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Examining Engineering Estimations in ascertaining Flood Force on River Intake Structures

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ABSTRACT: Flood force is a significant force in the design of River Intake Structures and is computed based on flow velocity, together with flood depth and scour depth, which helps calculate the drag forces. Standards provide detailed specifications for the computation of design flood and arising mean scour depth but do not give a simple, straightforward approach for estimating the requisite values of 'flood depth' and 'flow velocity'. Standing practice is to evaluate flood depth based on notional methods such as local investigation of past observations and using hypotheses to estimate flow velocity. A higher estimated value of flood force leads to increased cost of the hydraulic structure, and an under-estimated value is liable to place the structure at risk. This paper examines how Rating curves are an indispensable analytical tool for the correct assertion of flood force and its drag using information about the river's stage, flow velocity and discharge.

KEYWORDS: Flood force, Flood depth, Scour depth, Design flood, Flow velocity, Rating curves.

I. INTRODUCTION

The design flood is the largest flood selected depending on the standard of security that should be provided to the structure based on its importance and the consequences of its failure. Engineers essentially require the design flood for the Highest Flood Level (HFL) that will be able to pass the maximum flood discharge.

The design flood estimation depends on river flow data availability for the catchment. For ungauged locations with no runoff data and where discharge data of gauging stations in upstream, downstream or adjacent catchments is unavailable, it poses difficulty to propose a uniform and standard hydrological practice for the assessment of design flood. In such a situation, regional methods based on a hydro-meteorological approach involving the use of Empirical and Rational formulae are adopted.

Flood force (P), *i.e. the intensity of pressure due to water currents on a structure*, is a function of flow velocity (V). It is $P = 52 KV^2$, where K is a constant based on the shape of the structure parallel to the direction of the water current.

The pressure is directly proportional to the square of the velocity. Consequently, any error in the estimation of flow velocity would possibly result in an enhanced error in regard to the flood force. As the drag due to flood will act over the full depth of the intake structure from HFL to the mean scour depth, any error in the estimation of flood depth will result in a correlative error in the assessment of drag due to flood forces.

Following the methods outlined in standards, detailed specifications for the computation of design flood and arising mean scour depth are provided. Still, they do not have a straightforward approach for estimating the requisite values of 'flood depth' and 'flow velocity'.

The prevalent practice is to evaluate the flood depth based on the study of physical features near the river by finding the signs of high flood marks left on structures, records of the department of bridge & roads, and adding margin over those observations. For flood velocity, the hypothesis assumes a pace of about 3 m/s for large rivers and up to 5 m/s for small flashy rivers.

Fortunately, a relationship exists where the river stage, velocity and discharge information can be utilised to ascertain the values of 'flood depth' and associated 'flow velocity' using Rating curves*. These are established by computing the

river channel hydraulics to find mean flow velocity and discharge gradually for each portion of the cross-section, starting from the river bed and advancing to a higher level at the location of the intake structure.

The values are plotted in rectangular coordinates, where the measured discharge is in the abscissa against the corresponding stage for the 'Stage-Discharge curve', and velocity is the ordinate for the 'Velocity-Discharge curve'. These curves are then used to get the correct estimate of the 'flood depth' and 'flow velocity'.

**Rating curve at a particular river cross-section is a complicated interaction of channel characteristics depending upon the longitudinal slope of the river, channel geometry, cross-section, bed roughness, expansions and restrictions in the channel, and vegetation cover.*

II. LITERATURE REVIEW

Indian Roads Congress, Standard Specifications and Code of Practice for Road Bridges, "Section: I General Features of Design", IRC: 5-2015 (Eighth Revision), estimating maximum design flood and rating curves [1].

Indian Roads Congress, Standard Specifications and Code of Practice for Road Bridges, "Section: II Loads and Load Combinations", IRC: 6-2017 (Seventh Revision), calculating flood force [2].

Indian Roads Congress, "Guidelines of Road Drainage", IRC: SP:42-2014 (First Revision), approximating maximum flood discharge using empirical and rational formulae. [3].

India Meteorological Department, "Atlas of Statewise Generalised Isopluvial (Return Period) Maps of India (Part - I to IV)", area-specific rainfall maps of different return durations [4].

Survey of India, Department of Science & Technology, "Statewise Open Series Maps of India" (Scale 1:50,000), examining catchments [5].

Indian Roads Congress, Standard Specifications and Code of Practice for Road Bridges, "Section: VII Foundation and Substructure", IRC: 78-2014 (Revised Edition), determining mean scour depth [6].

III. EXPERIMENTAL EXAMINATION

Estimation of Design Maximum Flood Discharge

1. Empirical Method

Empirical formulae are determined attempts to arrive at an elementary form of interrelations for the highest flow on the river by selecting factors of decisive importance for the correlation study.

Dicken's Formula [IRC: SP:42-2014, Clause 6.4.1]

$$Q = CA^{3/4}$$

(Eq. 1)

Where;

Q = Maximum flood discharge (m^3/s)

C = Dicken's constant (Based on discharge observations at various regions in India)

A = Catchment area (km^2)

Empirical formulae do not consider the essential meteorological, physiographic and hydrological factors of rainfall components differing between catchments, which have an influential role in the flood formation process. They cannot be used to estimate floods of various frequencies. Also, the selection of constants is left to the engineer's insight, thus involving subjectivity.

2. Rational Method

The rational formula is an effort to estimate the design flood that would occur due to rainfall of a given frequency and for a specified duration.

Rational Formula [IRC: SP:42-2014, Clause 6.4.2]

$$Q = 0.278 CIA$$

(Eq. 2)

Where;

Q = Maximum flood discharge (m^3/s)

C = Runoff coefficient represents the ratio of the runoff volume to that of the rainfall.

I = Uniform rate of rainfall intensity (mm/h)

A = Catchment area (km^2)

Rainfall intensity can be obtained from area-specific Intensity-duration-frequency curves. The highest flow from a given rain occurs after a time equal to the time of concentration for the catchment calculated using the Kirpich equation. As the units of the quantities in the formula are numerically consistent, thus it is called Rational.

The below problem statement will attempt to show the estimation of design maximum flood for an ungauged location and puts forward an explanation for the determination of 'mean flow velocity' and 'stage' at discharge which may contribute to the better assertion of flood force on river intake structures.

PROBLEM STATEMENT: COMPUTATION OF DESIGN MAXIMUM FLOOD FOR UNGAUGED LOCATION

Catchment Area: 10,000 km^2 (*Open Series Maps of India, Survey of India, Department of Science & Technology*)

Catchment Location: Central India (Coastal Andhra and Orissa)

$$Dicken's\ constant = 28$$

$$Runoff\ coefficient = 0.62$$

Rainfall Intensity: 14.24 mm/hr (*Iso-pluvial maps of India, India Meteorological Department*).

The following values of design flood are obtained by Empirical & Rational formulae:

(a) **Maximum flood discharge by Dickens Formula:**

$$Q = CA^{3/4} = 28 \times (10000)^{3/4} = 28000\ m^3/s$$

(b) **Maximum flood discharge by Rational Method:**

$$Q = 0.278 CIA = 0.278 \times 0.62 \times 14.24 \times 10000 = 24544.06\ m^3/s$$

Design Maximum Flood (Maximum of (a) & (b)) = 28000 m^3/s

In accordance with the standard procedure, Cross-sectional Data for the river is gathered, which is particularly important and will be useful to examine the open channel hydraulics to establish 'mean flow' and 'discharge' for each stage.

This allows us to plot the 'Stage-Discharge Curve' and 'Velocity-Discharge Curve', which can be used to evaluate 'flood depth' and 'flow velocity'.

Computation of Cross-sectional Data

The site's cross-sectional flow area, wetted perimeter, hydraulic radius for all stages, slope (0.00075) and previously observed maximum flood level (286.90) were determined by surveys. The mean flow velocity (V) for each stage was computed using *Manning's Formula [IRC: SP:42-2014, Clause 7.2.1]*

$$V = 1/n R^{2/3} S^{1/2} \quad (\text{Eq. 3})$$

Where;

V = Mean flow velocity (m/s)

n = Manning's roughness coefficient*

R = Hydraulic radius (m) = Area of flow cross-section divided by wetted perimeter

S = Slope of the river bed

*The coefficient of Manning's 'n' was taken to be 0.03 based on the physical features of the river having a mountainous stream, with no vegetation in the channel, and banks having a steep bottom with gravel, cobbles and few boulders.

Discharge was obtained as the product of mean flow velocity and the corresponding cross-sectional flow area, as shown in Table 1.

Table 1. Computation of river channel hydraulics for mean flow velocity and discharge

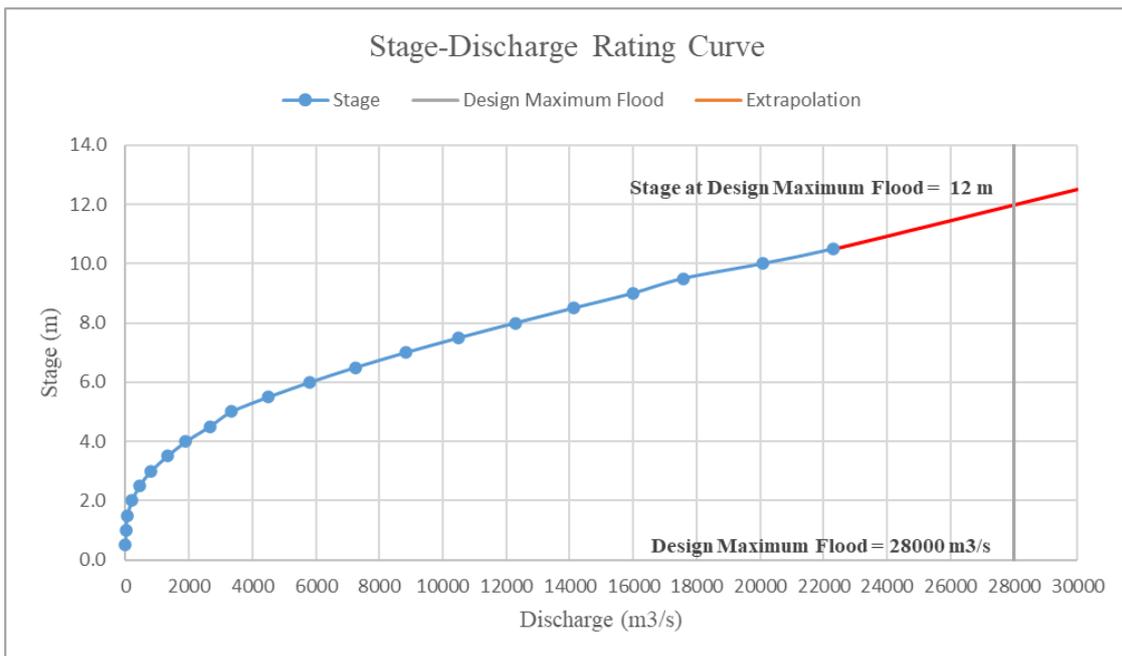
Level (m)	Stage (m)	Area of Flow Cross- Section (m ²)	Perimeter (m)	Length (m)	Wetted Perimeter (m)	Hydraulic Radius (m)	Mean Flow Velocity (m/s)	Discharge (m ³ /s)
275.50	0.5	1.57	34.84	17.42	17.43	0.090	0.182	0.29
276.00	1.0	25.73	121.58	60.78	60.80	0.423	0.513	13.21
276.50	1.5	100.48	430.81	215.37	215.43	0.466	0.548	55.02
277.00	2.0	237.44	527.36	272.90	254.46	0.933	0.871	206.92
277.50	2.5	427.75	721.95	360.89	361.05	1.185	1.023	437.45
278.00	3.0	653.00	832.20	415.99	416.21	1.569	1.234	806.07
278.50	3.5	900.19	892.36	446.05	446.31	2.017	1.461	1314.88
279.00	4.0	1166.29	974.86	487.27	487.60	2.392	1.637	1909.75
279.50	4.5	1453.23	1030.04	514.78	515.26	2.820	1.829	2657.35
280.00	5.0	1813.93	1274.09	636.69	637.40	2.846	1.840	3336.94
280.50	5.5	2180.13	1286.25	642.65	643.59	3.387	2.067	4507.18
281.00	6.0	2549.75	1298.42	648.63	649.79	3.924	2.281	5817.06
281.50	6.5	2922.79	1310.58	654.60	655.98	4.456	2.484	7260.66
282.00	7.0	3299.26	1322.75	660.58	662.17	4.982	2.677	8833.13
282.50	7.5	3679.47	1339.10	668.64	670.45	5.488	2.856	10510.05
283.00	8.0	4065.06	1358.84	678.41	680.43	5.974	3.024	12291.01
283.50	8.5	4457.29	1390.45	694.09	696.36	6.401	3.167	14114.32
284.00	9.0	4860.44	1434.24	716.14	718.10	6.768	3.287	15977.70
284.50	9.5	5286.73	1533.07	765.05	768.03	6.884	3.325	17576.35
285.00	10.0	5698.66	1516.39	756.64	759.75	7.501	3.522	20067.88
285.50	10.5	6187.98	1592.04	794.25	797.79	7.756	3.602	22286.03

The range of levels (285.50) over which gauging is carried out does not cover the entire range of observed maximum flood levels (286.90) due to their infrequent occurrences and the inherent difficulty of these measurements; thus, extrapolation* of rating curves is required. Severe flows are principal for design, and optimal estimates must be made.

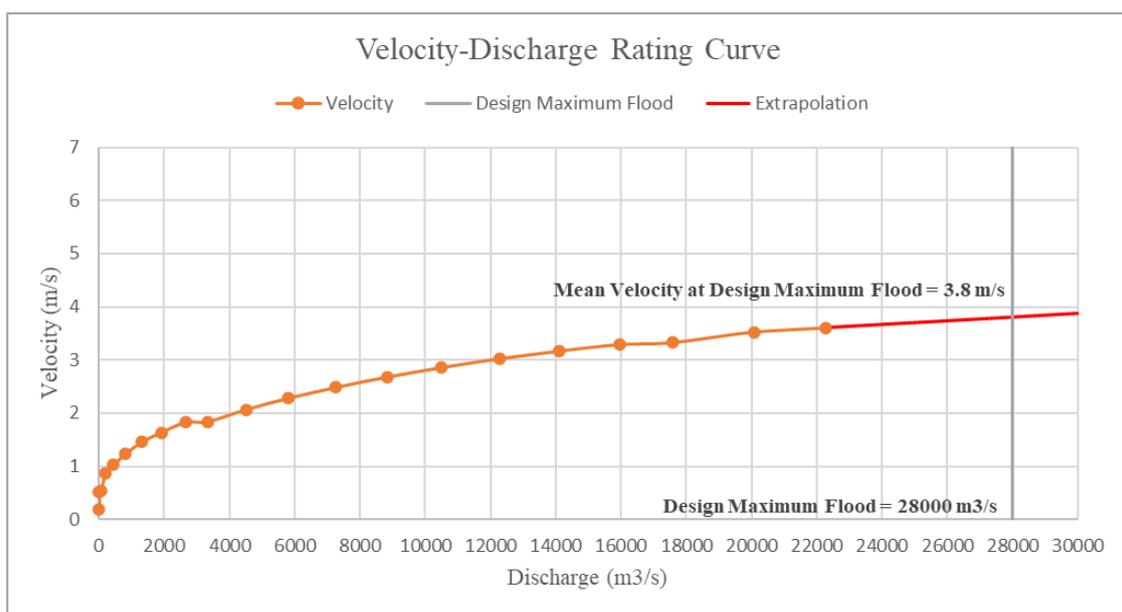
For stable controls, with a fairly steady flow, where the bed of the river and other hydraulic characteristics of the channel do not change much beyond the measured range, a simple extrapolation of the stage-discharge and velocity-discharge rating curves may be separately applied.

**Extrapolation is not simply a question of extending the rating from existing gauging to extreme levels; a different control may apply, the channel geometry may change, the flow may occur over the floodplain, and vegetation roughness coefficients may change.*

From the calculations presented in **Table 1**, The Stage-Discharge and Velocity-Discharge rating curves are illustrated in **(Fig.1)** and **(Fig.2)**. These curves had to be extended to cover the design maximum flood, which is about 2 m above flood plain level.



(Fig.1) Graphical illustration of Stage-Discharge Rating Curve



(Fig.2) Graphical illustration of Velocity-Discharge Rating Curve

IV. RESULTS AND DISCUSSIONS

Based on the results of the above rating curves, the correct ascertained value of flood depth is 12 m above the River Bed Level of 275.50 m (HFL = 275.50 m+ 12 m = 287.50 m) and flow velocity is 3.80 m/s, for the design maximum flood of 28000 m³/s. The values of HFL are proportional to the previously observed maximum flood level (286.90 ~ 287.50).

FLOOD FORCE INTENSITY ON RIVER INTAKE STRUCTURE [IRC: 6-2017, Clause 210]

$$P = 52 KV^2$$

(Eq. 4)

Where;

P = Flood force (kg/m²)

K = Constant for different shapes (for circular structures, $K = 0.66$)

V = Velocity of the current at the point where pressure intensity is being calculated (m/s)*

*The value of V^2 is assumed to vary linearly from zero at the point of deepest scour to the square of the maximum velocity at the free surface of the water (Fig.3)

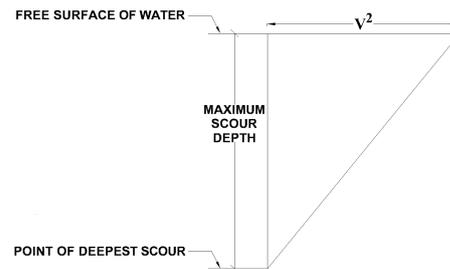
Thus, the maximum velocity of the water currents = $\sqrt{2} V$.

So, $P = 52 \times 0.66 \times (\sqrt{2} \times 3.80)^2 = 991.16 \text{ kg/m}^2$

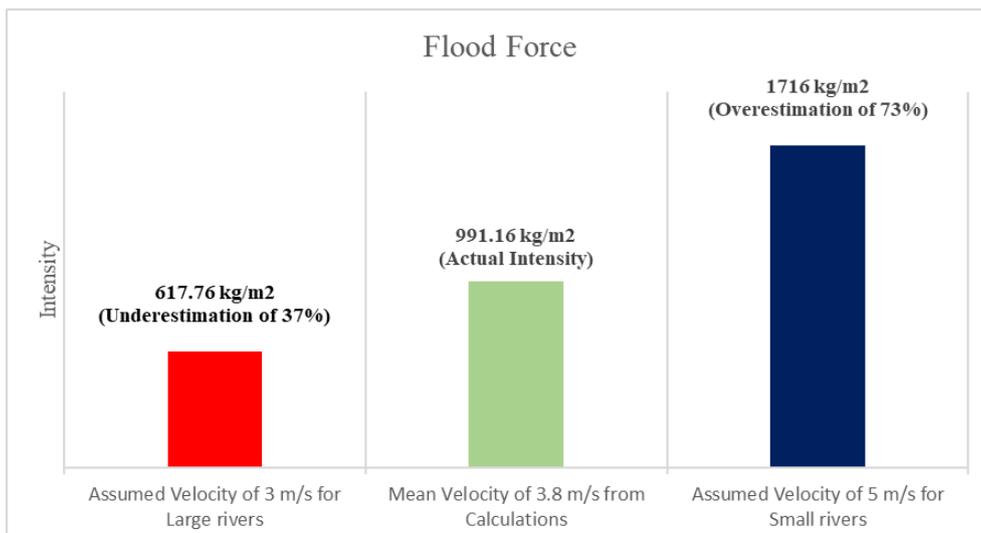
Also, assumed flood velocity by hypothesis (3 m/s for large rivers and up to 5 m/s for small flashy rivers)

For 3 m/s; $P = 52 \times 0.66 \times (\sqrt{2} \times 3)^2 = 617.76 \text{ kg/m}^2$

5 m/s; $P = 52 \times 0.66 \times (\sqrt{2} \times 5)^2 = 1716 \text{ kg/m}^2$



(Fig.3) Velocity Distribution



(Fig.4) Graph showing Underestimation and Overestimation of Flood Force along with actual Intensity.

It is evident from the illustration in (Fig.4) that if the hypothesis assumed flood velocity for the computation of flood force, the margin of error in evaluating the most significant force incident on the structure would have been about 37% underestimation or about 73% overestimation.

Extended Module for Determination of Mean Scour Depth [IRC: 78-2014, Clause 703.2]

The weighted mean particle diameter of bed material (d_m) = 0.57 mm
 Effective waterway = 800 m

Mean scour depth below HFL for natural channels flowing over a scourable bed can be calculated theoretically using the following equation:

$$d_{sm} = 1.34 (D_b^2 / K_{sf})^{1/3} \quad \text{(Eq. 5)}$$

Where;

d_{sm} = Mean scour depth (m)

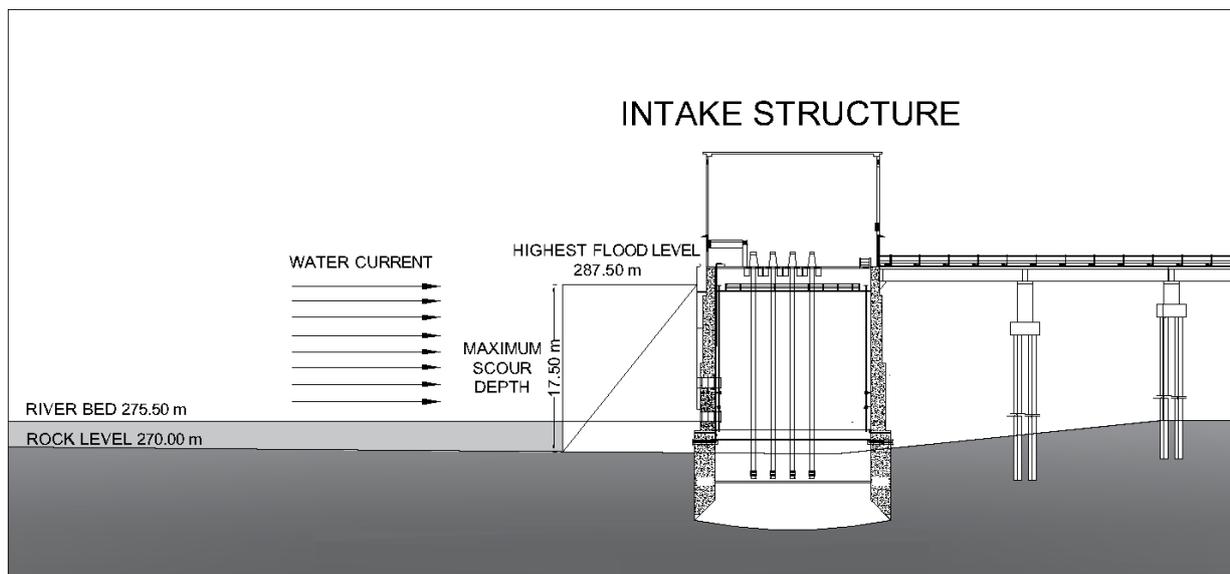
D_b = Discharge for foundation per meter width of effective waterway = 28000/800 = 35

K_{sf} = Silt factor = $1.76 (d_m)^{1/2}$
 = $1.76 (0.57)^{1/2} = 1.328$

Thus, Mean Scour Depth (d_{sm}) = $1.34 \times (35^2 / 1.328)^{1/3} = 13.04$ m

The maximum scour depth below HFL for the design of individual foundations of intake structure having piers is taken as two times the mean scour depth as given in IRC: 78-2014, Clause 703.3.

Therefore, Maximum scour depth = $2d_{sm} = 2 \times 13.04 = 26.08$ m



(Fig.5) River Intake Structure

As seen in (Fig.5), with HFL at 287.50 m and Rock level at 270 m, maximum scour depth is restricted; thus, it is considered up to the rock level, i.e. 17.5 m.

Flood drag = Flood force x 1/2 Diameter of Intake Well x Available maximum scour depth
 = $991.16 \times 20/2 \times 17.5 = 173453$ kg = 173.453 T

Lever arm = 2/3 x Available maximum scour depth
 = $2/3 \times 17.5 = 11.66$ m

Overturning Moment = Flood drag x Lever arm
 = $173.453 \times 11.66 = 2022.46$ T-m

V. CONCLUSIONS

1. To provide an overview of various estimation techniques available to ascertain design maximum flood, maximum scour depth and mean flow velocity for an ungauged location.
2. Rating curves are crucial to understanding HFL and mean velocity at the design maximum flood for the river.
3. The consistency of the observed river flow data should be discussed concerning the rainfall in the project catchment and observed data in adjacent locations/basins and must be proportional to the observed maximum flood.
4. Fitting stage-discharge and velocity-discharge relationships must not be considered simply a mathematical exercise in curve fitting. The staff involved should have familiarity with and experience in field hydrometrics.

VI. ACKNOWLEDGEMENTS

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BIOGRAPHY



Abhilash Vishwakarma is a Project Engineer accomplished in managing a varied range of projects both within the public and private sectors in the civil engineering industry. He is actively involved in detailed engineering for 'Water Infrastructure' works. As a professional, he is a frequent contributor on his blog *waterengineeringdaily.com* about technical aspects of water engineering. He is a Rotaractor with active service, Past President of Rotaract Club of RCOEM, Past Zonal Rotaract Representative under District 3030 and an honorary member of The Rotary Club of Nagpur MIHAN Town. When he is not working, you will find him spending time with his family and friends. His other personal interests include cooking, gardening, aquariums and long walks.



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