CHAPTER 5

ENERGY DISSIPATION AND DOWNSTREAM CHANNEL PROTECTION

Section I. Energy Dissipators

5-1. General. The outlet flow, whether it be from the world's largest dam or from a small storm drain, usually requires some type of energy-dissipating structure to prevent downstream channel degradation. The design may vary from an elaborate multiple basin arrangement to a simple headwall design, depending upon the size and number of conduits involved, the erosion resistance of the exit channel bed material, and the duration, intensity, and frequency of outlet flows. The structure(s) may consist of (a) abrupt expansions in high-pressure conduits (item 104), (b) hydraulic jumps in low-pressure conduits (item 130), (c) flip buckets, valves, and deflectors which spray high-velocity jets into the air before plunging into a downstream pool, and (d) conventional hydraulic-jump type stilling basins. The latter vary from sluice jets spreading on spillway faces and toe curves, to impact dissipators (item 46), to horizontal aprons with baffle piers and end sills (item 69). In many cases of low-pressure flow (storm drains, etc.), adequate dissipation of energy can be obtained by the use of riprap aprons, preformed scour holes (items 10 and 33), and other economical devices (item 34). This chapter treats in detail the design of the transition, hydraulic jump, and the rectangular cross-section stilling basin for a single conduit.

5-2. Hydraulic-Jump Type Stilling Basins.

a. General. The typical energy dissipator for an outlet works structure requires a stilling basin to produce a hydraulic jump. The stilling basin is joined to the outlet portal with a transition chute which has flared vertical sidewalls and a downward parabolic invert. Appendix F presents the procedure as set forth in this chapter for the design of outlet works stilling basin to include an illustration of a "low-level outlet with respect to tailwater" where an eddy problem may occur within the stilling basin for low and intermediate discharges.

b. Low-Level Outlets with Respect to Tailwater. The invert of the outlet portal of a conduit is "low" with respect to tailwater if for any operating discharge the d_2 curve intersects the tailwater for that discharge in the transition chute between the conduit and the stilling basin proper at a section where the slope of the chute invert is flatter than 1V on 6H (see plate C-40 for definition sketch, and items 85, 88, and 89). At several Corps installations such stilling basins performed adequately throughout the higher ranges of discharges; but at low and intermediate flows, an eddy formed in the basin and downstream flow was confined to a narrow section along one of the sidewalls. Rocks and debris were trapped in the eddy and were moved upstream to the point at which they met the efflux from the conduit; here they were agitated and some were bounced violently against the apron as they were picked up by the issuing jet and moved downstream where they again were trapped in the eddy. This action resulted in impact and abrasion damage to the concrete apron, baffles, and sidewalls. Thus, the idealized example problems given in Appendix F illustrate the procedure to determine whether eddy problems may or may not occur. If eddy problems are likely to occur, the trajectory should be designed with an inverted V as shown in para 5-2d(3). This divides low flows down both sides of the stilling basin and prevents an eddy from forming until the tailwater becomes excessively high. A model study should be made if the above guidance cannot be followed or if the flow from the outlet portal is not "ideal" with a horizontal transverse water surface and a uniform, symmetric velocity distribution. (See also para 2-7 relative to submerged outlets.)

c. Basic Considerations. Stilling basins are generally designed for optimum energy dissipation of controlled flows equal to the capacity of the outlet channel. Such flows usually occur for long periods of time and are the most critical to the life of the structure. Appreciably less than optimum performance can be accepted for higher flows of short duration as long as the jump is confined to the stilling basin. The design of stilling basins usually includes the following considerations: (1) the design discharge for the basin will exceed that for outlet works capacity and is recomputed assuming smooth pipe flow in the flood control conduit (see Moody diagram in plate C-4), design pool elevation, and negligible energy losses in the flow between the conduit exit portal and the stilling basin (see also para 2-18 relative to short conduits); (2) the minimum anticipated tailwater for the design discharge is used in establishing the basin floor elevation; (3) 0.85 to full d_2 downstream depth is recommended for design depending on the lateral distribution of flow as it enters the stilling basin, duration and frequency of high flows, foundation conditions, and submergence needed to minimize cavitation; (4) the riprap immediately downstream from the stilling basin is designed using the average velocity of the flow depth over the end sill; and (5) whether the conduit will operate in conjunction with spillway flows. In many instances, closure of the outlet works during spillway operation will effect appreciable economy in the outlet works stilling basin design.

d. Transition Chute.

(1) Sidewall Flare. The angle (ϕ) of the flared section between the projected conduit axis and the stilling basin sidewall is defined by the equation:

$$\phi = \tan^{-1}\left(\frac{1}{\Delta L}\right) \tag{5-1}$$

where ΔL is termed the flare ratio and represents the distance along the axis in the direction of flow for unit divergence. The sidewall flare should terminate at or upstream from the beginning of the stilling basin apron. If the flare ratio (ΔL) is too large, the length of chute between the outlet portal and the stilling basin becomes excessive. If the flare ratio is too small, the flow will not spread uniformly over the flared section and lateral nonuniform energy dissipation will occur in the stilling basin. In extreme cases two side rollers will form. Tests performed at the State University of Iowa (item 102) showed that the flare of a jet followed a curved path and was dependent upon the Froude number of the jet at the exit portal. Model studies with circular conduits indicate that a straight wall with a minimum flare ratio (ΔL) of twice the Froude number but not less than six produces a satisfactory design, i.e.,

$$\Delta L = 2\,\mathbb{F} = \frac{2V}{\sqrt{gD}} \quad \text{or} = 6\text{ , whichever is greater} \tag{5-2}$$

where

D = conduit diameter, ft

V = flow velocity at the exit portal, fps

This should also be satisfactory for rectangular conduit outlets. The transition chute sidewalls should be connected to the exit portal with a radius not less than five times the outlet diameter or height (5D) and the invert continued on conduit slope for the length of the corner fillets (see plate C-41). The length of the fillets for a circular conduit outlet transition should be approximately 1.5 times the conduit diameter or height (1.5D).

(2) Sidewall Restrictions and Abrupt Offsets. The possibility of a depressed pressure gradient throughout a conduit and subsequent more than normal discharge has been noted in laboratory and field tests. In model tests on an oblong-shaped conduit, side venting of the free-surface jet was apparently restricted by the sidewall design, and the energy gradient at the exit portal was depressed nearly to the conduit invert. The conduit shape was vertically oblong; the vertical sidewalls had a mitered flare (1 on

5.63) from the horizontal diameter; corner fillets were not provided at the intersection of the invert and sidewalls; and the transition invert curve was parabolic. Offsetting the walls laterally (1.5 ft on each side of the conduit) raised the pressure gradient and reduced the discharge; however, there was less satisfactory spreading of the jet into the stilling basin. Moreover, abrupt offsets result in flow riding up the sidewalls. Such effects on other conduit shapes have not been determined and this type of sidewall design should be avoided unless model-tested. These effects can exist at one discharge and disappear at either a higher or lower flow rate. (See Tuttle Creek data in plate C-3 and item 134.)

(3) Parabolic Drop. The profile of the transition chute invert from the outlet portal invert to the stilling basin floor is in the form of a parabolic curve based on the trajectory of a jet. The invert curve must not be steeper than the trajectory that would be followed by the high-velocity jet under the action of gravity, or the flow will tend to separate from the transition floor with resultant negative pressures. The floor profile should be based on the theoretical equation for a free trajectory:

$$y = -x \tan \theta - \frac{gx^2}{2\left(1.25\ V_{sm}\right)^2 \cos^2 \theta} \qquad (5\text{-}3)$$

where

x and y = horizontal and vertical coordinates measured from the beginning of the curve, ft

ℓ = angle with the horizontal of the approach invert at the beginning of the vertical curve, deg

g = acceleration due to gravity, ft/sec^2

V_{sm} = average velocity for smooth pipe flow at the beginning of the curve, fps

As a conservative measure to prevent separation of flow from the floor, the velocity (V_{sm}) in equation 5-3 has been increased 25 percent over the average flow velocity computed for smooth pipe flows. The trajectory should be joined to the stilling basin floor with a curve that has a radius equal to the entering depth, i.e., $R = d_1$. An outlet works stilling basin subject to low-flow eddies as discussed in para 5-2b should be designed with an inverted V beginning at the exit portal and sloping upward on a 1V on 7.9H slope for a distance equal to the length of the fillet L_f. The height of the inverted V above the invert of the exit portal at a distance L_f from the outlet will be 0.19D as shown in Plate C-41A (where D = equivalent diameter of the conduit). Plate C-41A shows an elevation view and section of an outlet works stilling basin with an inverted V. The equation of the new parabolic trajectory along the center line of the basin formed by the addition of the inverted V can be computed by the equation:

$$y' = -C_m x^2 \qquad (5\text{-}3a)$$

where y' and x are the vertical and horizontal coordinates measured from the beginning of the curve in feet. The center-line trajectory should intersect the floor of the stilling basin at the same distance downstream from the outlet as the ordinary trajectory. Thus, C_m for the center-line trajectory can be determined by using y' equal to the elevation at the beginning of the curve (outlet portal elevation + 0.19D) minus the elevation of the stilling basin apron, and x equal to the distance from the beginning of the curve to its intersection with the stilling basin apron (same as ordinary trajectory).

e. Elevation of Stilling Basin Floor. The stilling basin is designed as an energy dissipating device for the flow from the outlet works conduits. Its purpose is to reduce the high-velocity outlet flow to permissible exit channel velocities. The energy dissipation phenomenon is the hydraulic jump. The formula for a hydraulic jump in a level, rectangular section is:

* $$\frac{d_2}{d_1} = \frac{1}{2}\left(\sqrt{1 + 8\,\mathbb{F}^2} - 1\right) \qquad (5\text{-}4)$$

where

d_1 and d_2 = sequent depths

$\mathbb{F}$ = Froude number of the flow entering the jump, i.e.,

$$\mathbb{F} = \frac{V_1}{\sqrt{gd_1}} \qquad (5\text{-}5)$$

where V_1 and d_1 are the average flow velocity and depth, respectively, of the entering flow. It is of value for the designer to examine the type of jump to be expected with the Froude number involved. Chow (item 17) presents a discussion on the types of jump to be expected with various magnitudes of Froude numbers. The stilling basin design flow (generally, maximum discharge through the outlet channel) is used in determining the elevation of the basin floor. A floor elevation may be assumed in the case of a drop from the conduit outlet and the corresponding depth and velocity of flow entering the basin computed using Bernoulli's equation and neglecting energy loss between the conduit outlet portal and the stilling basin. This depth and velocity are used to compute the Froude number ($\mathbb{F}$). The depth of tailwater required to form a jump is computed as d_2 . The required depth (d_2) is then compared with the available depth (obtained from a tailwater rating curve) and the floor elevation assumption adjusted accordingly. Laboratory investigations have demonstrated that in the range of Froude numbers ($\mathbb{F}$) from 4 to 10, a satisfactory hydraulic jump can be made to form in a stilling basin with end sill and baffle blocks by a tailwater that produces 0.85 of the theoretical d_2 . The adequacy of the tailwater curve to fit d_2 values for flows less than the design discharge should also be checked. If downstream degradation is likely to occur after construction, estimates should be made of the possible lowering of the tailwater curve and the lowest expected tailwater curve should be used in designing the stilling basin. If the natural tailwater depth is greater than the computed d_2 depth (see para 5-2b), the length of the jump and position of the jump toe on the curved invert should be determined using HDC sheets and charts 124-1 and 124-1/1." If the basin floor is to be level with the conduit invert, equations 5-2 and 5-4 may be combined in a manner to relate the stilling basin width and depth for convenience in an economic study.

f. Basin Width. The effect of increasing the stilling basin width is to reduce the required depth of basin. Basically, the problem is an economic one in which various combinations of width and depth of basin are compared to obtain the least cost combination. (Also see para 5-2d(1) above.)

g. Basin Length. Basically, the length of a stilling basin is predicated on the length of the hydraulic jump for which it is designed. For basins with Froude numbers ($\mathbb{F}$) exceeding 3 and less than 12, a length of $3d_2$ is recommended. Longer basins should be considered when Froude numbers ($\mathbb{F}$) exceed 12 due to the magnitude of residual energy leaving the basin. When the outlet channel is located in rock (item 17), a basin length of $2.5d_2$ may be adequate. A basin length of $3.5d_2$ to $4.0d_2$ should be considered for highly erodible outlet channels. Stilling basins without baffle piers and end sills should have paved apron lengths of $4d_2$ to $5d_2$.

h. Baffle Piers. Baffle piers on the apron should have a height of d_1 or $1/6d_2$, whichever is less. They should be located $1.5d_2$ downstream from the toe of the transition chute for entering velocities ≤60 fps with Froude numbers of 3.5 to 6.0. For higher velocities they should be moved farther downstream. A second row of baffle piers is very effective in reducing scour downstream from the stilling basin. If the basin apron elevation is placed such that existing tailwater produces 85 to 90 percent of d_2 , a second row of baffle piers is recommended. The second row should be approximately $0.5d_2$ downstream from the first row. The width and spacing of piers should be equal to or slightly less than their height (d_1) . A distance of at least half of a pier width should be allowed between the end piers and the basin walls (see plate C-41). Velocities against the face of the baffles can be estimated from HDC 112-2/1.[n]

i. End Sills. Sloping end sills (1V on 1H) are preferable to vertical end sills because their self-cleaning characteristics reduce damage from trapped rocks and debris. However, they impart a vertical component to the bottom exit velocity increasing the intensity of the bottom backroller immediately downstream. End sill height of half of the baffle height is recommended (see plate C-41). Riprap at the downstream end of the stilling basin should be lower than the top of the end sill. This will help prevent backrollers from pulling rock into the basin which can cause concrete abrasion damage.

j. Training Walls. Vertical parallel training walls are recommended. Walls with as little as 4V-on-1H batter can create downstream eddies. The top of the stilling basin walls should be at the maximum tailwater elevation that may occur during operation of the outlet work in order to prevent side flow onto the hydraulic jump. Any higher tailwater resulting from spillway flows during outlet works operation must be considered, although such combined operation is not recommended. The exit transition flare should not be carried through the stilling basin. Freestanding training and dividing walls are designed to withstand static loads due to turbulence in the hydraulic jump. The static load is usually assumed to be that resulting from maximum tailwater on one side of the freestanding wall and no water against the opposite wall. A stilling basin with a high entering Froude number flow ($\mathbb{F}$ >10), foreshortened by virtue of baffle blocks and high end sill, has very violent turbulence. This dynamic loading created by the jump cannot be easily computed and where such loading is critical, model testing is recommended. Results of a study of pressure fluctuations in model stilling basin sidewalls is reported in item 35 and prototype tests results in item 48.

k. Wing Walls. Wing walls are usually not required if the exit channel invert is made at least $0.3d_2$ wider than the stilling basin and wraparound side slopes are provided (plate C-42). Quadrant wing walls at the end of stilling basins are effective in protecting the exit channel invert against scour. However, they permit more attack on the channel side slopes than freestanding basin walls with wraparound offset slopes.

l. Multiple Basins. Where more than one conduit discharges into a common outlet channel (items 124 and 126), the dividing wall or walls between basins should be sufficiently high to prevent side flow into a basin over the dividing wall when the adjacent conduit is not operated. Efficiency of the operating basin can be appreciably reduced by this flow. Whenever possible, operating schedules should provide for equal discharge from all conduits or symmetrical operation of conduits. The stilling basin design should be based on the tailwater with all conduits discharging their design flows. However, the design should be checked for design flow operation of a single conduit to be sure that the reduced tailwater is sufficient to hold the jump in the basin. Under this condition of operation a tailwater depth equal to $0.85d_2$ may be acceptable. The stilling basin design should ensure satisfactory energy dissipation for all anticipated conditions of operation. In such cases the designer must exercise considerable judgment and a model study may be desirable. Dynamic loading of the dividing wall(s) may be significant.

m. Dewatering Sumps. Dewatering sumps are required in the floor of all outlet works stilling basins to facilitate dewatering for inspection and maintenance. It is recommended that the sump be located close to the training wall in the low-velocity area between the baffle piers and the end sill and that the stilling basin floor have a slight slope toward the sump. When practical, drainpipes should be provided to alleviate standing water and to reduce pumping costs during inspections.

5-3. Low-Head Structures. Many types of energy dissipators have been developed for low-head outlet structures such as outfall storm sewers, drainage culverts, farm ponds, low dams, etc. (items 137 and 139).

a. Impact Energy Dissipator. The impact energy dissipator (items 46 and 139) is an effective stilling device even with deficient tailwater. Dissipation is accomplished by the impact of the incoming jet on a fixed, vertically hung baffle and by eddies formed by changes in direction of the jet after it strikes the baffle. Best hydraulic action occurs when the tailwater approaches, but does not exceed, a level halfway up the height of the baffle. The impact basin is recommended for outflow velocities between 2 and 50 fps. The dimensions of this energy dissipator in terms of its width are given in HDC 722-2.[n]

b. Stilling Wells. (Items 46 and 133.) Energy dissipation from a sloping conduit can be accomplished by expansion in an enlarged vertical stilling well, by the impact of the fluid on the base and walls of the stilling well opposite the incoming flow, and by the change in momentum resulting from redirection of the flow. The top of the well is usually set flush with the outlet channel. Its action is essentially independent of tailwater and WES tests indicate that it performs satisfactorily for discharge-pipe diameter ratios $(Q/D^{2.5})$ up to 10 with a stilling well-inflow pipe diameter ratio of 5. Q is the conduit flow in cubic feet per second and D is the conduit diameter in feet. Pertinent design information is given in HDC 722-1.[n]

c. Impact-Jump Basin. (Items 9 and 46.) The impact-jump basin was developed by the U. S. Department of Agriculture for small dams and achieves energy dissipation through impact on baffle piers and end sill in addition to that accomplished in an incomplete hydraulic jump. It involves a very short apron with chute blocks, baffle piers, and end sill. Basin widths greater than three times the conduit diameter have proven unsatisfactory for $Q/D^{2.5}$ greater than 9.5. Tailwater depth equal to at least $0.85d_2$ is required for acceptable performance. HDC 722-3[n] presents design dimensions in terms of the entering flows having velocities less than 60 fps and Froude numbers between 2.5 and 3.5.

d. Flared Outlet Transitions. Economical energy dissipation and scour control can be accomplished by a paved horizontal apron at a culvert outlet for discharge-conduit diameter ratios $(Q/D^{2.5})$ up to 5. Appreciable additional energy dissipation is obtained by setting the apron at an elevation up to 0.5 conduit diameters below the exit portal invert and adding an end sill of appropriate height. The necessary dimensionless design information is presented in item 34.

e. Riprap Energy Dissipators. Riprap energy dissipators for storm drain outlets have been developed by WES (items 10 and 33) for both horizontal aprons and preformed scour holes. This type of energy dissipator is adaptable to regions where riprap in the required sizes, gradation, and quantity is readily and economically available. The necessary information for sizing these structures can be computed using HDC 722-4 and 722-5.[n] The required D_{50} riprap stone size can be estimated using HDC 722-7.[n] The major dimensions of unprotected scour holes and the riprap size and horizontal blanket dimensions can be computed with CORPS H7220.[o]

Section II. Outlet Channel

5-4. General. The function of the outlet channel is to connect the outlet works to the downstream river channel. The flow leaving an outlet works energy dissipator is generally highly turbulent, and contains inverse velocity gradients and large surface waves. Provisions are recommended for an enlarged channel immediately following the hydraulic structure in which the flow can expand and dissipate excess energy. Generally, a riprapped-lined trapezoidal channel provides this function. Model tests (items 45 and 77) have demonstrated the advantages in providing for or preforming a "scour hole" in which the flow can expand and dissipate its excess energy in turbulence rather than in direct attack on the channel bottom and sides. A relatively small amount of expansion, preferably both vertically and horizontally, will greatly reduce the severity of attack on the channel boundaries. This makes it possible to stabilize the channel with rock of an economical size and provide additional factors of safety against riprap failure and costly maintenance (plate C-43). The provision of recreation facilities should be a consideration in the outlet channel design; for example, preformed scour holes provide areas of good fishing. Tailwater at the stilling basin should also be a consideration; and if feasible, the channel should be designed so that the tailwater curve will, as nearly as practical, approximate the d_2 curve for the full range of flows. Response time of tailwater to increase with increases in the outflow discharge may also be a factor. Avoid using a "perched" outlet channel spilling into a lower river channel in erodible material.

5-5. Riprap. Determination of the D_{50} size of riprap for the channel sides to a distance of $10d_2$ downstream from the upstream end of a stilling basin should be made in accordance with the guidance given in HDC 712-1[n] using the average flow velocity leaving the stilling basin. Beyond this point, channel riprap design based on EM 1110-2-1601[h] should be used. A riprap transition between the two riprap design sections is recommended. As riprap creates locally high boundary turbulence, a transition zone preceding the natural channel surface should be provided. This zone should have a length of three times the flow depth with a gradual downstream reduction in the D_{50} stone size. Design of exit channel riprap should provide protection against waves as well as velocity; therefore, reduction in stone sizes at upper levels is not recommended. All riprap gradation should be in accordance with EM 1110-2-1601.[h] Additional information is given in item 84.

5-6. Side-Slope Erosion. As noted in paragraph 5-2k, a quadrant wall c necting the training wall at the end of stilling basin to the channel ba has been found effective in protecting the floor of the exit channel aga scour. However, this wall permits more severe attack on the side slopes the outlet channel than does a training wall terminated at the end sill extended straight downstream as a freestanding wall. Therefore, except noneroding beds and banks, the training walls should terminate at the er sill and the toe of the side slopes should be offset at least $0.15d_2$ m ing the bottom of the outlet channel $0.3d_2$ wider than the stilling bas (plate C-42). Furthermore, the original streambed load should be consid in the outlet channel design. The bed load is cut off by the dam, resul in possibly more erosion downstream. Consideration should be given to m ing the outlet channel wider and lower in an area with erodible soil, as with a preformed scour hole.