STILLING BASIN WITH RAPIDLY DIVERGING SIDE WALLS FOR FLUMED HYDRAULIC STRUCTURES

S.K. Mazumder
Professor of Civil Engineering
Delhi College of Engineering
Delhi - 110 006

ABSTRACT

In a conventional stilling basin, the side walls are parallel to flow axis resulting in only one roller in the vertical plane. In the proposed basin with rapidly diverging side walls, two additional side rollers are formed in the horizontal plane in between the incoming high velocity jet and the side walls resulting in more dissipation of energy. Theoretically, the conjugate depth decreases and energy loss increases with increase in angle of divergence of the side walls. However, when the angle of divergence exceeds a limiting value of 4 to 5 degree, the jump front becomes skew resulting in jet flow on one side and back flow on the other, if the basin floor is kept level. There is hardly any energy dissipation and deep erosion occurs in the tail channel. Present study aims at developing suitable devices to stabilise and confine the side rollers within the basin so that the flow downstream becomes uniform and smooth without any separation and erosion in tail channel. Two devices developed to improve the basin performance have been discussed in the paper. The basin is highly efficient and economic since the dissipating and the transition structures are combined unlike a conventional basin where a long transition follows the dissipating unit.

INTRODUCTION

Numerous canal structures eg. structures eg. drops, regulators, flow meters etc. require energy dissipating arrangement to avoid scouring downstream. Uncontrolled erosion and deposition not only threaten the safety of the structure, it causes problems of maintenance with recurring annual cost. Proper design of energy dissipator is, therefore, extremely important. As shown in fig. 1, such structures are invariably flumed to reduce the cost. Extent of fluming is, however, governed by the incoming Proude's number of flow in the normal channel section (Mazumder, 1979). Transition structures connecting the flumed section with the normal section are provided upstream and downstream. Both the contracting and expanding transitions are conventionally designed by popular methods eg. Hinds (1928), Chaturvedi (1963), Vittal & Chiranjibi (1983) etc. Optimum axial lengths of such transitions were found by Mazumder (1967; 1978) experimentally. Conventionally, the expanding transition is provided after the energy dissipator as shown by dotted line (1-2-3) in fig. 1. The side walls of the conventional stilling basin are kept parallel to flow axis upto the jump end. In such a basin, hydraulic jump occurs in a prismatic channel of rectangular cross-section and the jump characteristics are well defined (Hager 1992). Flow in the expansion is sub-critical although the transition.
high turbulence level prevailing after jump, it may be possible to curtail the length of transition (Kline 1959). Further curtailment of length is possible by use of appurtenances (Mazumder 1971). In a hydraulic jump, turbulence level is highest near jump front (Rouse 1959). It is possible to adopt a basin with straight side walls diverging from jump front i.e. the toe of the spillway/glacis as shown in fig. 1 (Line 1-4). Such a basin will be more economic compared to the conventional one, since the transition and dissipating structures are combined. Several problems encountered in a basin with rapidly diverging side-walls were overcome through experimental research study (DST 1989). Results obtained (Mazumder 1987) are discussed in the following paragraphs.

HYDRAULIC JUMP CHARACTERISTICS IN A BASIN WITH DIVERGING SIDE WALLS

Spatial jump characteristics in abrupt and gradual expansions have been studied by several authors, viz. Unny (1960), Rajaratnam (1965), Bremen (1990). Conjugate depth and energy loss in a gradually expanding basin, obtained by Rajaratnam, are shown in figs. 2(a) & 2(b). It may be seen that the conjugate depth reduces and energy loss increases with increasing angle of divergence (Φ) of the side-wall compared to those in a jump in prismatic basin with parallel side walls (Φ = 0°).

However, several drawbacks, as observed in experiments are: (i) upto a certain angle of divergence (Φ = 5°), jump front is normal to flow axis and the downstream flow is uniform. As the angle of divergence exceeds the above limit, the flow becomes asymmetric with oblique jump front. There is jet flow on one side and return flow on the other side as shown in fig. 3. (ii) Weak mixing of the jet with the surrounding fluid resulting in highly non-uniform flow at the basin end (fig. 3). (iii) Extremely poor energy dissipation within the basin accompanied with surface waves and deep erosion of tail channel. (iv) The jet flow is unstable and it is found to periodically swing from one side to the other, thereby exposing the entire tail channel to jet action and scouring.

PARAMETERS GOVERNING BASIN PERFORMANCE

The different draw backs of spatial jump in a basin with rapidly diverging side-walls as pointed above, were overcome by systematic study of the effect of certain appurtenances (Mazumder 1988) on the basin performance. The different parameters used are:

- Efficiency of Basin (η)
- Basin efficiency is defined as the ratio of energy actually dissipated within the basin (ΔE') to the required loss of energy (ΔE) as shown in fig. 3 i.e.
  \[ \eta = \frac{\Delta E'}{\Delta E} \]

Higher the value of ΔE', less will be the residual kinetic energy of flow leaving the basin (ΔE - ΔE') and hence more efficient will be the basin.

Kinetic Energy Correction Factor at Basin Exit (κ₂)

It may be proved that in a channel with non-uniform flow distribution, the kinetic energy correction factor, κ₂, is given by the relation
where \( u \) is the local velocity through an elementary area \( dA \). \( A_2 \) is the area of flow section and \( V_2 \) is the mean velocity of flow at the basin exit. Higher is the non-uniformity of flow, greater will be \( \alpha_2 \) and more will be the residual kinetic energy flow given by

\[
\Delta E - \Delta E' = \left( \alpha_2 - 1 \right) \cdot V_2^2 \cdot 29
\]

As \( \alpha_2 = 1.00 \), \( \eta = 100\% \). Objective should be to obtain as low \( \alpha_2 \) and as high value of \( \eta \) as possible.

Scour Downstream of Basin

Basic performance is best reflected through local scour pattern downstream of the basin. An inefficient basin will bring about more scour. Objective should be to eliminate or minimise the scour downstream of the basin.

USE OF BED DEFLECTOR TO IMPROVE BASIN PERFORMANCE

Bed deflector as shown in fig. 4, was found to be the best. Results obtained with bed deflector and other apparatuses are given in reference (Mazumder 1988). Optimum geometry of the bed deflector and other details are also given there. All the experiments were performed in the hydraulics laboratory of Delhi College of Engineering in 120 cm wide masonry flume. The test basin was constructed below a straight glacial (3H:1V) type fall with a maximum flow 30 L/s, with tail water depth computed from Rajaratnam’s equation. Without deflector, the basin performance was extremely poor (\( \eta = 92.1\% \), \( \alpha_2 = 5.55 \)). Performance improved remarkably with use of bed deflector of optimum size (\( \eta = 99.5\% \), \( \alpha_2 = 1.22 \)). The FIG. 4 DISSIPATOR WITH BED DEFLECTOR

USE OF ADVERSE SLOPE TO BASIN FLOOR

Another ingenious device for improving the basin performance was developed by the author (Mazumder 1987) by providing adverse slope (\( \beta \)) to the basin floor as shown in fig. 5. The optimum angle of inclination (\( \beta_{opt} \)) was computed theoretically by equating the axial component of bed reaction (\( F_x \)) acting against the flow with the axial components of side wall reactions (\( 2P_x \)) acting in the direction of flow (fig. 5). Assuming linear variation of jump profile and hydrostatic pressure distribution before and after the jump, it may be proved that

\[
F_x = \frac{1}{3} \cdot Y_w \cdot L_a \cdot \tan \beta \cdot (bd_2 + Bd_1 + 2Bd_2 + 2bd_1)
\]

\[
2P_x = \frac{1}{3} \cdot Y_w \cdot L_a \cdot \tan \varphi \cdot (d_1^2 + d_2^2 + d_1 d_2)
\]

Equating Eq. (4) and Eq. (5), the value of \( \beta_{opt} \) is given by

\[
\beta_{opt} = \tan^{-1} \left[ \left( \frac{d_1^2 + d_2^2 + d_1 d_2}{bd_2 + Bd_1 + 2Bd_2 + 2bd_1} \right) \tan \varphi \right]
\]

where \( \alpha = d_1/d_2 \), \( \beta = B/b \). Values of \( \beta_{opt} \) determined from equation 6 were found to be 1°45', 2°37' and 5°14' corresponding to tan \( \varphi \) equal to 0.33, 0.50 and 1.0 respectively, for the given flow conditions, namely, \( Z_b = 53.3 \) cm, \( Z_B = 120 \) cm, \( d_1 = 2.35 \) cm, \( d_2 = 12.57 \) cm, \( Q = 30 \) LPS. \( F_s = 5.15 \) and tan \( \beta = 0.33 \). Experiments were performed with different inclinations (\( \beta \)) of basin floor and different \( F_s \) values. \( \beta_{opt} \) values were determined from graphical plot of \( \alpha_2 \) against \( \beta \). Minimum \( \beta \) value at which the downstream flow was normal (\( \alpha \) ranging between 1.10 to 1.20) was taken as \( \beta_{opt} \). Values of \( \beta_{opt} \), determined experimentally, differed from the theoretical values due to simplified assumptions made in the derivation of equations (4), (5) and (6). \( \beta_{opt} \) values were also
found to vary slightly with inflow conditions defined by angle of obliquity (°) as shown in fig. 6(a), (b) & (c). Fig. 7 gives the variation $\beta_{opt}$ with $\delta$ for $Q = 30$ LPS & $F_1 = 5.15$.

**FIG. 6(a)** SLUICE TYPE OUTLET ($\delta = 0^\circ$)  
**FIG. 6(b)** STRAIGHT CLAICES ($3H:1V$)  
**FIG. 6(c)** Ogee TYPE CLAICES ($\delta = 37.5^\circ$)

**FIG. 7** VARIATION OF $\beta_{opt}$ WITH $\delta$.

**FIG. 9** SHOWING LOCATION OF BATTLE BLOCKS & $\beta_{opt}$.

$\beta_{opt}$ increases with $F_1$ up to a certain limiting value of $F_1$, and it remains independent of $F_1$. For a given $F_1$, $\beta_{opt}$ increases with discharge intensity as shown in fig. 8. Table-1 indicates the performance of the basin for different conditions of flow over ogee type entry ($\delta = 37.5^\circ$) as shown in fig. 6(c).

**TABLE 1**

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$Q$(LPS)</th>
<th>$F_1$</th>
<th>$d_2$(cm)</th>
<th>$\alpha_2$</th>
<th>$\eta=\Delta E'/\Delta E$ REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.5^\circ$</td>
<td>15</td>
<td>18.8</td>
<td>3.25</td>
<td>72.0</td>
<td>68.8</td>
</tr>
<tr>
<td>$2.5^\circ$</td>
<td>30</td>
<td>13.6</td>
<td>4.91</td>
<td>78.0</td>
<td>41.5</td>
</tr>
<tr>
<td>$2.5^\circ$</td>
<td>50</td>
<td>10.7</td>
<td>9.10</td>
<td>86.0</td>
<td>30.8</td>
</tr>
<tr>
<td>$4.0^\circ$</td>
<td>15</td>
<td>18.8</td>
<td>5.0</td>
<td>2.6</td>
<td>99.8</td>
</tr>
<tr>
<td>$4.0^\circ$</td>
<td>30</td>
<td>13.6</td>
<td>6.5</td>
<td>3.7</td>
<td>98.8</td>
</tr>
<tr>
<td>$4.0^\circ$</td>
<td>50</td>
<td>10.7</td>
<td>7.3</td>
<td>17.6</td>
<td>84.3</td>
</tr>
<tr>
<td>$5.0^\circ$</td>
<td>15</td>
<td>18.8</td>
<td>3.6</td>
<td>1.3</td>
<td>97.9</td>
</tr>
<tr>
<td>$5.0^\circ$</td>
<td>30</td>
<td>13.6</td>
<td>5.6</td>
<td>3.3</td>
<td>93.8</td>
</tr>
<tr>
<td>$5.0^\circ$</td>
<td>50</td>
<td>10.7</td>
<td>6.1</td>
<td>9.2</td>
<td>89.0</td>
</tr>
<tr>
<td>$5.0^\circ$</td>
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<td>18.8</td>
<td>4.6</td>
<td>1.2</td>
<td>99.9</td>
</tr>
<tr>
<td>$5.0^\circ$</td>
<td>30</td>
<td>13.6</td>
<td>6.5</td>
<td>1.3</td>
<td>99.9</td>
</tr>
<tr>
<td>$6.0^\circ$</td>
<td>15</td>
<td>18.8</td>
<td>4.0</td>
<td>1.2</td>
<td>99.9</td>
</tr>
</tbody>
</table>

**FIG. 8** OPTIMUM SLOPE OF BASIN FLOOR

Fig. 8 shows the experimental $\beta_{opt}$ values for different $F_1$ and $Q$ values for a given $\delta$ equal to $18.4^\circ$ (fig. 6.b). It may be seen that for a given value of $Q$, $\beta_{opt}$ increases with $F_1$.
TABLE 1 (Contd.)

<table>
<thead>
<tr>
<th>θ</th>
<th>Q (LPS)</th>
<th>F₁</th>
<th>d₂ (cm)</th>
<th>α₂</th>
<th>Δn = ΔE'/ΔE</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0°</td>
<td>30</td>
<td>13.6</td>
<td>4.9</td>
<td>2.0</td>
<td>99.2</td>
<td>Without Baffle Block</td>
</tr>
<tr>
<td>6.0°</td>
<td>50</td>
<td>10.7</td>
<td>6.5</td>
<td>2.1</td>
<td>98.7</td>
<td>Do</td>
</tr>
<tr>
<td>6.0°</td>
<td>50</td>
<td>10.7</td>
<td>6.5</td>
<td>1.6</td>
<td>97.3</td>
<td>With one row of Baffle Block</td>
</tr>
</tbody>
</table>

A row of baffle block, as illustrated in Fig. 9, further improved the basin performance. Typical scour pattern are shown in fig. 10(a) and 10(b). Performance of the basin designed for a higher flow (with higher Q value) improved further at half and quarter supply condition as apparent from table 1.

EFFECT OF TAIL WATER VARIATION ON BASIN PERFORMANCE

When $\theta = \theta_{opt}$, the forces $F_x$ balance $2P_x$. Applying momentum and continuity

![FIG 10 EROSION PATTERN](image)

principles under such balanced condition, it may be proved that the conjugate depth relation is given by

$$F_1 = \frac{1}{\beta} \left( 1 - \alpha^2 \right) \alpha \gamma$$

With $r = 1$, classical conjugate depth relation for prismatic channel of rectangular section may be obtained from Eq. (8). For $r > 1$, conjugate depth $d_2$ will be lower than that in a prismatic basin. Higher is the value of $r$, lower will be $d_2$ required. Performance of the non-prismatic basin was obtained with $d_2$ given by eq. (8) as well as depths lower and higher than $d_2$. The basin performance was found to be excellent even with 50% reduction in $d_2$ obtained from eq. (8). However, when tail water depth exceeded the conjugate depth by 20 to 25%, the flow downstream was found to be asymmetric.

CONCLUSIONS

(i) Conventional stilling basin in a flumed hydraulic structure require long expensive transition. Cost of such structures can be considerably reduced by adopting the new basin where the dissipating and the transition structures are combined in the same unit.

(ii) Theory of hydraulic jump in a basin with expanding side walls indicate that conjugate depth is lower and energy loss is higher than those found in a conventional basin. However, it is found from experiments that there are several problems in widely diverging basin with level floor. Flow is highly non-uniform and deep erosion occur in the tail channel.

(iii) Performance of the basin could be remarkably improved by use of bed deflector of appropriate size & shape and also by adopting adverse slope ($\theta_{opt}$) in floor.

(iv) $\theta_{opt}$ value determined experimentally was somewhat different from that
found from theory due to simplified assumptions made in derivation. (vi) $\beta_{opt}$ value increases with $F_1$ initially and it remains constant after a limiting value of $F_1$. For a given value of $F_1$, $\beta_{opt}$ increases with discharge intensity ($q$).

(vii) $\beta_{opt}$ is also found to be slightly different for different approach flow conditions given by angle of obliquity, $\delta$, between incoming and outgoing flow.

(viii) Basin designed for higher design flow (Qmax) was equally efficient at half and quarter supply.

(ix) Basin performance remained unaffected even with 50% reduction in conjugate depth flow which is lower than that in a conventional basin.

(x) Basin performance deteriorated when the basin was submerged more than 25%.

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