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Improved Design of Stilling Basin for Deficient Tail Water

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ABSTRACT

Present study leads to a new design of hydraulic jump type stilling basin for tail water deficiency. Due to inadequate tail water depth the jump has a tendency to sweep out of the basin. To constrain the formation of free hydraulic jump inside the basin, a stepped weir is proposed at the end of the horizontal apron. A mathematical model is developed to design the weir that would be effective even for lower discharges up to 20% of the design discharge and the given range of tail water submergence. For experimental verification of the weir performance, a sectional model (scale 1:50) of spillway and an innovative design of stilling basin are constructed. Experiments show that in a stilling basin with horizontal slope, a stepped weir designed for tail water deficiency, restricted the hydraulic jump at the desired location even for discharges lower than the design discharge.

KEY WORDS: Hydraulic jump, jump location, submergence ratio, mathematical model, stepped weir.

INTRODUCTION

For energy dissipation in stilling basins, forced hydraulic jumps are formed with the assistance of baffles and/or sill with or without sub critical tail water (Bhowmik 1975). The maximum energy dissipation occurs when a free hydraulic jump forms near the toe of ogee spillway or front of jump coincides with the section where the supercritical pre jump depth is minimum (Chow 1959; Wu and Rajaratnam 1995). The required length of apron depends upon the length and location of the jump (for design discharge condition) which in turn depends on the pre jump depth (y_1) and the relative magnitudes of required post jump depth (y_2) and available tail water depth (y_t) (Rajaratnam and Subramanya 1966; Jeppson 1970) as shown in Fig. 1. In a rectangular stilling basin with horizontal slope, a front of hydraulic jump occurs at a location where the sequent depths satisfy Belanger momentum equation (Rajaratnam and Murahari 1971; Hager and Bremen 1989). In case of tail water deficiency condition, the tail water rating curve lies below the jump height curve for all discharges and

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the hydraulic jump may partially or fully sweep out of the basin. This may prove to be dangerous from the safety point of view of stilling basin, tail channel and other hydraulic structures (Tung and Mays 1982; Moharami *et al.*, 2000). In present practice, rise in y_2 is achieved either by depressing the apron or by constructing a rectangular broad crested weir at the end of the apron (Leutheusser and Kartha 1972; Ohtsu *et al*., 1991).
Thus at flood discharges lower than design discharge, a drowned or submerged jump is formed. The deleterious effects of drowned jump are well known (Vittal and Al-Garni 1992). To address this problem, a rectangular broad crested stepped weir geometry that would assure formation of free jump near toe of spillway for the design discharge as well as for the lower discharges is developed.

Problem Statement and Proposed Solution

For appropriate location of hydraulic jump inside the apron for all operating conditions with reference to varying discharges and the corresponding tail water depths few researchers who have tried in past have not taken corresponding tail water submergences into consideration (Vittal and Al-Garni 1992; Achour and Debabeche 2003). In the present study, average tail water submergence ratio has been considered as one of the input parameters. A stepped weir so designed involves two aspects. As shown in Fig.1, for any cumulative discharge Q_n , $y_2 = y' + h$. The widths of individual steps should be such that the summation of particular discharges contributed by individual steps under consideration should be equal to cumulative discharge.

MATERIALS AND METHODS

Design Methodology

Assumptions

1) Stilling basin is rectangular and prismatic with horizontal slope.
2) Flow is steady and head on upstream of spillway (H) is constant.
3) Spillway is either ungated or the gate opening is uniform.
4) Discharge conditions are varying. (Variation up to 20% of design discharge).
5) Coefficient of discharge C_d remains constant.

Development of Mathematical Model

The proposed stepped weir would cater to a wide range of discharge from design discharge (Q_{max}) to a minimum discharge equal to 20 % of the design discharge (Q_{min}). 'N' intermediate discharges between Q_{min} and Q_{max} with an increment of $(Q_{max} - Q_{min}) / (N+1)$ are considered resulting in (N+2) cumulative discharges corresponding to which there would be (N+2) steps in a stepped weir. The equation for discharge Q over a rectangular broad crested weir is given by

$$Q = \frac{2}{3} k \, C_d \, b \sqrt{2g} \; h^{3/2} \tag{I}$$

Where k=1 for free flow over weir and k < 1 for the submerged weirs. As $h = y_2 - y'$, the required width of weir can be expressed as

$$b = \frac{3}{2} \frac{Q}{k \; C_d \sqrt{2g} \; (y_2 - y')^{3/2}} \tag{II}$$

y_2 is calculated from the Belanger momentum equation. Using equation (II), for any cumulative discharge Q_n, the width of the corresponding step b_n can be calculated. As illustrated in Fig. 1, width of first step is given by

$$b_1 = \frac{3}{2} \frac{Q_1}{k \; C_d \sqrt{2g} \left[(y_2)_1 - y' \right]^{3/2}} \qquad \text{(III)}$$

$$b_n = b_{n-1} + a_n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots n > 1 \qquad \text{(IV)}$$

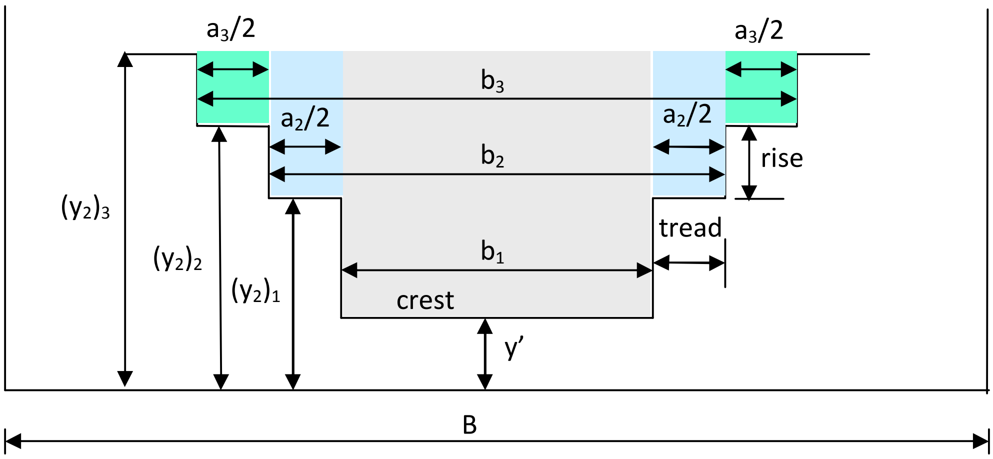

Fig. 1: Design of stepped weir (first 3-steps shown)

$$\because \quad a_n = \frac{3}{2} \frac{Q_n - \left[\sum_{i=1}^{i=n-1} (Q_n)_i \right]}{k \; C_d \sqrt{2g} \left[(y_2)_n - (y_2)_{n-1} \right]^{3/2}}$$

$$\because \quad (Q_n)_{i=1} = \frac{2}{3} k \; C_d \sqrt{2\,g}\, b_1 \left[(y_2)_n - (y') \right]^{3/2} \qquad \text{and}$$

$$(Q_n)_{i=2 \text{ to } (n-1)} = \frac{2}{3} k \; C_d \sqrt{2g}\; a_i \left[(y_2)_n - (y_2)_{i-1} \right]^{3/2}$$

In the above equations, $y' = (y_2)_1 / 4$ and it is designed for Q_{min} . For given average submergence ratio S_r, trial value of k can be obtained by following Villemonte's equation for rectangular sharp crested weirs, as similar guidelines are not available for rectangular broad crested weirs.

$$k = \frac{Q_s}{Q_f} = \left(1 - (S_r)^{3/2} \right)^{0.385} \qquad \text{(V)}$$

Where, Q_s and Q_f are the submerged and free flow discharges respectively and

$$S_r = \frac{(y_t - y')}{(y_2 - y')}$$

Experimental Verification of the Model

To experimentally verify the performance of mathematically obtained weir geometry, data of Bhama-Askhed dam in India is taken. A sectional model (scale 1:50) of spillway and horizontal stilling basin with rectangular broad crested stepped weir at its end is constructed as shown in Fig. 2. Table 1 gives various parameters related to prototype and model. As per Francis formula $C_d = 0.623$ is adopted (refer Appendix II). As rectangular broad crested weirs have high modular limit – 0.9 (Water measurement manual), k=1 is adopted for free flow or very low S_r. y' is found to be 0.025m.

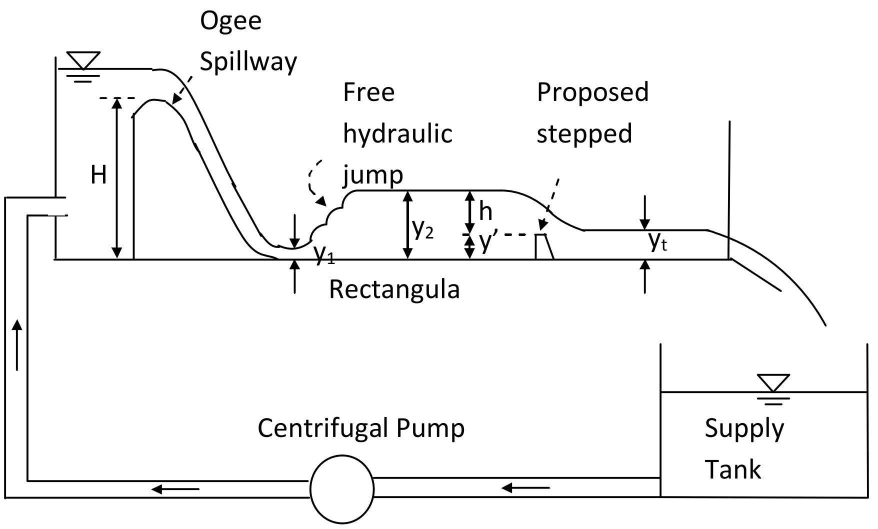

Fig. 2: Schematic of experimental setup

Table 1: Details of sectional model (scale 1:50)

Parameter	Prototype	Model
Height of Spillway (H)	21.2 m	**0.424 m**
Width of Stilling Basin (B)	55 m	**1.1 m**
Length of Stilling Basin (L)	75 m	**1.5 m**
Design Discharge (Qmax)	1736 m^3/s	**0.098 m^3/s**
20% of Design Discharge (Qmin)	350 m^3/s	**0.0196 m^3/s**
Range of Submergence Ratio (Sr)	0.15 To 0.25	**0.15 To 0.25**
Submerged Flow Coefficient (k)	1	**1**
Range of Froude Number (Fr)	**12.8 To 5.7**	**12.8 To 5.7**

Detailed geometry of a broad crested stepped weir with k = 1 is given in Table 2. The top and bottom lengths of weir are taken to be 0.04 m and 0.16 m respectively. The upstream face is kept vertical and downstream face is given a slope of 60°. As 2nd to 11th steps are having very low rise, the centers of all these steps are joined by a smooth surface. This has also avoided number of sharp edges and corners in the steps.

Table 2: Geometry of broad crested stepped weir

Step number	Rise (m)	Tread (m)		Step number	Rise (m)	Tread (m)		Step number	Rise (m)	Tread (m)
1	0.075	0.263		5	0.012	0.024		9	0.009	0.018
2	0.017	0.059		6	0.011	0.022		10	0.008	0.017
3	0.015	0.031		7	0.010	0.020		11	0.008	0.016
4	0.013	0.028		8	0.009	0.019				

The stepped weir performance is judged from the ability of weir to form free hydraulic jumps near toe of spillway from Q_{min} to Q_{max}. The observed-y_1, y_2 and y_t are measured with the help of a point guage attached with a vernier of 0.1 mm accuracy. y_1 is measured just downstream of toe of spillway. The observed-y_2, y_t and ideal-y_2 values for 4-trials are given in Table 3.

Table 3: Experimental results for the broad crested stepped weir

Q m^3/s	y_1-obs m	F_{r1} obs	y_2-ideal m	y_2- obs m	y_t-obs m
0.025	0.010	7.25	0.111	0.094	0.016
0.050	0.019	5.54	0.156	0.137	0.026
0.075	0.028	4.69	0.189	0.169	0.035
0.100	0.036	4.24	0.214	0.191	0.042

RESULTS AND DISCUSSION

Although the location of front of hydraulic jump, is found to be slightly fluctuating near the toe of spillway, the mean location of front of jump is found to be constant (near the toe of spillway) over a complete range of Q and corresponding range of S_r . On either side of stepped weir, in the corners, little part of flow is observed to be separated. These ideal y_2 depths, observed y_2 and y_t depths are plotted against Q in a non dimensional form in Fig. 3. It shows that, over a range of Q and the given S_r, an observed $y_2 / y_{t\text{-min}}$ – curve is raised above the $y_t/y_{t\text{-min}}$ curve due to presence of stepped weir and lie slightly below the ideal $y_2 / y_{t\text{-min}}$ – curve. This is because the ideal $y_2/y_{t\text{-min}}$ – curve does not include frictional losses. A satisfactory agreement is found between these two curves. This ensures that over a complete range of Q, front of hydraulic jumps is located near the toe of spillway. Fig.4 and Fig. 5 in Appendix I are showing front and top views of stilling basin with all dimensions. Also Fig.6 (Appendix I) shows photographs of different flow conditions in the experiments.

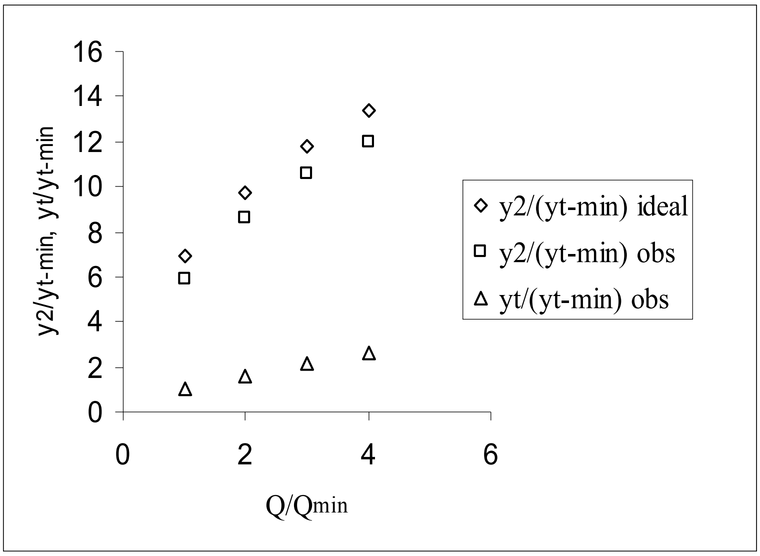

Fig. 3. Non-dimensional plots of ideal y_2, observed y_2 and y_t against Q

Unique Advantages of Proposed Stilling Basin

Following are the unique advantages of a proposed new design of a stilling basin which makes it different from the conventional designs.

1. As tail water level lies below the water level on apron, the chances of horizontal eddies bringing the sediments / riprap material back into the basin get nullified. (Khatsuria 2005)
2. The proposed stepped weir assures appropriate location of jump for all operating conditions and thus the corresponding F_{r1} and energy dissipation is maximum. It is particularly suitable in the case where tail water level requires certain time to develop to its full magnitude. This further reduces the chances of jump sweep out in such situation.
3. As air entrainment is directly proportional to F_{r1} (Khatsuria 2005), in the present case a maximum air entrainment would occur. This would be helpful to mitigate the cavitation damage to the basin floor and appurtenances against fluctuating pressures depressions.
4. The proposed basin requires no appurtenances like chute blocks or baffle blocks. Thus there is saving in their cost of construction.

Conclusions

A mathematical model is developed to design the geometry of rectangular broad crested stepped weir and is applicable for $F_{r1} \geq 4.5$. A guideline to determine C_d and formula to determine y' are given. With the help of sectional model (scale 1:50) of an existing spillway and a new design of stilling basin, the performance of stepped weir is experimentally verified as the location of front of hydraulic jump is restricted near the toe of spillway for different discharges (ranging from Q_{min} to Q_{max}) and given range of S_r.

Acknowledgements

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Notations

B	=	Width of stilling basin
b	=	Width of step of rectangular broad crested stepped weir
Cd	=	Coefficient of discharge for free weir
Cdm	=	Modified coefficient of discharge
Fr1	=	Supercritical Froude number
H	=	Head on upstream of spillway
h	=	Head over stepped weir crest
k	=	submerged flow coefficient
Q	=	Discharge
Sr	=	submergence ratio for the stepped weir crest
v1	=	Supercritical velocity (neglecting losses)
y’	=	Height of weir crest from the channel bed
y1	=	Pre jump depth
y2	=	Post jump depth or sequent depth
yt	=	Tail water depth

Appendix I

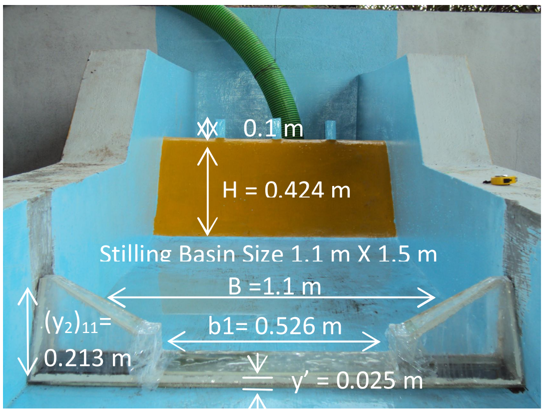

Fig. 4. Front view of stilling basin

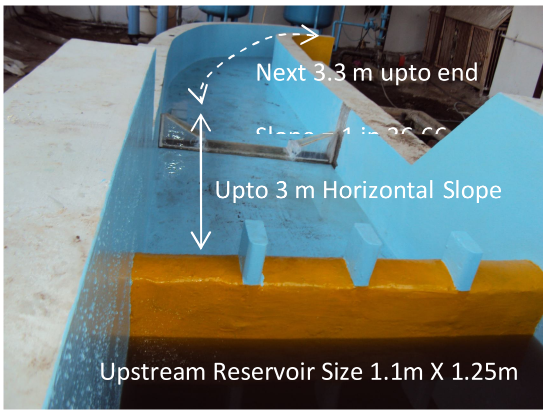

Fig. 5. Top view of stilling basin

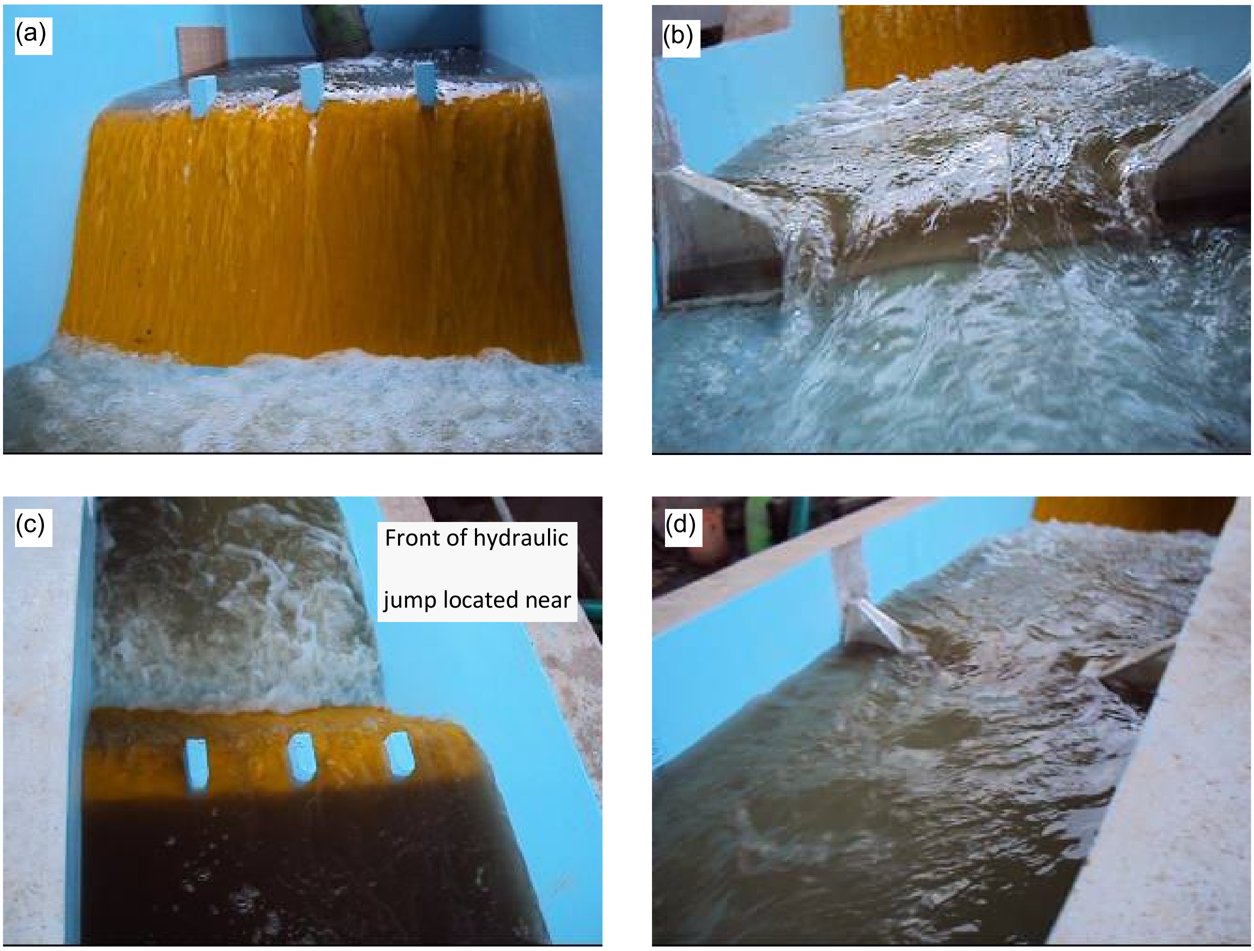

Fig. 6: Photographs showing different flow conditions

(a) flow over spillway (b) flow through stepped weir

Appendix II

In the mathematical design of stepped weir, a constant value of C_d = 0.623 is adopted according to Francis formula. The validity of the same has been empirically determined with the help of a laboratory scale model. As there are different kinds of uncertainties involved in the flow conditions, the analytical determination of C_d is hardly possible. To mention a few, there is presence of hydraulic jump and associated turbulence on upstream of stepped weir. Also the upstream reach for the stepped weir, being equal to length of stilling basin, is small. Still, authors have tried to incorporate the factors like variation of H with Q and end contraction effect of steps in the mathematical model. But it resulted into a non-realistic geometry of weir. Thus it is decided to conduct a laboratory model study (scale 1:183.33) and judge the appropriateness of C_d by the appropriateness of hydraulic jump location (which is most vulnerable to uncertainties due to various assumptions involved in the mathematical design of weir) which is the main aim of study (refer Fig. 7). Since, for given discharge, step width (b) varies (inversely) only with C_d. If require, stepwise different C_d values can be used in the mathematical design of weir. To start with, a broad crested stepped weir is designed with C_d = 0.6 and tested in a laboratory flume (0.3 m wide) under free flow condition for four discharges (i.e. 25%, 50%, 75% and 100% of Q_{max}). The jumps are found to be shifted in the downstream direction at 25% and 50% discharges and found to be totally out of the basin at

75% and 100% of Q_{max}. This shows that the area of flow section of stepped weir is larger and need to be reduced. This can be done by reducing the step widths (b) which requires increase of C_d. Thus in the second trial another stepped weir is designed with $C_d = 0.65$ and tested in a similar manner. During this, for all the discharges the jumps are found to be drowned which means the step widths are needed to be increased slightly. Thus for the third trial $C_d = 0.623$ is adopted and accordingly, as mentioned previously, tests are taken. For rectangular broad crested stepped weir with $C_d = 0.623$, for all 4 discharges the hydraulic jumps have formed inside the basin and the fronts of jumps in all the cases were found to be located near the toe of spillway. Thus $C_d = 0.623$ is confirmed empirically and is adopted for the pilot scale model study (scale 1:50) and has been further reconfirmed. For the free flow conditions, k=1 is adopted. And the same is decided to be continued with, owing to the fact that rectangular broad crested weirs have high modular limit (0.9 – as per USBR Water Measurement Manual). Practically this limit is found to be 0.65. Thus for higher submergences ($S_r > 0.65$), the coefficient of discharge will decrease and a modified coefficient of discharge $C_{dm} = k.C_d$, where k<1 and accordingly k can be determined empirically.

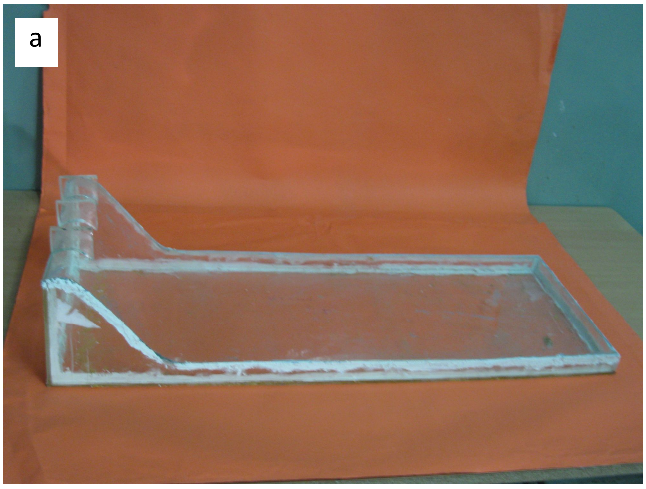

Fig. 7(a and b). Photographs showing details

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