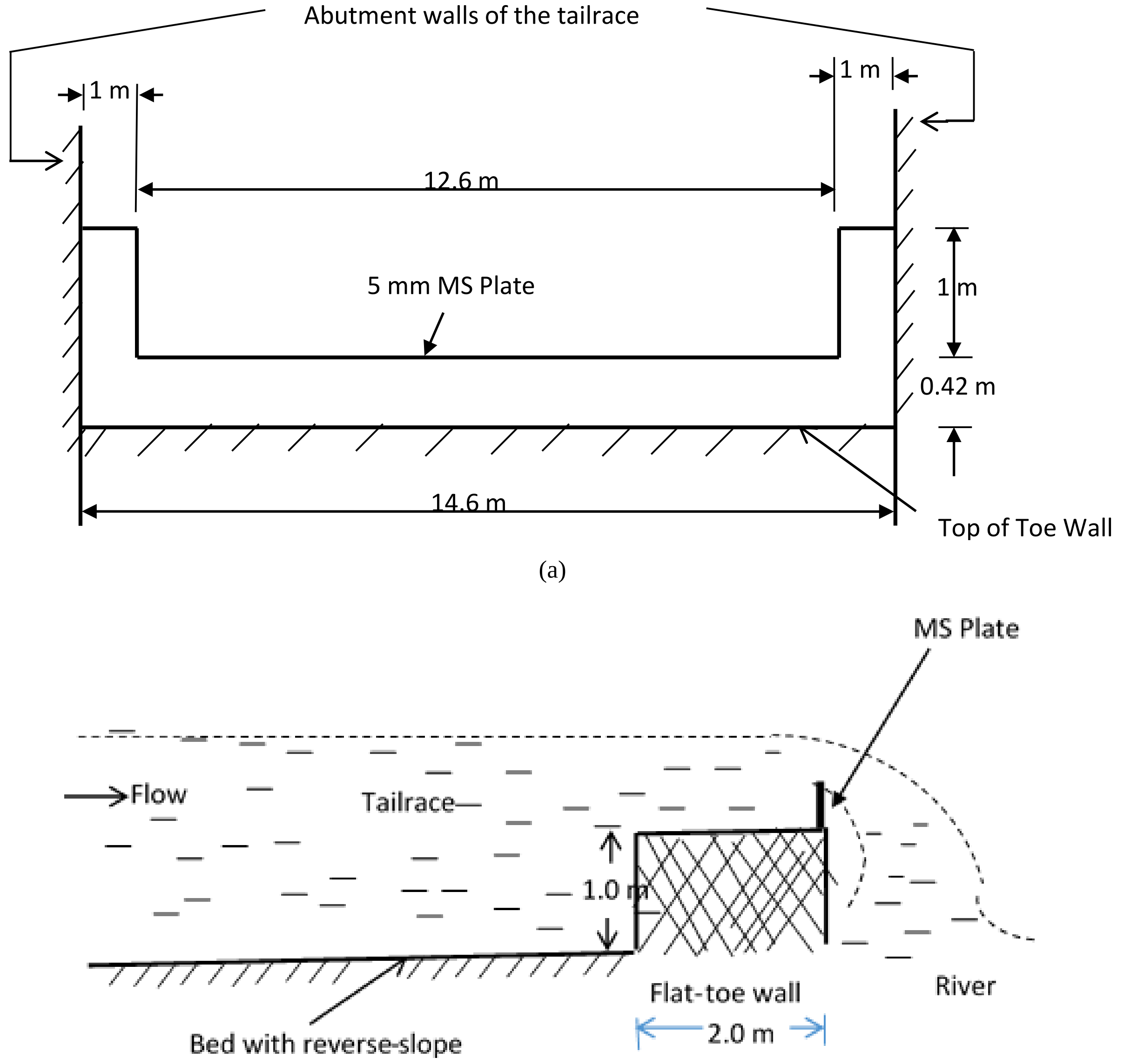
S.No.	**Discharge(m^3/s)**			
	Load (%)			
	100	**80**	**60**	**110**
1	17.835	14.275	11.392	19.503
2	17.571	14.964	11.421	19.608
3	18.100	14.995	12.414	19.873
4	18.033	14.932	11.893	19.942
5	17.771	14.941	11.602	19.988
6	17.534	14.987	11.795	19.730
7	18.026	15.235	11.752	19.840
8	17.514	14.980	11.644	19.815
9	18.428	14.584	11.699	19.731
10	17.957	14.640	11.635	19.525
11	17.857	14.702	11.777	19.585
12	17.665	14.960	11.972	19.364
13	17.555	14.841	11.342	19.143
14	18.399	14.810	11.862	20.002
15	17.494	14.770	11.416	19.856
Average	**17.849**	**14.841**	**11.708**	**19.700**

3. Nira- Deoghar SHP

At Nira-Deoghar SHP sharp crested weir and ultrasonic transit time flowmeter have been used for measuring the discharge. The test was conducted on the generating unit at 77%, 70%, 60%, 50% and 40% of the rated load, in that order. It could not be carried out as per practice over the range of 110% to 60% of the rated load because of limited water head available.

3.1 Discharge Measurement by using Sharp-Crested Weir

A sharp-crested weir was installed at the end of the tailrace on flat toe wall of width 2 meter from where it has a free water fall to the stream. The weir was made of 5 mm thick mild steel plate as shown in Fig. 3. The plate was chamfered at the downstream edge at 45^0(approx.) as prescribed in IEC-60041.



(a)

(b)

Figure3: Dimensions of (a) the Sharp-Crested Weir installed at (b) the flat toe wall at end of Tailrace for discharge measurement at Nira-Deoghar SHP

The water level over the weir was measured using two ultrasonic level sensors installed at the abutment walls of the tailrace at about 1.5m upstream of weir. The readings were taken at every minute for fifteen minutes and the mean head over the weir was determined from the average readings of the two ultrasonic level sensors.

The formula used for calculating discharge is given in Eq. (1).

$$Q = \frac{2}{3} Cb \sqrt{2g} h^{3/2} \qquad \text{…………… (1)}$$

Where;

Q is the discharge (m^3/s)

C is the discharge coefficient
b is the width of the weir crest (perpendicular to the flow) (m)
g is the acceleration due to gravity (m^2/s)
h is the measured water depth over the weir (m)
B is width of weir (m)

The crested weir has side contraction with b/B = 0.863 and accordingly the following value of discharge coefficient has been used:

$$C = 0.611 + 0.075\,(h_e/p_e) \qquad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where;

h_e = effective value of the head over weir (h) + velocity head
p_e = effective value of the height of weir
= (1.0 + 0.42) / 2
= 0.71 m

Discharge measured by sharp-crested weir at different loads is given in Table 6.

Table 6: Discharge measured by sharp-crested weir at different loads at Nira- Deoghar SHP station

Load (%)	Water depth over weir, h (m)	Velocity head (m)	Effective head, h_e (m)	Value of Coefficient C	Discharge, Q (m^3/s)
77	0.615	0.0270	0.642	0.679	12.990
70	0.580	0.0236	0.604	0.675	11.773
60	0.530	0.0192	0.549	0.669	10.130
50	0.480	0.0152	0.495	0.663	8.600
40	0.430	0.0117	0.442	0.658	7.184

3.2 Discharge Measurement by Ultrasonic Transit Time Flowmeter (UTTF) at Nira-Deoghar SHP

Discharge was measured using UTTF with transducers fixed in direct mode on the small straight length of the penstock (2m dia) of unit-1 just after it entering the power house building (Fig. 4). Readings of the UTTF were taken at an interval of one minute over the 15 minutes of test duration at each load. Discharge measured by UTTF is given in Table 7.

Figure 4: Ultrasonic Transit Time Flowmeter installed on penstock for Discharge Measurement

Table 7: Discharge measured by UTTF at Nira-Deoghar SHP station

	Discharge (m^3/s)

S.No.	Load (%)				
	77	**70**	**60**	**50**	**40**
1.	12.670	11.352	9.970	8.426	6.862
2.	12.670	11.313	10.081	8.502	6.920
3.	12.475	11.427	9.970	8.359	6.950
4.	12.460	11.330	10.040	8.398	6.870
5.	12.520	11.508	9.962	8.450	6.901
6.	12.502	11.539	10.087	8.475	6.892
7.	12.410	11.331	9.828	8.470	6.912
8.	12.620	11.515	10.123	8.492	6.901
9.	12.672	11.319	9.929	8.409	6.927
10.	12.593	11.349	9.942	8.497	6.921
11.	12.629	11.404	9.960	8.470	6.897
12.	12.640	11.418	9.971	8.412	6.879
13.	12.621	11.428	9.763	8.465	6.910
14.	12.651	11.335	9.973	8.433	6.875
15.	12.616	11.444	9.969	8.452	6.871
Average	**12.583**	**11.401**	**9.971**	**8.447**	**6.899**

4. Uncertainty in Discharge Measurement by different methods

4.1 Uncertainty in Discharge Measurement by UTTF

Total uncertainty in discharge measurement by UTTF is given as Eq. (3)

$$f_n = \pm\sqrt{{f_{E_m}}^2 + {f_E}^2} \qquad \ldots\ldots\ldots\ldots (3)$$

f_n is the total uncertainty in discharge measurement, expressed as a percentage
f_{E_m} is the systematic uncertainty
f_E is the random uncertainty

The systematic uncertainty is given as Eq. (4)

$$f_{E_m} = \pm\sqrt{{u_e}^2 + {s_e}^2} \qquad \ldots\ldots\ldots\ldots (4)$$

u_e is the uncertainty in average velocity measurement by UTTF with
Transducers fixed in direct mode = ± 1.5 %
s_e is the uncertainty in cross- sectional shape and dimensions of penstock = ± 1.01 %

The random uncertainty is given as Eq. (5)

$$f_E = \pm\frac{s_q}{\sqrt{n}} \qquad \ldots\ldots\ldots\ldots (5)$$

s_q is the standard deviation in the discharge measurement
n is number of measurements

Random uncertainty, systematic uncertainty and total uncertainty calculated from Eq. (3), Eq. (4) and Eq. (5) at different loads for discharge measurement by UTTF at Radhanagri and Nira -Deoghar SHPs are given in Fig. 5 and Fig. 6 respectively.

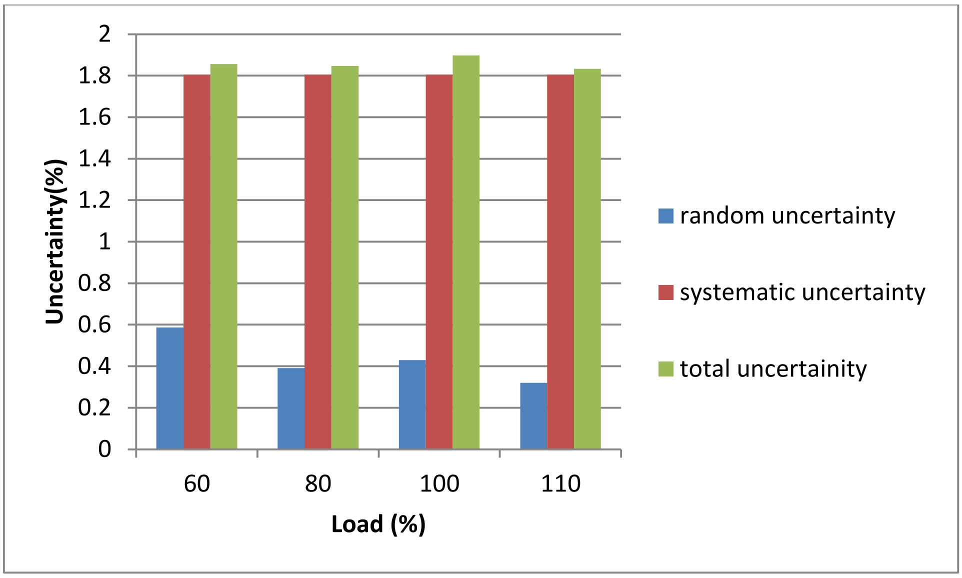


Figure 5: Uncertainties in discharge measurement at Radhanagri SHP

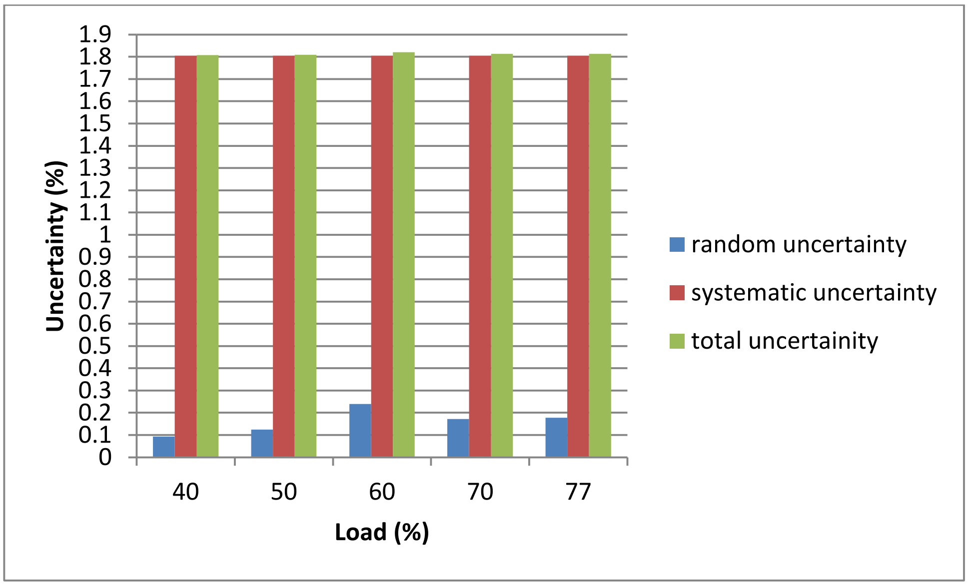


Figure 6: Uncertainties in discharge measurement at Nira-Deoghar SHP

4.2 Uncertainty in Discharge Measurement by H- ADCP

Uncertainty in velocity profile measurement with H-ADCP = ± 0.5 %
Uncertainty of average velocity assessment from velocity profile = ± 0.5 %
Uncertainty in measurement of width of channel = ± 1.0 %
Uncertainty in measurement of depth of water = ± 1.0 %

Therefore, uncertainty in discharge measurement with H-ADCP at 100% load is given as Eq. (6)

$$f_q' = \sqrt{0.5^2 + 0.5^2 + 1.0^2 + 1.0^2} \qquad \ldots\ldots\ldots \ (6)$$

$= \pm 1.58$ %

Additional uncertainty in discharge measurement at other loads due to indexing

$= \pm 1.0$ %

Therefore, uncertainty in discharge measurement with H-ADCP at other loads is given as Eq. (7)

$$f_q' = \sqrt{0.5^2 + 0.5^2 + 1.0^2 + 1.0^2 + 1.0^2} \qquad \text{------------- (7)}$$

$$= \pm 1.87\ \%$$

4.3 Uncertainty in Discharge Measurement by Sharp-Crested Weir

Uncertainty in discharge measurement by sharp- crested weir is given as Eq. (8) [ISO 1438 (2017)]

$$x_{q_r} =\pm \sqrt[2]{x^2{}_{c_e} + x^2{}_{b_e} + 1.5^2 x^2{}_{h_e}} \qquad \text{……….. (8)}$$

x is the uncertainty, expressed as a percentage;

x_q is the uncertainty in the calculated value of the discharge;

x_{c_e} is the uncertainty in the coefficient of discharge;

x_{b_e} is the uncertainty in the effective width for a rectangular weir;

x_{h_e} is the uncertainty in the effective head.

The uncertainty in effective width (b_e) is given as Eq. (9)

$$x_{b_e} = \pm\frac{100\sqrt{{e_b}^2+e_{kb}^2}}{b} \qquad \text{………. (9)}$$

In which

e_b is the uncertainty in the measured width;

e_{k_b} is the uncertainty in the width correction factor.

The uncertainty in effective head (h_e) is given as Eq. (10)

$$x_{h_e} = \pm\frac{100\sqrt{{e_h}^2+e^2{}_{h_o}+e^2{}_{k_h}+(2S_h)^2}}{h} \qquad \text{……….. (10)}$$

e_h is the uncertainty in measured head;

e_{h_o} is the uncertainty in the gauge zero;

e_{k_h} is the uncertainty in head correction factor;

$2S_h$ is the uncertainty in the mean of n readings of the head.

The uncertainty in a discharge measurement made with a rectangular weir under the following condition: b=12.6m; p= 0.42m; h=0.615m; standard deviation based on readings= 0.05mm.

Uncertainty given in this calculation

Coefficient of discharge $x_{c_e} = \pm 1.5\%$

Head correction $e_{k_h} = \pm 0.30$mm

Width correction $e_{k_b} = \pm 0.030$mm

Uncertainty estimated by the user

Head $e_h = \pm 10.0$mm

Head gauge zero $e_{h_o} = \pm 0.30$mm

Standard deviation $2S_h = \pm 2.26$mm

Width $e_b = \pm 1.0$mm

The uncertainty in b_e, from equation (9)

$$x_{b_e} = \pm\frac{100\sqrt{1.0^2 + 0.030^2}}{12600}$$

$$= \pm\ 0.00794\%$$

The uncertainty in h_e, from equation (10)

$$x_{h_e} = \pm \frac{100\sqrt{10.0^2 + 0.30^2 + 0.30^2 + (2.26)^2}}{615}$$

$= \pm 1.668\%$

The uncertainty in discharge measurement by sharp crested weir, from equation (8)

$$x_{q_r} = \pm \sqrt{1.5^2 + 0.00794^2 + 1.5^2 * 1.668^2}$$

$= \pm\ 2.917\%$

5. Comparison of discharge measurement by using different methods

A comparison of discharge measurements by H-ADCP and UTTF used at Radhanagri SHP and UTTF and weir used at Nira-Deoghar SHP, is given in Table 8 and Table 9 respectively. Values of flow from UTTF method are found to be less than the flow values measured by weir method**.**

Table 8: Comparison of discharge measured by UTTF and ADCP at Radhanagri SHP

Load (%)	Discharge Measurement (m^3/s)				Difference	
	H-ADCP	Uncertainty (%)	UTTF	Uncertainty (%)	Discharge (m^3/s)	%
100	17.962	1.87	17.849	1.90	0.113	0.633
80	14.804		14.841	1.85	0.037	0.249
60	11.530		11.708	1.86	0.178	1.520
110	19.912		19.700	1.83	0.212	1.076

The difference in discharge measurement is on an average of 0.87% of discharge computed from repeated measurement.

Table 9: Comparison of discharge measured by UTTF and Weir at Nira- Deoghar SHP

Load (%)	Discharge Measurement (m^3/s)				Difference	
	H-ADCP	Uncertainty (%)	UTTF	Uncertainty (%)	Discharge (m^3/s)	%
77	12.990	2.917	12.583	1.81	0.407	3.23
70	11.773		11.401	1.81	0.372	3.26
60	10.130		9.971	1.82	0.159	1.59
50	8.600		8.447	1.81	0.153	1.81
40	7.184		6.899	1.81	0.285	4.13

The difference in discharge measurement on an average of 2.8% of discharge computed from repeated measurement.

4. Conclusions

Discharge measured by UTTF at two small hydro power stations has been compared with the different methods at the same SHP stations under same conditions. Uncertainty of discharge measurement by UTTF, ADCP and sharp crested weir are found to be as 1.90%, 1.87% and 2.917% respectively. Discharge measured by UTTF is found to be less than the discharge measured by ADCP and sharp crested weir at respective SHP station. Further discharge measured using sharp crested weir at Nira- Deoghar SHP is around 2.8% more than the discharge measured by UTTF and at Radhanagri SHP and discharge measured by ADCP is around 0.87% more than the discharge measured by UTTF.

5. Acknowledgement

The support from Ministry of New and Renewable Energy, Govt. of India for the initiative of getting SHP stations duly tested and getting instruments and project owner for sponsoring the testing costs is thankfully acknowledged. The contributions of all team members namely Prof H K Verma, Dr. Manoj Tripathi, Mr. S.S. Patnaik, Mr. Dependra Kumar and Mr. AS Addi for taking the field observations are sincerely acknowledged.

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