NASHVILLE STORMWATER MANAGEMENT MANUAL

VOLUME 3—THEORY

CHAPTER 10

Outlet Protection

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Chapter 10
OUTLET PROTECTION

SYNOPSIS

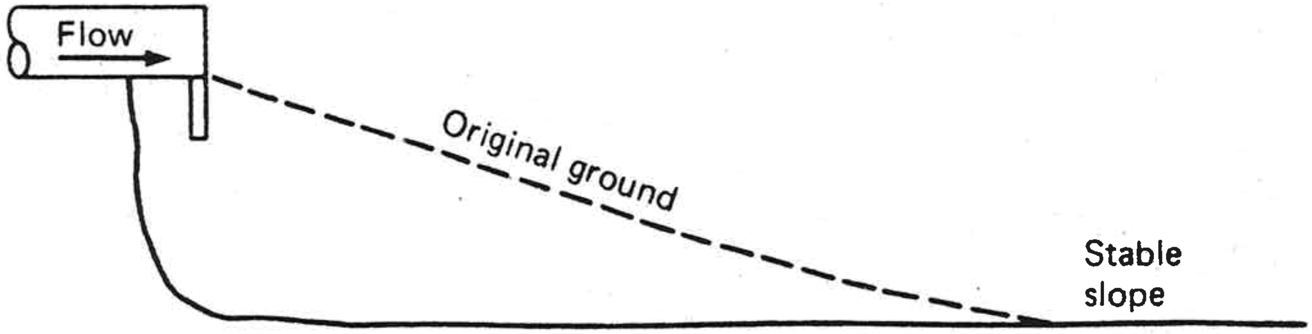
When a pipe or culvert discharges into a natural channel, potential exists for erosion at the outlet. The ground surface immediately downstream of the conduit may be eroded and the conduit itself can be undermined. To control such erosion, outlet protection devices can be used to reduce the velocity of the flow before it discharges into the natural channel. The type of device used depends on the flow characteristics, site layout, cost, and suitability for a specific location.

10.1 TYPES OF SCOUR

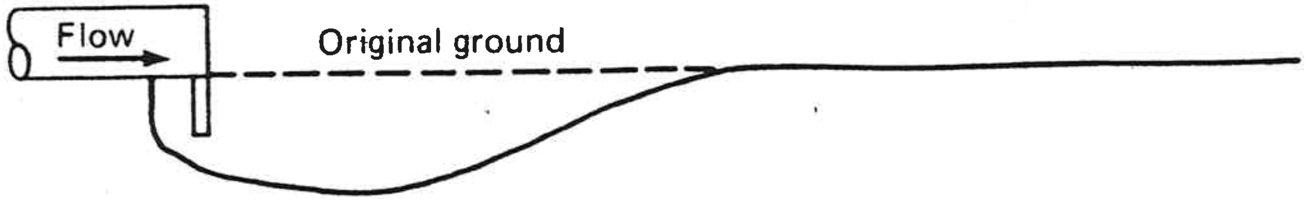
Figure 10-1 illustrates the two types of outlet erosion: gully scour and scourholes. Gully scour occurs when the stability limits of the soil are exceeded because of the flow velocity and the natural ground slope. In such a case, outlet protection should be provided to the point where the slope becomes gentle enough to be stable. For a steep slope downstream of a discharge structure, gully scour should be considered in the design of outlet protection.

Scourholes are a more localized form of erosion, caused by flow expansion from the conduit into the wider natural channel. Even when the channel slope is negligible, scourholes can form from the impact of the high velocity outflow on the ground and the turbulence of the flow expansion.

For both types of outlet erosion, the solution is to reduce the flow velocity or energy before flow is discharged onto the natural ground surface. In the case of a scourhole, the hole itself is an energy dissipator and will only enlarge to a certain size as a function of the flow conditions (see Volume 2). If the expected scourhole size is acceptable, it may simply be allowed to develop. Because a scourhole is usually undesirable, however, some type of outlet protection structure is required. Protection should always be provided if there is potential for gully scour.



A) CHANNEL EROSION



B) SCOURHOLE

Reference: Bohan (1970).

FIGURE 10-1
Types of Outlet Erosion

10.2 TYPES OF OUTLET PROTECTION

One major type of outlet protection is an impact structure, which dissipates energy through the impact of the outflow stream on a wall, impact blocks, or other obstacle. Some energy is also dissipated by the resulting turbulence, but most is lost during impact. The second major type of outlet protection dissipates energy by forcing the flow to go through critical depth and a hydraulic jump. Energy is lost when the jump occurs and in the resulting turbulence. In general, impact type dissipators are more efficient and less expensive then hydraulic jump dissipators.

The United States Bureau of Reclamation (USBR) has developed descriptions for selected types of energy dissipators, listed in Table 10-1. In addition to the USBR structures defined, riprap aprons or basins are effective energy dissipators. Riprap aprons are the simplest impact structures; energy is lost through the impact of the flow on angular rocks and the resulting turbulence. In a riprap basin, the flow drops into a rock-lined basin, where a hydraulic jump occurs. Additional energy is lost through turbulence and impact with the rocks. Riprap structures are generally a cost-effective choice for many small applications.

Suggested guidelines for selecting the type of outlet protection to use for various Froude number and outlet velocity conditions are presented in Volume 2.

10.3 HYDRAULIC JUMPS

The hydraulic jump is a natural phenomenon that occurs when supercritical flow changes to subcritical flow. This abrupt change in flow conditions can be accompanied by considerable turbulence and dissipation of energy. The effectiveness of a hydraulic jump for outlet erosion protection depends on the flow conditions, which can be evaluated using the Froude number, and the structure designed to contain the jump.

10.3.1 JUMP CATEGORIES

Critical flow exists with an upstream Froude number of 1.0, and a jump cannot occur. When the Froude number is greater

Table 10-1

SUMMARY OF OUTLET PROTECTION STRUCTURE TYPES

Type	Primary Means Of Energy Dissipation	Description
USBR Type II	Hydraulic jump	Used on high spillways and large canal structures for Fr > 4.5. Contains row of chute blocks at basin inlet and a dentated end sill.
USBR Type III	Hydraulic jump	Used on small spillways, outlet works, etc., for Fr > 4.5. Contains row of inlet chute blocks, row of baffle piers, and solid end sill.
USBR Type IV	Hydraulic jump	Used when 2.5 < Fr < 4.5. Uses chute blocks and solid end sill and may also be followed by rafts or other wave suppressors.
USBR Type VI (Baffled Outlet)	Impact	Used for pipe or open channel outlets. Uses a small box and vertical hanging baffle wall, with flow energy reduced by impact with wall and flow emerging beneath the baffle.
Riprap apron	Impact	Consists of a flat rock-lined apron. Used for low Froude numbers.
Riprap basin	Hydraulic jump	Similar to a riprap apron, but lowered so that discharging flow passes critical depth; rocks cause turbulence and help induce jump.

Fr = Froude number.

than 1.0 but less than 1.7, the upstream flow is slightly below critical depth and an undulating water surface occurs at the transition to subcritical flow. As the Froude number increases to the range of 1.7 to 2.5, a rolling transition begins to appear, signaling the conditions generally considered as the weak jump range. The energy loss for these conditions is generally no more than 20 percent.

An oscillating form of jump can occur for Froude numbers between 2.5 and 4.5, with a jet alternating from flow near the bottom to along the surface. Erosion can become a problem if surface waves are allowed to form.

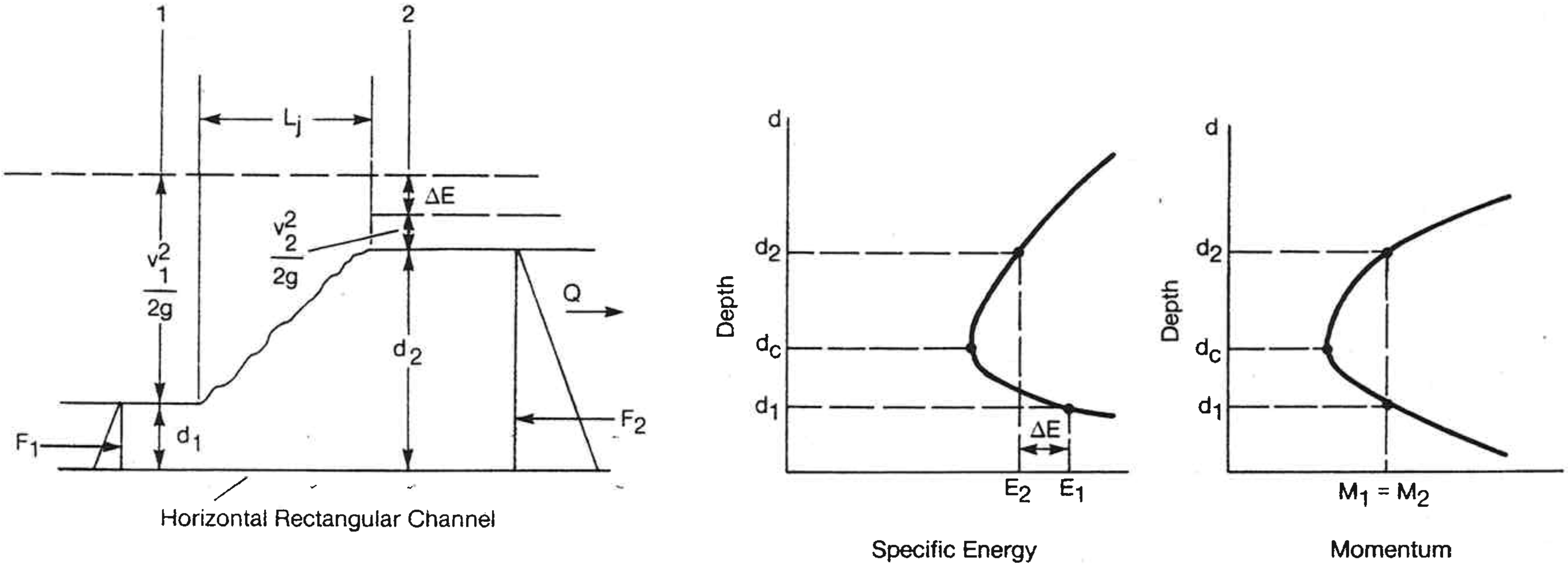
A well balanced and stable jump occurs when the incoming Froude number exceeds 4.5. Turbulence can generally be confined to the jump for this type of flow and the downstream water surface is comparatively smooth up to a Froude number of 9.0. Energy dissipation for this type of steady jump generally ranges from 45 to 70 percent.

When the Froude number exceeds 9.0, energy losses up to 85 percent are possible but downstream erosion may result from the unstable water surface. The high velocity incoming jet intermittently grabs slugs of water that roll down the face of the jump.

10.3.2 DEPTH EQUATIONS

The idealized sketch of a hydraulic jump presented in Figure 10-2 defines a control volume and the forces to consider. Control section 1 is supercritical flow upstream of the jump where the water surface is relatively undisturbed. Control section 2 is far enough downstream of the jump for flow to be again considered as longitudinal.

A hydrostatic pressure distribution can be assumed to occur at both control sections. The momentum entering and exiting the control volume is balanced by the resultant of the pressure and boundary friction forces acting on the control volume. Since the jump length is relatively short, the boundary friction forces can be neglected and the conservation of momentum gives the following general relationship:



Q = Discharge
F = Hydrostatic force
d_1 = Flow depth upstream of jump
d_2 = Flow depth downstream of jump
d_c = Critical depth
E = Specific energy = $d + \frac{v^2}{2g}$
M = Momentum = $\frac{\gamma}{g} Qv$
ΔE = Head loss through jump = $E_1 - E_2$
v = Velocity
γ = Specific weight of water
L_j = Length of jump

Reference: Morris and Wiggert (1972).

FIGURE 10-2
Hydraulic Jump Variables with Energy and Momentum Diagrams

$$F_1 - F_2 = \frac{\gamma}{g} Qv_2 - \frac{\gamma}{g} Qv_1 \qquad (10\text{-}1)$$

where:

F_1 = Upstream hydrostatic force, in pounds

F_2 = Downstream hydrostatic force, in pounds

γ = Density of water, 62.4 pounds/cubic foot

Q = Design flow rate, in cfs

g = Acceleration due to gravity, 32.2 feet/second^2

v_1 = Upstream velocity, in feet/second

v_2 = Downstream velocity, in feet/second

For the case of a horizontal rectangular channel, the following depth relationships can be derived from the general momentum equation (French, 1985):

$$\frac{d_2}{d_1} = \frac{1}{2}\left[(1 + 8Fr_1^{\,2})^{0.5} - 1\right] \qquad (10\text{-}2)$$

$$\frac{d_1}{d_2} = \frac{1}{2}\left[(1 + 8Fr_2^{\,2})^{0.5} - 1\right] \qquad (10\text{-}3)$$

where:

d_1 = Upstream flow depth, in feet

d_2 = Downstream flow depth, in feet

$Fr_1 = v_1 \ (gd_1)^{0.5}$ = Upstream Froude number, dimensionless

$Fr_2 = v_2 \ (gd_2)^{0.5}$ = Downstream Froude number, dimensionless

v_1 = Upstream, velocity in feet/second

v_2 = Downstream velocity, in feet/second

g = Acceleration due to gravity, 32.2 feet/second²

Because Equations 10-2 and 10-3 contain three independent variables, two must be known before a third can be estimated. It is important to note that the downstream depth is not a result of upstream conditions but of downstream control. In other words, if the downstream control causes a depth equal to d_2, then a jump will form.

For non-rectangular prismatic and horizontal channels, depth equations analogous to Equations 10-2 and 10-3 cannot be deriven. The general form of the momentum equation could be solved by trial and error or semi-empirical approximations, and other analytical techniques, as presented by French (1985), are available.

The hydraulic jump dissipator structures listed in Table 10-1 could also be analyzed using the general momentum equation. For these structure, a solution can become difficult because the forces acting on baffle blocks and end sills must be included in the analysis. Designs of these structures, as presented in Volume 2, are usually based on empirical relationships between the structure dimensions and the Froude number derived from physical model studies.

10.3.3 ENERGY LOSS

In a horizontal channel, the energy loss across the jump, as shown on the simplified sketch in Figure 10-2, is expressed as:

$$\Delta E = E_1 - E_2 \qquad (10-4)$$

where:

ΔE = Energy loss from section 1 to 2, in feet

$E_1 = d_1 + \frac{v_1^2}{2g}$ = Specific energy at section 1, in feet

$E_2 = d_2 + \frac{v_2^2}{2g}$ = Specific energy at section 2, in feet

d_1 = Depth at section 1, in feet

d_2 = Depth at section 2, in feet

g = Acceleration due to gravity, 32.2 feet/second²

For a rectangular channel, Equation 10-4 can be expressed as (French, 1985):

$$\Delta E = \frac{\left(d_2 - d_1\right)^3}{4d_1 d_2} \qquad (10\text{-}5)$$

where:

ΔE = Energy loss in the jump, in feet

d_1 = Upstream water depth, in feet

d_2 = Downstream water depth, in feet

The efficiency of a jump in a rectangular channel can be estimated as follows (French, 1985):

$$\frac{E_2}{E_1} = \frac{\left(8Fr_1^2 + 1\right)^{3/2} - 4Fr_1^2 + 1}{8Fr_1^2\ (2 + Fr_1^2)} \qquad (10\text{-}6)$$

where:

E_1 = Specific energy at section 1, in feet

E_2 = Specific energy at section 2, in feet

Fr_1 = Upstream Froude number, dimensionless

For non-rectangular channel sections, either the general specific energy equation must be solved on a case-by-case basis or a general graphical solution must be obtained.

10.3.4 JUMP LENGTH

The length of a hydraulic jump is generally defined to be the distance from the front face of the jump to a point on the surface of the flow immediately downstream of the roller created by the jump (see Figure 10-2). In general, the jump length cannot be derived from theoretical considerations and experimental testing is required.

For horizontal rectangular channels, Silvester (1964) has demonstrated the suitability of the following relationship:

$$\frac{L_j}{d_1} = 9.75\ (Fr_1 - 1)^{1.01} \qquad (10\text{-}7)$$

where:

L_j = Length of jump, in feet

d_1 = Upstream depth, in feet

Fr_1 = Froude number at section 1, dimensionless

An alternate approach is to use a graphical relationship presented by Bradley and Petraka (1957).