35.1 Chute Spillways

35.1.1 General

The Chute Spillway is an obvious choice wherever the foundation strata pose difficult problems. Chutes are also employed in canals for conveying water from a higher to lower elevation with a consequent energy dissipation. The U.S.B.R. specifies broadly, that when canal drops are about 60 m, the Chute discharge carriers should be employed. The principle hydraulic elements of a Chute Spillway are: (1). the inlet (approach) channel and a high coefficient crested spillway (control structure). (2). Chute. (3). Energy dissipator (or Terminal Structure).

Control Structure

The control structure should have a proper approach channel. It is usually located on the flanks where the height of body wall either of masonry or concrete of spillway is considerably small. The Crest gates for flood control if necessary may be provided. Water overflowing the spillway is let into the chute.

Chute Discharge Carrier

The Chute portion will be a steep channel to convey water from a higher to lower elevation (i.e. to the natural river course at very high velocity. The cross section of the Chute may be rectangular or trapezoidal).

Energy Dissipators

These are located at the downstream end, after the fall is completely negotiated and in the vicinity of the natural stream. It may include Chute blocks, baffle blocks, stilling basin, end sill and side (training) walls. It is preferable to keep them vertical on water side for the satisfactory formation of Hydraulic jump. When the velocity at entry of stilling basin is high, Chute and baffle blocks are omitted.
35.1.2 Location, Alignment

Chute Spillways are used mostly in the case of earthen dams. The important features of chute spillways are their adoptability for any type of foundation condition and overall economy effected due to the use of the material excavated for the chute portion for the embankment. Chute spillways can be built on foundations ranging from solid rock to soft clay. The location of spillway (control structure) will be on the flank and its alignment depends on the location and topography. The simplest alignment is a straight with constant width. Varying widths or curves in alignments lead to complex flow situation (Example: Hat creek). Under certain circumstances the axis of entrance channel as well as axis of chute will have to be curved. In such cases it is better to have the curved entrance channel to have low velocities. The bottom slab of the curved channel may require to be elevated to accommodate the super elevation effect of curved channel. Usually the control structure (spillway) is built in line with the axis of the main dam.

35.1.3 Hydraulic Aspect of Design

For hydraulic design it is better to conduct model studies. When the various elements are finalised then the structural analysis is taken up. Flow in the upstream of Control structure (Crest) is subcritical. In the chute as the flow accelerates the velocity will be increasing. Flows in chute are usually maintained at supercritical. For satisfactory hydraulic performance abrupt vertical changes or sharp vertical curves (concave or convex) in the profile of the Chute should be avoided. For a satisfactory hydraulic jump to occur, the kinetic flow factor (K=F^2) is between 20 to 100 (i.e) Froude number is between 5 to 10 for stable jump to occur. The required tail water depth should be made = 0.9 y_2 (the sequent depth). Length of apron floor can be taken as 5 to 6 times of (y_2 - y_1) with Chute blocks, baffle blocks. But at higher velocities it is not advisable to provide chute and baffle blocks, when they are not provided the apron length (L_b) should be increased. In the case of Hebballa project (drop of 81.18 m in 354.33 m distance) where chute spillway is adopted, the length of apron is kept at about 7 (y_2-y_1) in view of the absence of the baffle blocks and Chute blocks based on hydraulic model studies. In
this case, the velocities developed in the model were slightly lower than the theoretical velocities. The depths must be suitably adjusted for bulking due to self aerated flow. Gumnesky has provided (Fig. 35.1) graphs for determining the bulkage and could be used. Jump height and tailwater-rating curves will have to be plotted to decide the apron level. For the designed discharge, corresponding elevation in the natural stream has to be determined. This data is very essential to decide the apron floor level. It is always best to see that jump-height elevation coincides with the elevation of tail water for designed discharge. If jump height is \( y_2 \) and tail water elevation is \( y_t \) then the apron floor should be fixed at \( y_t - y_2 \).

![Figure 35.1 - Air entrainment data for high spillways (after Gumensky)](image)

35.1.4 Structural Design

1. Chute

(a) The side walls of Chute may be with a vertical face towards water side. The Chute may also be of trapezoidal section. In the case of side retaining walls, designs must be done for worst conditions of backfill being saturated without taking into consideration
water pressure. The soil characteristics such as the dry density, internal angle of friction (33° 10') are to be obtained from field. Corrections for saturated conditions must be introduced (correction factor at 0.6 times the value for the dry condition). For trapezoidal section sides are usually 220 mm to 300 mm thickness. Plain Cement concrete is provided with nominal reinforcements at the surface in harder strata and masonry packing to the chute slabs will be required in soft soils. The sides slabs are to be well anchored to the side ground to prevent being pushed away by water.

(b) BASE SLAB: The base slab of chute is not designed for any uplift. Uplift due to water (upstream of spillway) will exist always. To calculate uplift, flow net will have to be drawn and uplift at various points determined. Since the slab thickness is to be kept at a minimum, it is enough to provide the pressure relief measures to take care of the uplift pressure. Longitudinal and Cross-drains with inverted filters are provided. Porous tiles or pipes are imbedded in the filter to collect the seepage water and convey them to a suitable point along the base slab and drain the water to the valley or stilling basin.

35.1.5 Superelevation in Chute Bends

One of the problems in the design of chutes is the determination of the path of the water around vertical and horizontal curves. Concave vertical curves present no difficulty in design, except for stresses created by the centrifugal force. Convex vertical curves must not be made steeper than the trajectory that would be followed by the high velocity water under the action of gravity. If the flume bottom is steeper than this trajectory the water will leave the bottom and may rise above the top of the side walls as observed by Hall at that Creek chute. The trajectory will be a parabola - tangent to the slope of the chute.

The equation of the curve neglecting air resistance is an adaptation of the usual equation of the path of a projectile.
To have acquired a velocity equal to the vertical component, the water would have dropped a vertical distance $y_t$.

$$y_t = \frac{v^2 \sin^2 \theta}{2g}$$

Meanwhile, the flow would cover a horizontal distance $x_t$.

The point of tangency to the parabolic curve is at coordinates $(x_t, y_t)$ from the point of origin. The equation of the curve is $x^2 = my$ in which $m = \frac{2v^2 \cos^2 \theta}{g}$

In many constructed chutes, it is formed that the water does not follow the bottom of the Channel on convex vertical curves. This may be due to that the method of calculation did not yield the actual velocity of the stream. Even if the actual mean velocity has been obtained, it is necessary to determine the maximum velocity in the channel that will occur near the surface of the centre portion of the cross section. In short chutes this maximum velocity will be nearly equal to the theoretical velocity resulting from the existing vertical drop. In longer chutes, the maximum velocity will be 15% to 20% higher from mean velocity Lane found that the maximum velocity in the UnCompahgre chute was 15% greater than the mean velocity.

Aside from the possibility of damage to the concrete in the chute from the cavitation, or from the tendency to lift the entire slab, there appears to be no serious objection in allowing the stream to leave the floor of the chute on convex vertical curves, provided the side walls are of sufficient height to prevent the side walls are of sufficient height to prevent overtopping by the spray. The observations at the flat Creek chute by Hall indicate that the spreading of the jet over a greater cross section increased the friction and aided in the dissipation of the energy. This point may be kept in mind while designing, where it is desirable to reduce the velocity of the stream before discharging the jet from the end of the chute.

Since the flow in the chute is supercritical, changes in horizontal direction are more difficult to implement and if possible should be avoided. If a horizontal curve becomes
necessary, it should be preferably be provided near the head of the chute before the water has acquired high velocity.

The water surface across the channel of a chute constructed on a curve will be tangent to a parabola. Of course, this is assuming that the channel is relatively narrow permitting the use of the radius of the centre line \( r_c \) as the average curvature of the section. Then the inclination of the tangent with the horizontal curve is given by

\[
\tan \theta_1 = \frac{V^2}{gr_c}
\]

This suitability of this equation was verified based on the observations made in south canal chute by Hall, (See Table), where the difference in elevation of the water surface between the inner and outer walls approximated the slope \( \theta_1 \). In model tests conducted by the East Bay Municipal District, Kennedy demonstrated that the flow of water around a horizontal curve is greatly improved if the bottom of the flume is superelevated on the outer wall as given by this equation.

### Superelevation of water surface, South Canal Chute

#### Another Project

Radius of curve \( r_c = 43.28 \text{ m} \)

<table>
<thead>
<tr>
<th>Station chainage (in feet)</th>
<th>Observed velocity ( V_o ) (m/s)</th>
<th>( \tan \theta )</th>
<th>Gauge Readings (m)</th>
<th>Difference in elevation m</th>
<th>Slope in a 2.4 m width ( \theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Left side</td>
<td>Right side</td>
<td></td>
</tr>
<tr>
<td>23 + 00</td>
<td>5.06</td>
<td>0.060</td>
<td>0.573</td>
<td>0.838</td>
<td>0.265</td>
</tr>
<tr>
<td>23 + 25</td>
<td>5.85</td>
<td>0.08</td>
<td>0.655</td>
<td>0.732</td>
<td>0.077</td>
</tr>
<tr>
<td>23 + 50</td>
<td>6.62</td>
<td>0.103</td>
<td>0.488</td>
<td>0.883</td>
<td>0.395</td>
</tr>
<tr>
<td>23 + 75</td>
<td>7.68</td>
<td>0.139</td>
<td>0.518</td>
<td>0.792</td>
<td>0.274</td>
</tr>
<tr>
<td>24 + 00</td>
<td>8.78</td>
<td>0.181</td>
<td>0.427</td>
<td>0.792</td>
<td>0.365</td>
</tr>
<tr>
<td>24 + 25</td>
<td>9.02</td>
<td>0.192</td>
<td>0.427</td>
<td>0.777</td>
<td>0.35</td>
</tr>
<tr>
<td>24 + 50</td>
<td>9.30</td>
<td>0.204</td>
<td>0.366</td>
<td>0.838</td>
<td>0.472</td>
</tr>
</tbody>
</table>
The superelevation of the station 23 + 00 or the P.C. of the curve is due to cross waves resulting from the curvature of the channel upstream.

Trajectory of water surface at convex vertical curve flat creek chute \((11.185 \text{ m}^3\text{s}^{-1})\)

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean Velocity (ms)</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Observed</td>
<td>Corrected</td>
</tr>
<tr>
<td>2 + 75</td>
<td>23.13**</td>
<td>0.564</td>
<td>0.527</td>
</tr>
<tr>
<td>3 + 00</td>
<td>23.16</td>
<td>1.0729</td>
<td>0.890</td>
</tr>
<tr>
<td>3 + 25</td>
<td>23.10*</td>
<td>1.40</td>
<td>1.16</td>
</tr>
<tr>
<td>3 + 50</td>
<td>22.82</td>
<td>1.067</td>
<td>0.884</td>
</tr>
<tr>
<td>3 + 75</td>
<td>22.03</td>
<td>0.60</td>
<td>0.518</td>
</tr>
</tbody>
</table>

* corrected for slope

** Total drop at 2 + 75 is 39.41 m. Theoretical velocity is 27.83 m/s.

\[
t_{\text{velocity coefficient}} = \frac{\text{Actual velocity}}{\text{Theoretical velocity}} = 0.83
\]

\[
m = \frac{2v^2}{g \cos^2 \theta}
\]

Maximum computed for theoretical velocity of 27.83 m/s was 32.00 at \(x_t = 28.69 \text{ m}\) and \(y_t = 6.236 \text{ m}\).

### 35.1.6 Curves in Chutes

Flat creek chute: The 1st 83.82 m of the chute consisted of tangents connected by short - radius vertical curves.

1st one 7.62 m radius upto bed near 0 + 25 convex.

2nd one 7.62 m radius upto bed between 1 + 25 to 1 + 50 convex.
3 rd one 7.62 m radius upto bed between 2 + 00 to 2 + 25 concave.

1 st one 7.62 m radius upto bed near 0 + 25 convex

2 nd one 7.62 m radius upto bed between 1 + 25 to 1 + 50 convex

3 rd one 7.62 m radius upto bed between 2 + 00 to 2 + 25 concave}

2 + 75 short convex vertical curve leading to an inclination of 34° 45' \( r_0 = 36.58 \) between 2 + 75 (little less say around (2+70) to (2+90).
The lower part of the curve below stn 3 + 60 was a concave vertical curve forming outlet - bucket \( R = 18.32 \) m.

Flow details at is 2 + 75 is in this section of the channel waves (shocks) formed along the side-wall gave the appearance of higher water levels than in the centre portion. However, the levels were some when checked. The entire surface of the flow was composed of these small waves or rollers which ranged from 0.13 m to 0.18 m in height above the main body of the stream.

At this stn (2+75) the curvature was too sharp to be followed by the trajectory of the flow, with the result that the upper layers of water left the bottom of the channel. At the maximum velocity and some of the spray over topped the side walls in this section. At 2 + 70, water is apparently slightly higher along the sides of the chute than in the centre due to wave action caused by retardation along the side walls. The velocity at this point was 22.86 m/s.

35.1.7 Curves in Rapid Flume

It is a wooden chute having a horizontal curve to the right near the upper end and a concave vertical curve near the terminal end of the channel. The total vertical drop is 44.20 m in a distance of 203.30 m measured along the chute.

(1) A horizontal curve to the right to station 2 + 00.

(2) A long vertical concave curve of variable radius extending from stn 2 + 75 to 5 + 25.
South Canal chute

Length 1077.54 m
height (drop) 42.67 m.

13 number horizontal curves of radii varying from 30.5 m to 91.4 m.
The sharpest angle = 98°, i = 43.28 m.
The bed of these curves are not superelevated.
The total angular deflection in the entire chute is 4 22° 32'

As the channel curves are not superelevated the water piled up on the outside of each curve and produced standing cross waves in the tangent section below the curve, in addition to the choppy roller and surface waves elsewhere noted in normal chute flow.
The formation of cross waves leads to an error in computing the wetted area at some sections as only side gauge readings were available.

In the 3.05 m width of channel the super elevation of the water surface at the outer side of the curve did not form a uniform slope across the entire cross section, due to a larger percentage of the flow following the outer wall. However on the 2.213 m channel widths the slope of the water surface was more or less uniform so that the difference in level between the gauge readings on the outer and inner walls of the curves indicated the slope of the water surface across the stream. On the curve of 43.28 m radius, is 2.133 section (width). Constructed on a 10 % grade, the flow was highly turbulent. (stn 25 + 50). The discharge in this section tended to proceed in a series of chords with a result that water crowded at certain points on the outside that water crowded at certain points on the outside of the curve, permitting spray to discharge over the top of the wall. Between these points the water surface was well below the top of the wall.
If the profile of a spillway crest is either angular or too rapidly curved, zones of locally reduced pressures and consequent separation will prevail. In order to avoid such conditions of instability and possible cavitation the crest is customarily shaped to conform at design flow to the lower surface of the ventilated nappe from a sharp crested weir of the relative height.

Application of the specific energy diagram as given for supercritical flow, is no longer possible to pass from one curve to another (Specific energy curves) except for evaluating the effects of changes in bottom elevation, the specific head curves are of little aid in the solution of problem of Supercritical flow. In addition, the following modifications of the basic theory are also found necessary for certain Supercritical conditions.

1. In steep chutes, the depth measured normal to the bottom no longer represents the pressure head on the bottom.

2. Owing to the high velocity heads, vertical curvature of the flow will produce dynamic pressure on the bottom greatly in excess of the hydrostatic pressure.
(3) In long transitions, air entrainment will cause bulking of the flow, and depths will have to be determined for the water-air mixture rather than for the water-discharge alone.

\[ H_0 = \frac{V^2}{2g} + y \cos \theta \]

In certain cases \( \theta \) may also be a variable. The rate of change of \( \theta \) at each section then corresponds to a definite curvature in the vertical plane, and the resulting Centrifugal effects must be taken into account (i.e. the pressure distribution over the section will no longer be even approximately hydrostatic). The resulting dynamic pressure may be very high, and when negative which may easily lead to cavitation and separation of the flow from the boundary. The radius of \( r_c \) for which cavitation would result (why aeration is prevented) can be approximated for convex, vertical curvature in steep chutes from

\[ 10.03 - h_v \approx \frac{V^2 y}{gr_c} - y \cos \theta \]

in which \( h_v \) is the vapour pressure head in meter. The right side of the equation can also be used to estimate the pressure on the bottom of the chute if \( r > r_c \). If the pressure is to remain atmospheric or above the value of the radius, (becomes very large for the high velocities) which may be encountered.

\[ r \approx \frac{V^2}{g \cos \theta} \]

It must be remembered that actual curvatures at many sections of a high velocity structure are often not predictable, as they depend upon the accuracy with which the design can be reproduced in the field. If the alignment of the flume shows curvatures reversed form those discussed above (i.e. Concave, Vertical Curves), the dynamic pressure is added to the static pressure as indicated by
\[ \frac{p}{\gamma} = y\cos\theta + \frac{V^2y}{gr} \]

In addition to foregoing effects of slope and vertical curvature, the entrainment of air is to be considered.

**35.1.8 Cross waves**

When the surface configuration of supercritical flows in rectangular channels may be visualised by considering a curved section of walls placed by a sequence of short chords each one of which is deflected relative to the preceding one by a small angle \( \Delta \theta \), for a convex and concave portion. The disturbance lines caused by convex and concave walls at a wave angle given by \( \beta = \sin^{-1} \frac{1}{F} \).

The depths can be found all along the wave line. However, the method of characteristics can be applied to study these in curves. The diagrams given by Ippen cannot be used for determining the flow conditions for negative deflection angles, since negative shock waves are not possible on the assumption of Hydro Static pressure. \( \Delta n \) negative disturbance lines diverge. Steep fronts commonly be produced by concentrating the lines at their origin - the equivalent of introducing the sharper curvatures. For an abrupt change of wall alignment, the resulting curvature would be infinite. Near the wall discontinuity the surface configurations will not agree with actual measurements owing to the necessarily sharp curvatures of the theoretical streamlines, good agreement is nevertheless obtained at some distance from the wall, where streamline curvatures are decreased.

**35.1.9 Designing of Super critical flow curves and patterns**

The effects of wall deflections are transmitted along disturbance lines at angles \( \beta \) to the oncoming flow. This fact leads to the unsatisfactory surface conditions in plain circular curves. Along the outside of the curve, positive hence converging, negative disturbances are successively produced and the surface rises. On the inside, the
surface drops, and negative disturbances are started which diverges as they traverse the flow at angles $\beta$. In the case of a curve with concentric walls, positive and negative disturbance lines deflect the flow in the same sense by the amount by $\Delta \theta$ assigned in the analysis to each finite disturbance line. As negative lines start to cross positive lines, the deflections are added. In a curved channel, the outer wall which turns inward to the flow will produce an oblique hydraulic jump and a corresponding positive wavefront. Similarly when the inner wall turns outside from the flow it produces negative wave front. When the disturbance lines thus produced by both outer and inner walls will be reflected back and forth between walls and will interfere with each other resulting in a disturbance pattern of cross waves. The central angle $\theta$ to the point of maximum depth along the outside wall is therefore given by

$$\theta = \tan^{-1} \frac{b}{\left(r + \frac{b}{2}\right) \tan \beta}$$
Wave front

β = wave angle

Cross waves
Figure 35.3 - Cross wave pattern in a curved channel with constant width in super critical flow

A series of maxima and minima of surface elevation approximately at angles of $\theta$, $3\theta$, $5\theta$, ... from the starting of the curve occur. The angle $\theta$ marks half the wavelength of the disturbance pattern. For practical purposes it may be assumed that the maxima and minima occur at phase angle of $\theta$ on the same radial line. Actually the location of the first maximum and minimum do not occur exactly on the radial line, but slightly on the right side and the left side of the radial line.

Ippen and Knapp obtained that increases in depth obtained for supercritical flow were more than twice the increase for sub critical flow. The depth past the maximum section will decrease. Owing to the successive influence of the negative disturbance lines arriving at the outside wall, until the positive lines reflected from the inside wall return to the outside wall. The maxima occur at an interval $\theta$. The distance between successive maxima along either channel wall is

$$L^{-1} = \frac{2b}{\tan \beta}$$