3.2. ENERGY DISSIPATION

The water flowing over the spillway acquires a lot of kinetic energy by the time it reaches near the toe of the spillway due to the conversion of potential energy into kinetic energy. If arrangements are not made to dissipate this huge kinetic energy of the water, and if the velocity of the water is not reduced, large-scale scour can take place on the downstream side near the toe of the dam and away from it. These arrangements are known as energy dissipation arrangements or energy dissipaters.

For the dissipation of the excessive kinetic energy possessed by the water the two common methods adopted are:

i. By converting the supercritical flow into subcritical flow by hydraulic jump.

ii. By using different types of buckets, i.e. by directing the flow of water into air and then making it falls away from the toe of the structure.

3.2.1 Jump Height and Tail water Rating Curves

Hydraulic jump can form in a horizontal rectangular channel when the following relation is satisfied between the pre-jump depth (y_1) and post – jump depth (y_2).

$$y_2 = \frac{y_1}{2}\left[-1 + \sqrt{1 + 8\,F_r^{\,2}}\right] \qquad (7.1)$$

Where y_1 = pre-jump (initial) depth

y_2 = post- jump (sequent) depth

F_{r1} = Froude number of the incoming flow

For a given discharge intensity q over a spillway, y_1, will be equal to q/v_1; and v_1 (mean velocity of incoming flow) is determined by the drop H_1 $\left(V_1 = \sqrt{2gH_1}\right)$, if head loss is neglected, (see fig. 2.1)

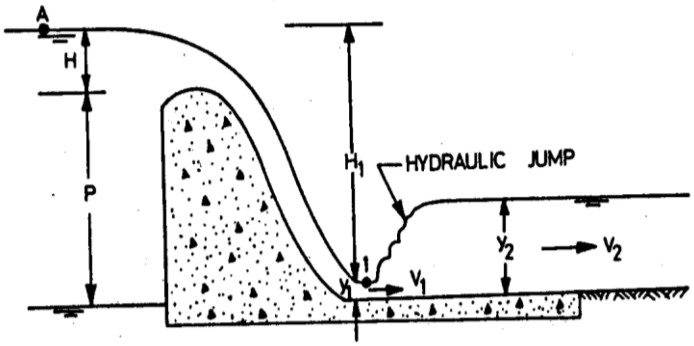


Fig 2.1 Hydraulic jump at the toe of a spillway

Hence, for a given discharge intensity and given height of spillway, y_1 is fixed and thus y_2 is also fixed. But the availability of a depth equal to y_2 in the channel on the downstream cannot be *guaranteed* as it depends upon the tail water level y_0 which depends on the hydraulic conditions of the river channel on the downstream side. The values of y_o corresponding to different values of q may be obtained by actual gauge discharge observations and plot of y_o versus q prepared, known as Tailwater Rating curve (T.W.R.C.). The post-jump depth (y_2) for all those discharges, are also computed from equation (7.1) and a plot of y_2 versus q may be made which is known as jump height curve (J.H.C.). If J.H.C. and T.W.R.C. are plotted on the same graph, five possibilities exist regarding the relative positions of these curves.

1. T.W.R.C. (y_2') coinciding with y_2 curve for all discharges
2. T.W.R.C. (y_2') lying above the y_2 curve for all discharges
3. T.W.R.C. (y_2') lying below the y_2 curve for all discharges
4. T.W.R.C (y_2') lying below the y_2 curve for smaller discharges and lying above y_2 curve for larger discharges
5. T.W.R.C. (y_2') lying above the y_2 curve for smaller discharges and lying below the y_2 curve for larger discharges

The energy dissipation arrangement that can be provided is dependent upon the relative positions of T.W.R.C. and y_2 curve.

Condition 1: In this case for the entire discharges jump will develop close to the toe of the spillway. In such a case, a simple horizontal concrete apron may be provided whose length is equal to the length of the jump corresponding to the maximum discharge over the spillway.

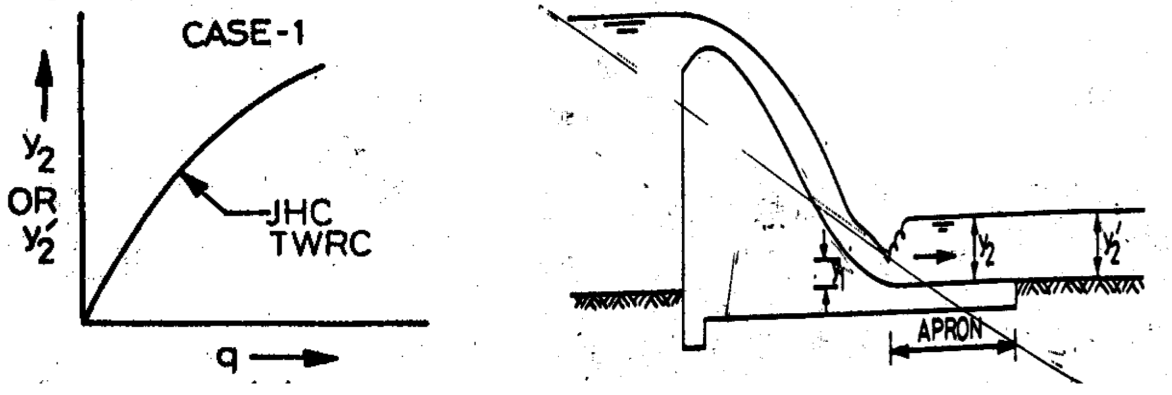


Fig 2.2a Condition 1

Condition 2: The jump forming at toe will be drowned out by tailwater, and little energy will be dissipated.

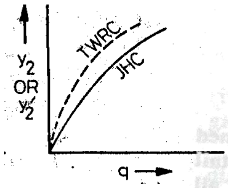


Fig.2.2b Condition 2

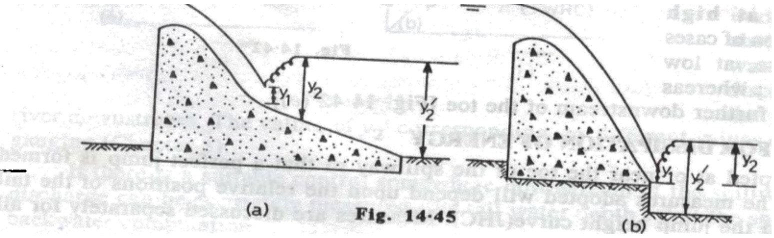


Fig 2.2c Hydraulic jump on a sloping apron

Water may continue to flow at high velocity along the channel bottom for a considerable distance. The problem can be solved:

i) By constructing a sloping apron over the riverbed extending from the downstream surface of the spillway. The jump will form on the sloping apron where depth equal to y_2 (lesser than the tailwater depth at toe) is available.

The slope of the apron is made in such a way that proper conditions for a jump to occur somewhere on the apron at all discharges.

ii) By providing a roller bucket type energy dissipater. Also a drop provided in the riverbed to lower the TWL can be used to dissipate the energy.(Fig 7.2c).

Condition 3: In this case the jump will develop at a certain section far downstream of the toe of the spillway. This is the most frequent one, and shows that a stilling basin (with a depressed horizontal apron) is required for all discharges in order to produce a jump close to the toe of the spillway.

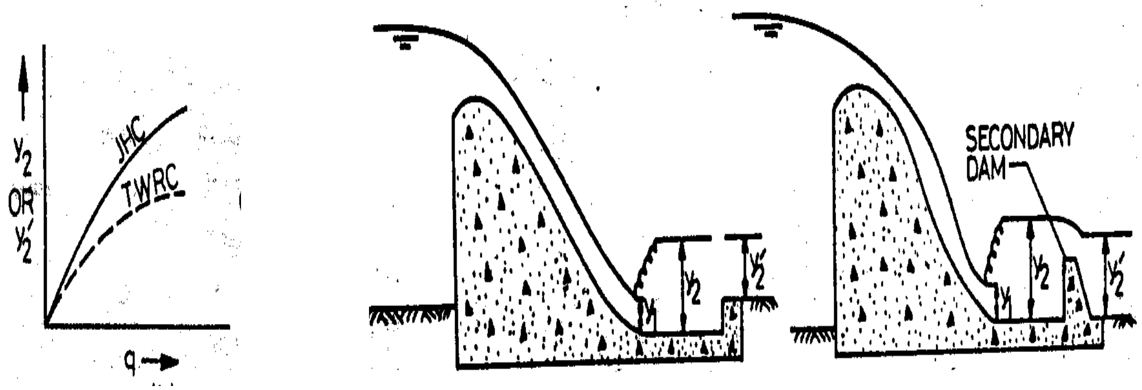


Fig 2.2d Condition 3

If the tailwater is very low, ski-jump type dissipator may be provided. But it needs sound rock at the riverbed, since part of the dissipation takes place by impact; the rest being dissipated by aeration and diffusion in air.

***Condition 4**:* In this case the following measures may be taken to develop jump close to the spillway.

i) Provide a stilling basin with an end sill for developing a jump at low discharges and combine the basin with a sloping apron for developing a jump at high discharges.

ii) Provide a sloping apron which lies partly above and partly below the riverbed so that jump will develop at lower portion of the apron at low discharges and at higher portion of the apron at high discharges.

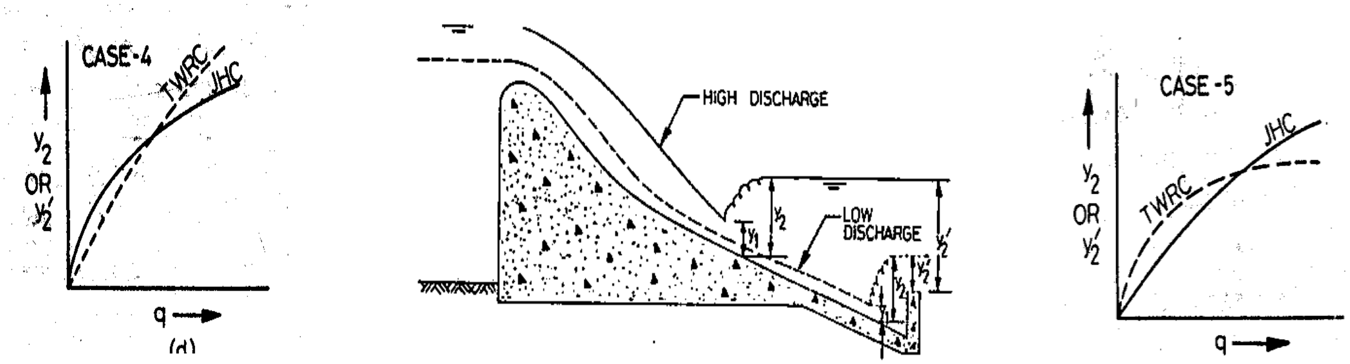


Fig. 2.2e.Condition 4

In this case, the tail water depth is insufficient at low discharges and is greater at high discharges.

***Condition 5*:** This condition is just the reverse of condition (4) and the same arrangement that was made for condition (4) will serve the purpose. (**Fig 2.2e)**

3.2.2 Stilling Basin

A stilling basin consists of a short, level apron at the foot of the spillway. It must be constructed of concrete to resist scour. The function of the basin is to decelerate the flow sufficiently to ensure the formation of a hydraulic jump within the basin. The jump dissipates much of the energy, and returns the flow to the subcritical state.

Hydraulic Jump Stilling Basin

The passage of water from a reservoir into the downstream reach involves a number of hydraulic phenomena such as the transition into supercritical flow, supercritical non-aerated and aerated flow on the spillway, entry into the stilling basin with a transition from supercritical to subcritical flow, and echoes of macro-turbulence after the transition into the stream beyond the basin. It is, therefore, possible to consider the energy dissipation process in the following stages, all of which may be combined.

- On the spillway surface
- In the stilling basin
- At the outflow into the river.

Energy Dissipation n Spillway Surface

The energy loss on the spillway surface may be expressed as

$$e = \zeta \alpha \frac{V'^2}{2g} \qquad (7.2)$$

Where V' = the (supercritical) velocity at the end of the spillway

α = Coriolis coefficient (energy coefficient)

ζ = head loss coefficient.

The total energy, E, can be expressed as

$$E = \zeta \alpha \frac{V'^2}{2g} + \alpha \frac{V'^2}{2g} \qquad (7.3)$$

and taking $\varphi = \frac{\text{actual velocity}}{\text{theoretical velocity}}$

Hence, $\frac{1}{\varphi^2} = 1 + \zeta$ (7.4)

The ratio of the energy loss, e, to the total energy E (i.e. relative energy loss) is

$$\frac{e}{E} = \frac{\zeta V'^2}{2g} \Bigg/ \left(\frac{V'^2}{2g} + \zeta \frac{V'^2}{2g} \right) = \frac{\zeta}{1+\zeta} = 1 - \varphi^2 \qquad (7.5)$$

For the ratio of the height P of the spillway crest above its ending and the overflow head H, with P/H < 30, and smooth spillways (Novak & Cabelka, 1981),

$$\varphi \cong 1 - 0.0155 P/H \qquad (7.6)$$

For a given P, φ increases as H increases, i.e., if for a given discharge Q the spillway width b decreases and thus q increases.

Thus, for P/H = 5, φ = 0.92 and the relative head loss (e/E) is 15%, where as for P/H = 25, φ = 0.61 and relative head loss is 62 %.

The value of head loss coefficient (ζ) could be increased (and φ decreased) by using a rough spillway or by placing baffles on the spillway surface. However, unless aeration is provided at these protrusions, the increased energy dissipation may be achieved only by providing an opportunity for cavitation damage.

3.2.3 Energy Dissipation in the Stilling Basin

Referring to the notation is Fig (7.3) and to equations (7.2) and 7.4) we can write

$$E = y_1 + \frac{\alpha q^2}{2g\varphi^2 y_1^2} \qquad (7.7)$$

$$y_2 = \frac{y_1}{2}\left[-1 + \left(1 + \frac{8\,q^2}{g\,y_1^3}\right)^{1/2}\right] \qquad (7.8)$$

The stilling basin depth is then given by

$$y' = \sigma' y_2 - y'_2 \qquad (7.9)$$

and the length of the stilling basin is given by

$$L = k(y_2 - y_1) \qquad (7.10)$$

Where σ′ and k are coefficients derived from laboratory and field experiments.

According to Novak and Cabelka Coefficients σ′ and k can be taken as $1.1 < \sigma' < 1.25$ and 4.5 < k < 5.5,where the lower value of k applies for $F_{r1}>10$ and the higher for $F_{r1} \leq 3$.

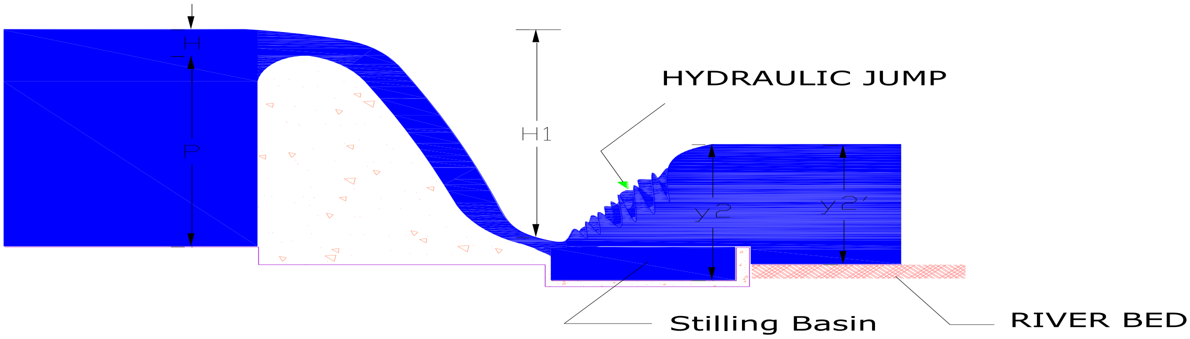


Fig. 2.3 Definition sketch for hydraulic jump stilling basin

When applying equations (7-7) – (7-10) we start with a known discharge q and the corresponding downstream depth y_0 and apply the iterative procedure, which follows:

Take the energy (reference) datum at downstream riverbed level, and compute E assuming an initial value of $y' = 0$;

Choose a suitable value of φ; $\left(\varphi = 1 - 0.0155 p / H\right)$;

Compute y' for q_{max} from equation (7.7); y_2 from equation (7.8); and y' from equation (7.9) (From a chosen value of safety coefficient, σ');

Compute y_0 (from uniform flow equation – Manning, Chezy) and compare it with y_2

If $y_2 < y_0$, no stilling basin is required; if $y_2 \geq y_0$ stilling basin is required and therefore compute y' with $1.1 < \sigma' < 1.2$ (≈ 1.2) from equation (7.9);

Take new reference datum at basin bed level; and calculate new E and repeat steps 2-4 to check that $\sigma' \geq 1.1$.

Repeat the above steps at least for one smaller q to check whether the designed stilling basin is adequate for lower discharges as well.

Note: Equations (7.8) and (7.10), and thus the design under discussion, apply to basins with a horizontal floor only.

3.2.4 Additional Considerations in Stilling Basin Design

The hydraulic jump entrains a substantial amount of air additional to any incoming aerated flow. The main significance of the presence of air in the jump region is the requirement of higher stilling basin sidewalls due to higher depth of flow.

The major problems in spillway stilling basin are cavitation, uplift, and abrasion.

The highly turbulent nature of the flow in the hydraulic jump induces large pressure fluctuations and is the cause of cavitation. Cavitation number can be expressed as

$$\sigma = P' \Big/ \left(\frac{1}{2}\rho V_1^2\right)$$

where P´ is the deviation of the instantaneous pressure P from the time average pressure. If σ falls below a critical value, σ_c, then cavitation occurs.

Another serious structural problem in hydraulic jump stilling basins is the effect of uplift pressures due to the dam drainage system or the tailwater level or the water table in the basin bank, which is aggravated by the macro-turbulent pressure fluctuations underneath the jump. Therefore, it is sensible to design the floor slab for the full downstream uplift pressure applied over the whole area of the floor with the basin empty or the uplift pressure head equal to the root mean square value of pressure fluctuations of the order of $0.12V_1^2/2g$ (V_1= inlet supercritical velocity) applied under the whole full basin. Furthermore, all contraction joints should be sealed, no drain openings should be provided, and the floor slab should be as large as possible and connected by dowels and reinforcement (ICOLD, 1986).

Abrasion of concrete in the basin could take place if this is also used for bottom outlets carrying abrasive sediments (unlikely to happen for $V<10$m/s), or from sediment drawn into the basin from downstream either by bad design or operation. The basin should be self-cleaning to flush out any trapped sediment.

The prevention of vibration of basin elements (due to turbulence of the flow) also requires massive slabs, pinned to the foundation when possible.

3.2.5 Standard Stilling Basins

Although the stilling basin based purely on a simple hydraulic jump works well and relatively efficiently, in certain conditions other types of basins may produce savings in construction costs. Certain accessories such as chute blocks, baffle blocks (or floor blocks), and end sills (or baffles) are usually provided in the stilling basins to reduce the length of the jump and thus to reduce the length and the cost of the stilling basin. Moreover, these accessories also improve the dissipation action of the basin and stabilize the jump.

The type of stilling basin to be provided depends on the type of jump, which in turn depends on the Froude number F_{r1} of the incoming flow.

3.2.5.1 U.S.B.R. Stilling Basins

Stilling basin for $1.7 < F_{r1} < 2.5$ (Type I)

Only horizontal apron needs to be provided. The flow does not have much turbulence and hence no accessions are required. However, the apron must be sufficiently long to contain the entire jump. The length of the apron should be the length of the jump (i.e. $5y_2 = L$, and ($L \geq 4y_2$) where y_2 = sequent depth).

Stilling Basin for $2.5 < F_{r1} < 4.5$ (Type IV)

Type IV stilling basin is found effective. It is provided with chute blocks and end sill is optional. The length L of the stilling basing may be obtained from the following table.

F_{r1}	2	3	4	5
L/y_2	4.3	5.3	5.8	6

Stilling Basins for $Fr_1 > 4.5$

True hydraulic jump will form. Depending on the incoming velocity of flow two types of basins are developed:

a) **$V_1 < 15$ m/s**: ***Type III stilling basin may be adopted***. This basin utilizes chute blocks, baffle blocks and end sill (the size, spacing and location of the chute and baffle blocks are shown in the **Figure**). The length of the stilling basin and the height h_3 and h_4 of the baffle blocks and the end sill may be obtained for different values of Fr_1 as follows:

F_{r1}	5	6	8	10	12	14	16
$\frac{L}{y_2}$	2.3	2.5	2.6	2.7	2.8	2.8	2.8
$\frac{h_3}{y_1}$	1.5	1.7	2.0	2.3	2.7	3.0	3.3
$\frac{h_4}{y_1}$	1.2	1.3	1.5	1.6	1.7	1.8	1.9

The use of chute blocks, impact baffle blocks, and an end sill shortens the jump length and the stilling basin. This basin relies on dissipation of energy by the impact blocks and on the turbulence of the jump phenomena for its effectiveness. Because of the large impact forces to which the baffles are subjected by the impingement of high incoming velocities and because of the possibilities of cavitation along the surfaces of the blocks and floor (due to downstream suction), the use of this basin should be limited to heads where the velocities do not exceed 15 m/s.

b) **V_1 > 15 m/s**: Here impact baffle blocks are not employed and they are designated as ***Type II stilling basin***. Because the dissipation is mainly accomplished by hydraulic jump action, the basin length will be greater than that indicated for type III basin.

However, the chute blocks and dentated end sill (instead of solid end sill) will still be effective in reducing the length from that which would be necessary if they were not used. In this basin baffle blocks are not provided because.

i) due to the high velocities of incoming flows these blocks will be subjected to excessively large impact forces, and

ii) There is a possibility of cavitation along the downstream face of these blocks and the adjacent floor of the basin due to large negative pressure being developed in this region.

The length L of Type II stilling basin may be obtained for different values of F_{r1} from the following table

F_{r1}	5	6	8	10	12	14
L/y_2	3.85	4.0	4.2	4.3	4.3	4.3

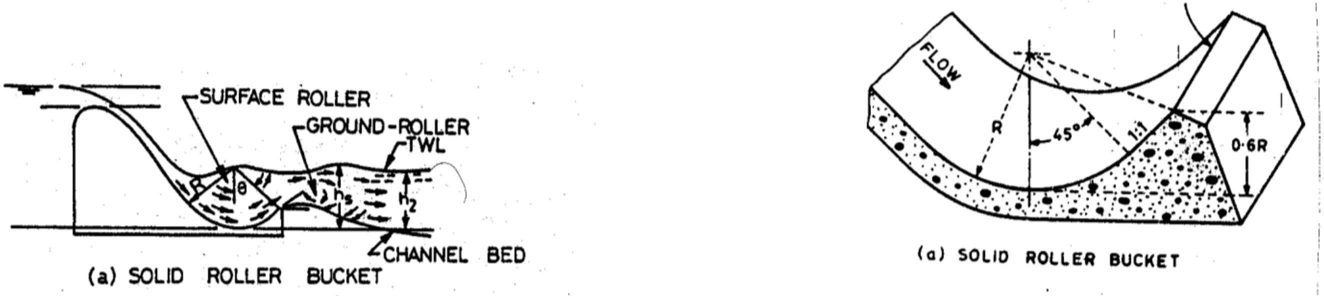
3.2.6 Submerged bucket dissipaters

When the tail water depth is too great for the formation of a hydraulic jump (i.e. when TW depth are too large as compared to the sequent depths required for the formation of hydraulic jump), dissipation of the high energy of flow can be effected by the use of submerged bucket deflector.

They are of two types, viz.

i) Solid roller bucket
ii) Slotted roller bucket

Solid Roller Bucket: Consists of a bucket like apron with a concave circular profile of large radius and a deflector lip. When water flows over the bucket the entire sheet of water leaving the bucket is deflected upwards by the bucket lip and two rollers are developed. One of the rollers, called bucket roller, moves in counterclockwise direction and is developed on the surface of the bucket. The other roller moving in clockwise direction, called ground roller, is developed on the ground surface immediately downstream of the bucket. The movement of the rollers, also with the intermingling of the incoming flows, causes the dissipation of energy.



(a) SOLID ROLLER BUCKET

(a) SOLID ROLLER BUCKET

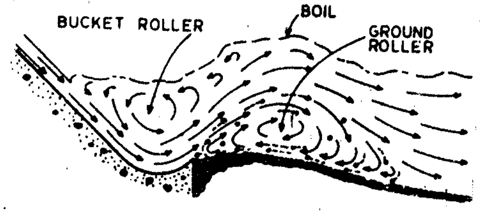
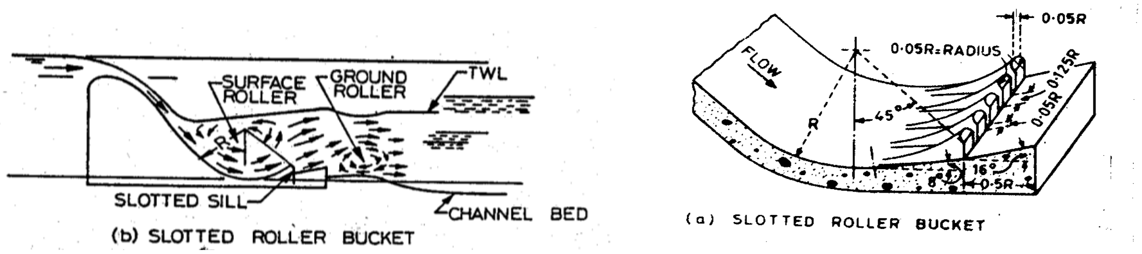


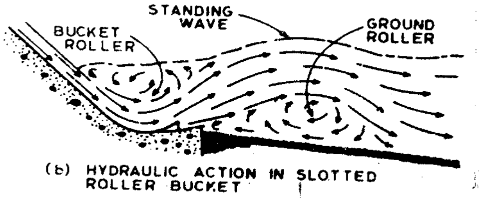
Figure 2.4 (b) HYDRAULIC ACTION IN SOLID ROLLER BUCKET

3.2.7 Slotted Roller Bucket: Consists of a bucket like apron with a concave circular profile of large radius and a slotted or dentated deflector lip. Its action is, in general, same as solid roller buckets. The two rollers are also developed in this case. However, in this case water leaves the lip at a flatter angle and only a part of it is deflected upwards. Thus surface boil is considerably reduced and less violent ground roller occurs which results in a smoother flow on the downstream side.



(b) SLOTTED ROLLER BUCKET

(a) SLOTTED ROLLER BUCKET



(b) HYDRAULIC ACTION IN SLOTTED ROLLER BUCKET

Figure 2.5 Ground and surface rollers

Ski – Jump /Deflector Bucket

This type of dissipater has a longitudinal profile, which resembles the submerged bucket. However, the deflector is elevated above the tail water level, so a jet of water is thrown clear off the dam and falls into the stream well clear off the toe of the dam. Spillways may be arranged in pairs, and then the jets made to angle inwards so that they converge and collide in mid – air. This breaks up the jets, and is very effective means of energy dissipation.

The ski – jump bucket may be used where the tail water depth is less than the sequent depth required for the formation of hydraulic jump and the riverbed is composed of stiff rock. In this case, the energy is dissipated by air resistance, breaking up of the jet into bubbles and the impact of the falling jet against the riverbed and tail water.

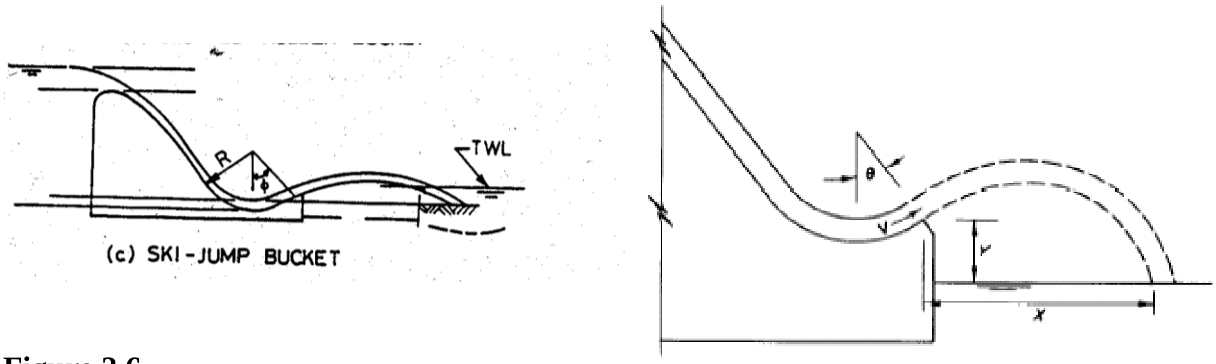


Figure 2.6

The use of ski-jump brings substantial economies where geological and morphological conditions are favorable, and particularly where the spillway can be placed over the power station. The head loss in the jet itself, whether solid or disintegrated, is only about 12% (Novak, 1996). But if the jet is split into several streams, which collide, substantial energy will be dissipated. The main benefit for energy dissipation from jet spillways is in the impact into the downstream pool. The major amount of energy dissipation occurs in the region where the jet plunges into the tailwater.

The key parameters for flip-bucket (ski-jump bucket) design are:

- The approach flow velocity and depth
- The radius R of the bucket, and
- The lip angle, θ.

At low flow, the bucket acts like a stilling basin with water flowing over the lip and the downstream face; the foundation of the bucket has, therefore, to be protected against erosion.

As the flow increases, a ‘sweep-out’ discharge is attained at which point the flip-bucket starts to operate properly wit a jet. Here, the impact zone of the jet has to be as far away as possible from the bucket to protect the structure against retrogressive erosion. The jet trajectory is hardly affected by air resistance for $v < 20$ m/s, but for velocities of 40 m/s the throw distance can be reduced by as much as 30% from the theoretical value given by $(V^2/g)\sin 2\theta$.

The throw distance x can also be computed from

$$\frac{x}{H_v} = \sin 2\theta + 2\cos\theta\sqrt{\sin^2\theta + \frac{y}{H_v}}$$

Where x = throw distance, m

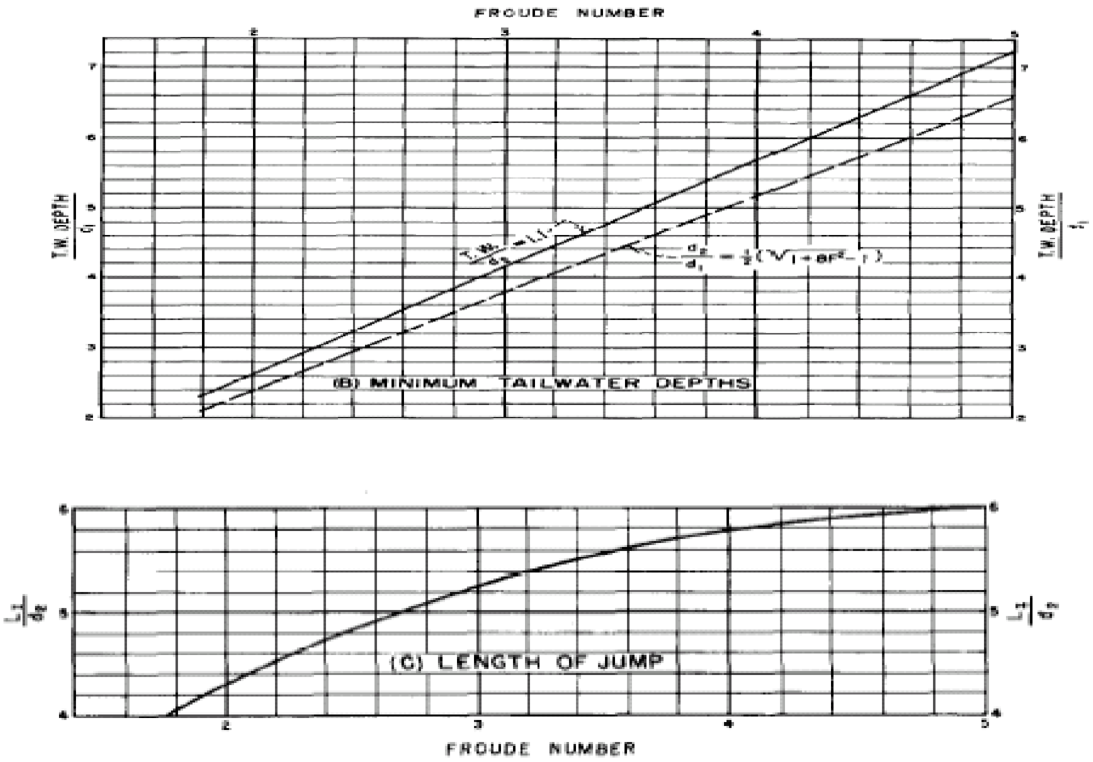
y = vertical drop from lip to tail water surface, m

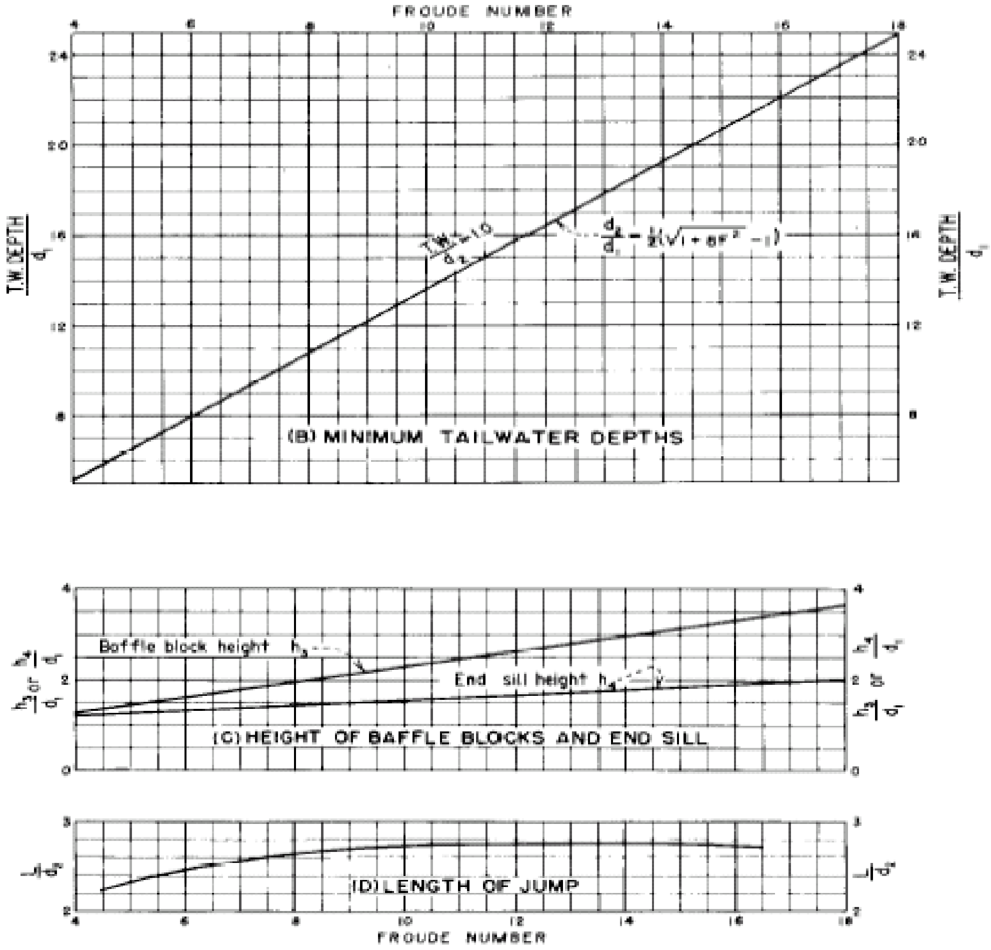
$H_v = V^2/2g$ = velocity head of jet at bucket lip, m

θ = bucket lip angle

Factors affecting horizontal throw distance include:

1. Initial velocity of jet
2. Bucket lip angle
3. Difference in elevation between lip and tail water


FROUDE NUMBER
2
3
4
5
T.W. DEPTH / d_1
$\frac{T.W.}{d_2} = 1.1$
$\frac{d_2}{d_1} = \frac{1}{2}(\sqrt{1+8F^2}-1)$
(B) MINIMUM TAILWATER DEPTHS
2
3
4
5
6
7
L_I / d_2
(C) LENGTH OF JUMP
4
5
6
FROUDE NUMBER


FROUDE NUMBER
4
6
8
10
12
14
16
18
T.W. DEPTH / d_1
8
12
16
20
24
$\frac{T.W.}{d_2} = 1.0$
$\frac{d_2}{d_1} = \frac{1}{2}(\sqrt{1+8F^2}-1)$
(B) MINIMUM TAILWATER DEPTHS
$\frac{h_3}{d_1}$ or $\frac{h_4}{d_1}$
Baffle block height h_3
End sill height h_4
(C) HEIGHT OF BAFFLE BLOCKS AND END SILL
0
2
4
L / d_2
(D) LENGTH OF JUMP
2
3
FROUDE NUMBER