

Culvert Hydraulics Basics (HDS-5)

A culvert is a hydraulic structure first. Whether it floods the road, scours its own outlet or fills with sediment depends on how water passes through it. This course is built on FHWA Hydraulic Design Series No. 5 (HDS-5), Hydraulic Design of Highway Culverts, 3rd Edition (FHWA-HIF-12-026, April 2012). It covers inlet and outlet control, the outlet-control energy equation, entrance loss coefficients, performance curves, allowable headwater, roadway overtopping, outlet velocity, scour and sedimentation, and how repairs and liners change hydraulic behavior. The aim is to let bridge and culvert inspectors and engineers read field evidence hydraulically and understand what a hydraulic analysis is telling them. All worked numbers not quoted from HDS-5 are labeled illustrative.

Learning objectives

- Distinguish inlet and outlet control
- Use performance curves
- Explain headwater limits
- Recognize outlet scour issues

Why culvert hydraulics matters to inspectors

HDS-5 describes a culvert as a structure that conveys flow through a roadway embankment and notes that, unlike a bridge, which is normally designed with freeboard, a culvert is commonly designed to run with its inlet submerged and water ponded upstream. That one difference explains most of what inspectors see. A culvert works by using some of the head available upstream to push water through a restricted opening. When the headwater used is more than the designer intended, because the barrel is partly blocked, the tailwater has risen, the barrel has roughened or the design flow has grown, the extra head shows up as upstream flooding, overtopping, embankment saturation or piping.

The hydraulic reasoning in HDS-5 also explains outlet damage. A culvert usually confines the channel flow to a narrower, deeper section, so water leaves the barrel faster than it moves in the natural stream. That velocity, and the turbulence as the flow spreads back out, drive the outlet scour holes and perched outlets that culvert inspections so often record. Sediment deposition in a barrel, in turn, is tied to barrel slope and roughness compared with those of the channel.

An inspector does not need to run HY-8 to use this material. But knowing whether a culvert is likely to be in inlet or outlet control tells you which field conditions actually affect its capacity. For an inlet-control culvert the entrance matters most: its edge, any debris and any damage to it. For an outlet-control culvert the barrel roughness and length and the downstream tailwater also matter. This course works through those ideas in the order HDS-5 presents them. It is meant to be read alongside [BR-CU01 Culvert Inspection](#), which covers the structural side, and [BR-H01 Scour Fundamentals](#), which covers scour at bridges.

Where HDS-5 came from

HDS-5 states that its methods rest on research by the National Bureau of Standards (NBS) for the Bureau of Public Roads beginning in the 1950s, documented in seven reports. That research led to the inlet and outlet control nomographs first published in HEC-5 (1965) and later in HEC-13 (1972) and HDS-5. The 3rd edition (2012) merges this design material with chapters on aquatic organism passage (AOP), special topics such as broken-back culverts and energy dissipators, and culvert

repair and rehabilitation. HDS-5 reports that the nomograph and equation methods are generally accurate to within about plus or minus 10 percent in headwater.

The basic idea: control sections

HDS-5 explains culvert flow in terms of a **control section**: the location where there is a unique relationship between flow rate and the upstream water level. A culvert can be controlled at its entrance (**inlet control**) or at its exit or further downstream (**outlet control**). The manual's design philosophy is the **minimum performance** concept. The designer calculates the headwater required under both types of control and designs for whichever gives the higher headwater, that is, the lower performance. The culvert may in fact run more efficiently at times, but it will never do worse than the controlling case.

Flow regimes

HDS-5 distinguishes several flow states inside a barrel:

- **Full flow**: the barrel flows completely full. HDS-5 calls this pressure flow. It is common in outlet control with submerged outlets.
- **Partly full (free surface) flow**: open-channel flow inside the barrel. It may be subcritical or supercritical.
- **Just-full flow**: a barrel that is full but not under pressure, a special boundary case.

The Froude number, $Fr = V/\sqrt{gy}$, separates subcritical flow ($Fr < 1$) from supercritical flow ($Fr > 1$). HDS-5 defines the hydraulic depth y as A/T (flow area over top width) for general shapes. Supercritical flow is fast and shallow and is controlled from upstream. Subcritical flow is slower and deeper and is controlled from downstream. Critical depth, where $Fr = 1$, is the hinge between them. In inlet control the flow passes through critical depth near the entrance and is supercritical downstream. In outlet control the barrel flow is subcritical or under pressure.

USGS flow types

HDS-5 notes that the U.S. Geological Survey classified culvert flow into 18 types for measuring flow at culverts. The design methods group these into the inlet and outlet control cases. Inlet control corresponds to USGS Type 1 (unsubmerged) and Type 5 (submerged), and the outlet-control nomographs assume full-barrel flow (Type 4). You do not need to memorize the 18 types. What matters is that a culvert's flow type can change as the discharge rises.

Inlet control

In inlet control the barrel can carry more water than the entrance will let in. The control section sits just inside the entrance, where the flow passes through critical depth, and the barrel downstream runs partly full at supercritical velocity. HDS-5 lists the factors that govern inlet control headwater as:

- headwater depth above the inlet invert;
- inlet area (the barrel cross-section at the face);
- inlet edge configuration;
- inlet (barrel) shape;
- barrel slope, to a small degree.

Barrel roughness, barrel length and tailwater do *not* affect inlet-control headwater (HDS-5, Table 1.1). This is one of the most useful facts for an inspector. If a culvert is in inlet control, a rough, corroded or partly lined barrel does not change its capacity

as long as it stays in inlet control. A crushed, debris-choked or damaged entrance, on the other hand, does.

Three regions of inlet control

HDS-5 describes three regions of inlet-control behavior:

1. **Unsubmerged:** at low headwater the entrance acts like a **weir**, with flow passing over a lip into the barrel.
2. **Submerged:** once the headwater is well above the crown the entrance acts like an **orifice**, and flow varies roughly with the square root of head.
3. **Transition:** a poorly defined zone between the two, which the equations bridge with a tangent line. It is built into the nomographs.

Slope effect

The inlet-control nomographs assume a barrel slope of 2 percent. HDS-5 notes that the equations include a slope correction term of $0.5S$. For the standard 2 percent assumption this lowers the required headwater by about $0.01D$. The effect is small, which is why slope is listed as a minor inlet-control factor. HY-8 uses the actual slope.

Inlet edge configurations

Edge condition matters most when the inlet controls. HDS-5 describes common configurations including thin-edge projecting (corrugated metal sticking out of the fill), mitered to the fill slope, square edge in a headwall, and groove (socket) end projecting. Thin-edge projecting inlets contract the flow the most. Beveled edges reduce the contraction. HDS-5 recommends 45° bevels at 0.042 ft/ft (0.5 in/ft) on all culverts with headwalls, notes that 33.7° bevels at 0.083 ft/ft (1 in/ft) perform slightly better, and says a preserved groove or bell end of concrete pipe performs about like a beveled edge.

The inspection consequence: an inlet whose bevel, groove end or headwall edge has spalled, been crushed or been buried changes the entrance condition the designer assumed. In inlet control, that directly changes capacity.

Outlet control

In outlet control the barrel cannot carry as much water as the inlet would admit. The control is at the exit or further downstream. The barrel flows full, or partly full at subcritical velocity, and every factor in HDS-5 Table 1.1 applies:

- headwater and the inlet factors above, plus
- barrel roughness;
- barrel area and shape;
- barrel length;
- barrel slope;
- tailwater elevation.

HDS-5 identifies barrel slope as the primary factor deciding which control applies. Steep culverts tend toward inlet control and flat culverts toward outlet control. High tailwater alone can force outlet control. HDS-5 notes that downstream obstructions, including beaver dams, can raise tailwater. Barrel roughness in the outlet-control equations uses Manning's n . HDS-5 cites typical values of about 0.012 for smooth barrels and about 0.024 for corrugated barrels, with Appendix B giving values by material and corrugation.

The energy equation

For full flow HDS-5 writes the total loss through the culvert as the sum of entrance, friction, exit and minor losses:

$$H_L = H_e + H_f + H_o + H_b + H_j + H_g$$

Here H_b is the bend loss, H_j the junction loss and H_g the grate loss. The three that usually matter are:

- **Entrance loss:** $H_e = k_e(V^2/2g)$, with k_e from Table C.2.
- **Friction loss:** $H_f = [K_u n^2 L / R^{1.33}](V^2/2g)$, where $K_u = 29$ in English units (19.63 SI), L is the barrel length and $R = A/p$ is the full-barrel hydraulic radius.
- **Exit loss:** $H_o = 1.0(V^2/2g - V_d^2/2g)$. HDS-5 notes this may overestimate the loss. The downstream velocity V_d is usually neglected, giving $H_o = V^2/2g$.

Neglecting minor losses and combining gives HDS-5 Equation 3.5:

$$H = [1 + k_e + K_u n^2 L / R^{1.33}](V^2/2g)$$

The headwater depth above the inlet invert in outlet control is then found by adding H to the hydraulic grade line elevation at the outlet and subtracting the fall of the barrel. HDS-5 writes this as $HW_o = h_o + H - LS$, where h_o is the outlet hydraulic grade line depth (tailwater or the approximation described later), L is the barrel length and S the slope.

Entrance loss coefficients (Table C.2)

The entrance loss coefficient k_e is the single input most directly tied to what an inspector sees at the inlet. HDS-5 Appendix C, Table C.2 lists the values used in the outlet-control nomographs. The ones most often met in the field are:

Barrel and entrance	k_e
Concrete pipe projecting from fill, socket (groove) end	0.2
Concrete pipe projecting from fill, square-cut end	0.5
Concrete pipe, headwall, socket end	0.2
Concrete pipe, headwall, square edge	0.5
Concrete pipe, rounded (radius $D/12$)	0.2
Concrete pipe mitered to conform to fill slope	0.7
End section conforming to fill slope (pipe)	0.5
Beveled edges, 33.7° or 45°	0.2
Side- or slope-tapered inlet	0.2
Corrugated metal pipe or pipe-arch projecting from fill (no headwall)	0.9
Corrugated metal, headwall, square edge	0.5
Corrugated metal mitered to fill slope, paved or unpaved	0.7
Concrete box, headwall parallel to embankment, square-edged on 3 edges	0.5

Concrete box, headwall, rounded (D/12 or B/12) or beveled on 3 sides	0.2
Concrete box, wingwalls at 30° to 75°, square-edged crown	0.4
Concrete box, wingwalls at 30° to 75°, crown rounded or beveled	0.2
Concrete box, wingwalls at 10° to 25°, square-edged crown	0.5
Concrete box, wingwalls parallel (extension of sides), square-edged crown	0.7

A note to Table C.2 says that manufacturers' end sections conforming to the fill slope, metal or concrete, were found in limited hydraulic tests to be equivalent in operation to a headwall in both inlet and outlet control. Some end sections that incorporate a closed taper perform better and can be designed using the beveled-inlet information.

Reading the table as an inspector

The table spans a factor of more than four, from 0.2 to 0.9. A projecting corrugated metal pipe loses 0.9 velocity heads at the entrance, while the same pipe with a beveled headwall loses 0.2. When an inspection finds that a headwall has been lost, a bevel crushed, or an end section torn away so the barrel now projects from the fill, the culvert's entrance condition has moved down the table. If the culvert is in outlet control, that raises the headwater needed for the same flow. If it is in inlet control, the inlet-control relationship for the new edge condition applies, which is generally less efficient as well.

The reverse is also true, and it is a theme HDS-5 returns to in Chapter 6. Improving the entrance is often the cheapest way to restore capacity in an inlet-control culvert.

Illustrative outlet-control calculation

The following example is **illustrative**. The inputs are assumed for teaching and do not come from HDS-5 or any real site. It applies HDS-5 Equation 3.5 and the outlet-control headwater relationship by hand, as the HDS-5 manual method does.

Assumed data (illustrative)

- Corrugated metal pipe, D = 4.0 ft, length L = 100 ft, slope S = 0.01 ft/ft
- Manning's n = 0.024 (assumed corrugated value)
- Design flow Q = 100 ft³/s
- Tailwater depth above outlet invert TW = 2.5 ft
- Critical depth d_c = 2.9 ft (assumed, as if read from a critical depth chart; not computed here)
- Entrance: projecting from fill, k_e = 0.9 (Table C.2)

Step 1: velocity and velocity head

$$A = \pi D^2/4 = 12.57 \text{ ft}^2. \quad V = Q/A = 100/12.57 = 7.96 \text{ ft/s.} \quad V^2/2g = 7.96^2/(2 \times 32.2) = 0.98 \text{ ft.}$$

Step 2: hydraulic radius

For a full circular pipe R = D/4 = 1.0 ft, so R^{1.33} = 1.0.

Step 3: friction term

$$K_u n^2 L / R^{1.33} = 29 \times 0.024^2 \times 100 / 1.0 = 29 \times 0.000576 \times 100 = 1.67.$$

Step 4: total loss

$$H = (1 + 0.9 + 1.67) \times 0.98 = 3.57 \times 0.98 \approx 3.50 \text{ ft.}$$

Step 5: outlet hydraulic grade line

$$(d_c + D)/2 = (2.9 + 4.0)/2 = 3.45 \text{ ft. This exceeds TW} = 2.5 \text{ ft, so } h_o = 3.45 \text{ ft.}$$

Step 6: headwater

$$\text{The barrel falls LS} = 100 \times 0.01 = 1.0 \text{ ft. HW}_o = h_o + H - \text{LS} = 3.45 + 3.50 - 1.0 \approx 5.95 \text{ ft, so HW/D} \approx 1.49.$$

Because HW is well above 1.2D, the approximate method is reasonable under HDS-5's guidance. A full design would also compute inlet-control headwater and keep the larger value.

Same culvert with a beveled headwall (illustrative)

Change k_e to 0.2: $H = (1 + 0.2 + 1.67) \times 0.98 \approx 2.81$ ft, so $\text{HW}_o \approx 3.45 + 2.81 - 1.0 \approx 5.26$ ft. In this assumed case, improving the entrance lowers the outlet-control headwater by about 0.7 ft. That is a small change in k_e but a meaningful change in water level at a road with a tight allowable headwater.

Same culvert, barrel smoothed by an invert lining (illustrative)

HDS-5 Section 3.1.4 gives a composite roughness formula: $n_c = [\Sigma(p_i n_i^{1.5})/p]^{0.67}$. Its own example, a 6 ft corrugated metal pipe ($n = 0.026$) with a smooth concrete lining ($n = 0.013$) over 40 percent of the perimeter, gives $n_c \approx 0.021$. Applying a similar reduction to the illustrative pipe above, say n from 0.024 to 0.020 (assumed), cuts the friction term to $29 \times 0.0004 \times 100 = 1.16$. With $k_e = 0.9$, $H = (1 + 0.9 + 1.16) \times 0.98 \approx 3.00$ ft and $\text{HW}_o \approx 5.45$ ft. This shows why HDS-5 says invert linings often reduce outlet-control losses, as long as they do not reduce area much.

The approximate outlet hydraulic grade line

When the outlet is not submerged, the barrel is not full at the exit and the outlet water surface is not simply the tailwater. HDS-5 explains that the exact solution is a backwater calculation that starts at the outlet from the higher of critical depth or tailwater and proceeds upstream. For hand work, HDS-5 gives an approximation based on observation: the extended full-flow hydraulic grade line pierces the outlet plane about halfway between critical depth and the top of the barrel. The designer therefore begins the hydraulic grade line at $(d_c + D)/2$ above the outlet invert, or at the tailwater if that is higher, and extends the straight full-flow line upstream at the friction slope.

HDS-5 sets limits on this shortcut:

- It works best when the barrel flows full over at least part of its length.
- It becomes less accurate as the headwater drops below the top of the barrel at the inlet.
- If outlet control governs and the headwater is less than 1.2D, the barrel may flow partly full along its entire length. Use caution, and check with backwater calculations if a more accurate headwater is needed.
- Below a headwater of 0.75D the approximate method should not be used.
- Critical depth cannot exceed D.

Software such as HY-8 performs the backwater calculation directly, which is one reason HDS-5 recommends software for anything beyond routine designs.

Horizontal and adverse slopes

HDS-5 Section 3.3.4 notes that the standard procedures assume a positive barrel slope. For horizontal or adverse slopes the procedures need modification. An inspector who finds a barrel that has settled into a sag or rotated to an adverse slope has found a condition the original analysis did not assume. That deserves a note for the hydraulic engineer even if the structure looks sound.

Performance curves

HDS-5 Section 3.2 defines a performance curve as a plot of flow rate against headwater depth or elevation for a flow control device. A weir passes flow through critical depth, and its flow rises roughly with head to the 1.5 power. An orifice is fully submerged upstream, and its flow rises roughly with the square root of head. A culvert behaves like a weir at low flow and like an orifice or pipe at high flow.

A culvert installation has several possible control sections: the inlet, the outlet (barrel), and the roadway, which acts as a weir once it overtops. HDS-5 says each has its own performance curve, and the overall culvert performance curve is made up of the controlling, meaning highest-headwater, portion of each curve at each flow.

How the curves are built

- **Inlet control:** compute unsubmerged and submerged headwaters for a range of flows bracketing the design flow using the Appendix A equations, joining them with a tangent line through the transition zone. Alternatively, read headwaters from the nomographs, where the transition is built in.
- **Outlet control:** compute total losses for a series of flows with Equations 3.1 to 3.6 or the nomographs, and add them to the outlet hydraulic grade line. Backwater calculations are used where necessary.
- **Roadway overtopping:** add the weir flow across the road for headwaters above the crest.

Why both curves are drawn

HDS-5 stresses that control can shift. A culvert may be in inlet control at low flows and switch to outlet control at higher flows as the tailwater rises, or the reverse. Plotting both curves shows where the switch happens and what headwater results at the design flow and at check flows. A culvert that meets the allowable headwater at the design flow but crosses into a much steeper outlet-control curve just above it has little reserve. That is useful context when an inspector reports frequent overtopping.

Reading a performance curve (illustrative)

Imagine (illustrative) a culvert whose inlet-control curve gives 5.0 ft of headwater at 100 ft³/s and whose outlet-control curve gives 5.9 ft at the same flow. The culvert is in outlet control at 100 ft³/s, and the design headwater is 5.9 ft. If the roadway sag is at 7.0 ft above the inlet invert, overtopping begins only when one of the curves reaches 7.0 ft. Above that point the roadway weir flow is added, and the combined curve flattens sharply because the long roadway crest passes a lot of water for each added foot of head.

Headwater, tailwater and allowable headwater

HDS-5 measures headwater depth from the inlet invert at the culvert face, and tailwater depth from the outlet invert. Both are depths, not elevations. Mixing up the datum is a common error in field comparisons, for example when high-water marks are compared with design values.

Allowable versus design headwater

HDS-5 Section 2.2.5 separates two ideas. The **allowable headwater** is the maximum possible headwater or ponding depth at the upstream side of the culvert. The **design headwater** is the headwater that will actually occur for the culvert selected. The design headwater should not exceed the allowable headwater. If it does, other configurations must be evaluated until one works.

HDS-5 notes that when barrel cost is the only consideration, the most economical culvert uses all the available headwater, because capacity rises with head. Other factors limit how much headwater is acceptable. HDS-5 says the allowable headwater generally hinges on four factors:

1. **Economic considerations:** high headwater can cause embankment piping around the culvert exterior, which can lead to damage and possible failure, and higher outlet velocities with severe outlet scour that may need an energy dissipator. Sites with significant debris potential may use a lower allowable headwater. Site-specific limits are often tied to a critical point such as the roadway shoulder, the overtopping elevation, the flood damage elevation of an upstream building, or another upstream road crossing.
2. **Regulatory constraints:** under the National Flood Insurance Program administered by FEMA, the allowable increase in the base (100-year) flood elevation varies from 0 to 1 ft (0.3 m), depending on location, existing encroachments and whether there is a regulatory floodway. HDS-5 says that regardless of the design return period, the 100-year flood must be checked for the culvert's effect on the base flood elevation (23 CFR 650 Subpart A).
3. **Aquatic organism passage (AOP):** ponded conditions create rapidly changing, turbulent flow that is generally unfavorable to fish and other organisms. The most acceptable AOP design often has flow characteristics similar to the natural channel, which usually means larger structures with minimal headwater.
4. **Agency constraints:** many agencies limit headwater to the barrel height or a multiple of it, expressed as HW/D. HDS-5 states that the allowable ratio commonly ranges from 1.0 to 1.5 and must be followed unless a design exemption is granted.

Inlet depression

HDS-5 notes that available headwater can sometimes be increased by depressing the inlet, that is, constructing the inlet invert below the streambed while keeping the outlet invert on the streambed. This is advantageous for steep culverts in inlet control. The required face depression is $FD = HW_i - HW_a$, where $HW_a = EL_a - EL_{sf}$ (allowable headwater elevation minus streambed elevation at the face). If FD is zero or negative, no depression is needed. HDS-5 cautions that depression may increase sediment deposition in the barrel and the sump, and that too much rotation can change the culvert to outlet control.

Tailwater in the field

HDS-5 obtains design tailwater from normal depth calculations in the downstream channel or from field observations. Inspectors can contribute here. A new downstream culvert, a constricting bridge, vegetation, a beaver dam or an aggrading channel all raise tailwater, and HDS-5 notes that high tailwater alone can force outlet control.

Roadway overtopping

HDS-5 Section 3.1.5 explains that overtopping begins when the headwater reaches the roadway elevation, usually at the low point of a sag vertical curve, and that the flow resembles flow over a broad-crested weir. The overtopping flow is:

$$Q_o = C_d L (HW_r)^{1.5}$$

Here $C_d = k_t C_r$ is the overtopping discharge coefficient from HDS-5 Figure 3.11 (curves for deep and shallow overtopping and a submergence correction, drawn from HDS-1 and HY-7). L is the crest length, and HW_r is the upstream depth above the roadway crest. In SI units HDS-5 multiplies the English-unit coefficient by 0.552.

For a sag curve HDS-5 suggests either breaking the roadway into horizontal segments and summing the flow over each, or, often adequate for culvert design, representing the sag by a single horizontal segment. Its length is the top width of the overflow, its depth is the hydraulic depth (overflow area divided by top width), and its crest is at the lowest point of the sag. Because the culvert flow plus the overtopping flow must equal the total flow, the split is found by trial and error or by superimposing performance curves.

Illustrative overtopping check

Illustrative only: suppose a coefficient C_d of 2.9 (assumed for teaching, not read from Figure 3.11), a crest length of 80 ft, and $HW_r = 0.5$ ft. Then $Q_o = 2.9 \times 80 \times 0.5^{1.5} \approx 2.9 \times 80 \times 0.354 \approx 82$ ft³/s. Half a foot of water over a long sag can pass a flow comparable to the culvert itself, which is why roadway overtopping limits headwater rise once it starts, and why it can quickly erode an unprotected embankment.

What inspectors should note

- Evidence of overtopping: debris lines on the road or guardrail, eroded shoulders and embankment faces, displaced pavement edges.
- Where the sag low point is and whether it is above or below the culvert's reported allowable headwater.
- Embankment conditions on the downstream face, where overtopping flow does the most damage.

Outlet velocity

HDS-5 Section 3.1.6 says culvert outlet velocities should be calculated to decide whether erosion protection or an energy dissipator is needed, and notes that culverts usually produce outlet velocities higher than natural stream velocities.

Inlet control

In inlet control, the barrel flow is supercritical and the water surface converges toward normal depth down the barrel. HDS-5 says that even in short culverts, normal depth can be assumed at the outlet to define the flow area and velocity. The result may be slightly higher than the actual velocity. Normal depth is found by trial and error with Manning's equation or with software such as the FHWA Hydraulic Toolbox.

The practical consequence is that a steep, smooth barrel in inlet control delivers a fast, shallow jet to its outlet. Smoothing such a barrel, for example with a liner, can raise outlet velocity even though it does nothing for capacity.

Outlet control

In outlet control, HDS-5 defines the outlet flow area from the barrel geometry and:

- critical depth, if the tailwater is below critical depth;
- tailwater depth, if the tailwater is between critical depth and the top of the barrel;
- the full barrel area, if the tailwater is above the top of the barrel.

Illustrative outlet velocity

Illustrative: in the earlier 4 ft pipe example in outlet control with $TW = 2.5$ ft and an assumed $d_c = 2.9$ ft, the tailwater is below critical depth, so the outlet area is the segment area at 2.9 ft depth. For a circle at $y/D \approx 0.73$, the flow area is roughly 0.78 of the full area, about 9.8 ft² (approximate geometry). $V \approx 100/9.8 \approx 10$ ft/s, faster than the 8 ft/s full-barrel velocity. Values like this are why outlet aprons and dissipators exist.

Velocity control

HDS-5 describes ways to deal with high outlet velocity, including energy dissipators, and, for culverts in inlet control, changing the barrel profile or adding roughness. One example is the broken-back culvert, which breaks a steep culvert into a steep upper section followed by a flat runout. HDS-5 Section 5.6 treats broken-back culverts as internal energy dissipators if they are designed so that a hydraulic jump occurs in the runout. It notes that sufficient tailwater is needed and that roughness baffles or similar devices are ordinarily used to force the jump. HDS-5 points to HY-8 or the Nebraska Broken-back Culvert Analysis Program for the hydraulics.

Scour at inlets and outlets, and sedimentation

HDS-5 Section 5.3 places culverts in the context of fluvial geomorphology, the ongoing interplay of erosion and sedimentation described in HEC-20. It notes that past experience shows significant problems with erosion at inlets and outlets and with sediment buildup in barrels.

Scour at inlets

A culvert usually constricts the channel. As flow contracts, vortices and high-velocity flow can scour the upstream fill slopes beside the culvert, and a scour hole may form upstream of the culvert floor as flow accelerates into the barrel. HDS-5 lists upstream slope paving, channel paving, headwalls, wingwalls and cutoff walls as protection.

Scour at outlets

HDS-5 calls outlet scour a common occurrence. Flow confined to a narrower, deeper section leaves the barrel faster, and turbulence and eddies form as it spreads back out. Contributing factors include bed and bank material, the velocity and depth of flow at the outlet, and sediment and debris in the flow. HDS-5 describes scour prediction as subjective because of the variability involved. It separates two mechanisms:

- **Local scour:** a scour hole at the outlet caused by high exit velocities, extending a limited distance downstream. Coarse material from the hole often forms a low bar just downstream. The hole is generally deepest at the peak flow and can partly refill afterward. HEC-14 gives methods for estimating its dimensions.
- **Stream degradation:** lowering of the channel over long distances and periods, caused by watershed changes that may or may not involve the culvert. Examples include flow concentration by an embankment, reduced sediment supply,

channel straightening and bed lowering downstream. HDS-5 illustrates a downstream main channel whose degradation sent headcuts up tributaries and endangered a culvert. HEC-20 covers degradation evaluation.

The inspection point is that a scour hole at an outlet and a perched outlet are not the same diagnosis. A local hole may be stable and partly self-healing. Degradation keeps advancing and can undermine the outlet, the cutoff wall and eventually the barrel. Because partial refilling after floods is described in HDS-5, a shallow hole at low water does not prove that scour during the peak was shallow.

HDS-5 also notes that many DOTs use riprap aprons (HEC-14 Section 10.2) as minimum protection for small culverts against small storms. Protection for large floods or serious erosion needs HEC-14 design.

Sedimentation

HDS-5 identifies a barrel slope flatter than the natural channel and a roughness greater than the channel as key indicators of sedimentation problems. Culverts located on and aligned with the natural channel generally do not have sediment problems. A culvert in a degrading channel faces erosion, while one in an aggrading channel may accumulate sediment. Storm flows tend to flush sediment, and HDS-5 notes that helical corrugations promote this cleansing when the barrel flows full. Sediment reduces the barrel area and, in outlet control, changes the effective roughness, so heavy deposition reduces capacity.

Debris and stream stability

HDS-5 Section 2.3.1 calls debris accumulation a major problem at many culvert locations. Floods carry floating and submerged debris that can block the entrance or accumulate in the barrel. At minimum this raises maintenance costs. At worst it causes upstream flooding, overtopping and embankment failure. HDS-5 says debris and the need for debris control structures should be an integral part of design.

HDS-5 divides countermeasures into non-structural measures, mainly routine and emergency maintenance to remove debris, and structural measures that intercept debris upstream, deflect it near the entrance, or orient it to pass through. Examples it illustrates are steel rail debris deflectors, steel debris racks and concrete debris fins with sloping leading edges. It also notes that a relief opening, such as a vertical riser or a relief culvert higher in the embankment, may be desirable. HEC-9 covers debris control in detail.

Hydraulically, debris at an inlet-control culvert reduces the effective inlet area and changes the edge condition, so headwater rises directly. Debris inside an outlet-control barrel adds loss and reduces area. In both cases the culvert performs below its design performance curve.

Stream stability

HDS-5 Section 2.3.2 calls a stream stability assessment critical to long-term performance. Its examples map directly onto inspection findings:

- an actively degrading channel can leave a culvert perched, with significant outlet scour, and can undermine an open-bottom culvert unless its foundations are deep enough;
- a depositional reach can quickly fill the barrel, limiting capacity and creating ongoing maintenance costs;
- lateral instability can change the alignment of flow into the barrel over time and cause embankment erosion;
- channels carrying gravel and cobbles cause invert abrasion, which can influence material selection.

Inspectors who record channel alignment, bed material, bank condition and the elevation of the outlet relative to the downstream bed give the hydraulic engineer the information needed to tell these processes apart. [BR-H03 Stream Stability](#) covers HEC-20 concepts in more depth.

Shapes, materials and tapered inlets

HDS-5 compares barrel shapes and materials. In general terms, for the same rise a box carries the most flow, followed by an arch and then a circular pipe, reflecting the area each shape provides within a given height. Smooth materials such as concrete and plastic, with n around 0.012, lose less to friction than corrugated metal, with n around 0.024. That matters only in outlet control.

Tapered inlets

HDS-5 Section 3.4 describes tapered inlets as flared entrances with an enlarged face and a hydraulically efficient throat. They can dramatically improve performance in inlet control, mainly by reducing contraction at the throat, which becomes the control section. Some designs also depress the control section to gain head. HDS-5 notes that any inlet-control culvert entrance can be depressed, but edge conditions are normally improved first. Two types have design methods: side-tapered inlets (with or without an upstream depression) and slope-tapered inlets. Design charts exist for box and circular culverts.

In outlet control HDS-5 says tapered inlets perform effectively the same as beveled edges, both with $k_e = 0.2$. Tapered inlets are therefore not recommended on outlet-control culverts, because a simple bevel gives the same benefit. HDS-5 also notes that tapered inlets may be inappropriate in some situations, such as AOP designs.

Return period and risk

HDS-5 Section 2.1 explains return period as the reciprocal of annual exceedance probability. A flood with a 2 percent chance of being equaled or exceeded in any year has a 50-year return period. HDS-5 stresses that this does not mean the flood occurs every 50 years: two such floods could occur in successive years.

Illustrative extension: using the standard probability relation $1 - (1 - p)^n$, which this course applies and HDS-5 does not tabulate here, the chance of at least one 100-year flood ($p = 0.01$) in 30 years is $1 - 0.99^{30} \approx 26$ percent. An inspector who sees evidence of a large flood should not assume the next one is decades away.

Hydraulics of repair and rehabilitation

HDS-5 Chapter 6 covers repair and rehabilitation and closes with a section (6.4) on the hydraulic analysis of repair actions. Its point is that understanding inlet and outlet control lets the designer predict how any repair changes headwater and outlet velocity. This is directly useful to inspectors recommending work.

Replacement

Replacing a culvert with a different size, shape or type is analyzed like any new culvert. HDS-5 stresses verifying that the design discharge has not changed, particularly in urbanizing watersheds.

Frequent overtopping

Frequent overtopping often suggests an undersized culvert, which may lead to a recommendation for replacement or additional barrels. HDS-5 notes, however, that if the culvert is in inlet control, the only rehabilitation needed might be adding

a bevel or tapered entrance to the existing barrel.

Liners

HDS-5 says a liner may improve or reduce hydraulic performance:

- In **outlet control**, a liner typically reduces capacity because of the smaller area, but the loss may be offset by lower roughness.
- In **inlet control**, performance could improve if the step between the original culvert and the smaller liner creates a beveled inlet condition.
- Area reduction matters more in small culverts. HDS-5 gives the example that slip lining a 24 inch pipe with an 18 inch pipe cuts flow area by about 44 percent, while lining a 60 inch pipe with a 54 inch pipe cuts it by about 19 percent.

Joint repairs and invert linings

HDS-5 says joint repairs and invert linings typically have no effect on an inlet-control culvert, because barrel condition is not a factor in inlet control. The exception is when they add enough friction or reduce area enough to shift the culvert to outlet control. Joint repairs usually reduce friction by closing gaps, and invert linings often lower the composite n with little area loss. In outlet control the effect should be evaluated with a new n and area in the energy equation.

Applying this in an inspection recommendation

Before recommending a liner for a deteriorated barrel, ask (and record for the structural engineer) the following:

- Is the culvert likely in inlet or outlet control? Look for a steep barrel with a free outlet versus a flat barrel with a submerged outlet.
- Has the culvert overtopped or ponded, and how high? Record high-water marks relative to the inlet invert.
- What is the barrel diameter? A liner that is minor on a 60 inch pipe may be major on a 24 inch pipe.
- What is the condition of the outlet, and would a smoother barrel raise velocity onto an already scoured outlet?

Field indicators and a hydraulic checklist

The following checklist is this course's synthesis of HDS-5 concepts for field use. It is a study aid, not an HDS-5 procedure, and it does not replace a hydraulic analysis.

Upstream and inlet

- Edge condition: projecting, mitered, headwall, beveled, groove end, end section. Compare it with the plans. A changed edge changes k_e and the inlet-control curve.
- Debris at the face, racks or deflectors, and their condition.
- Sediment at the inlet or in any depression sump.
- High-water marks, and their depth above the inlet invert compared with the barrel rise (HW/D).
- Embankment seepage, sinkholes or voids near the barrel. HDS-5 links high headwater to piping.
- Inlet scour of fill slopes or the channel bed.

Barrel

- Roughness changes such as corrosion, paving, liners or deposits. These matter mainly in outlet control.

- Area loss from sediment, deformation or liners.
- Profile changes such as sags, adverse slope or separated joints.

Outlet and downstream

- Tailwater controls: downstream constrictions, beaver dams, vegetation.
- Local scour hole size and position, and any bar just downstream.
- Perching: the drop from the outlet invert to the downstream bed, a sign of degradation.
- Apron or dissipator condition.
- Bank erosion caused by the jet.

Common misreadings

- Assuming a rough barrel always reduces capacity. In inlet control it does not.
- Assuming a liner always reduces capacity. It depends on control and size.
- Treating a shallow outlet hole at low water as proof of shallow peak scour. HDS-5 notes holes partly refill.
- Comparing headwater elevations with depths. HDS-5 depths are measured from the inlet invert.

For how hydraulic findings feed load and structural evaluations, see [BR-CU03 Culvert Load Rating](#). For how culverts are reported in the national inventory, see [BR-S01 SNBI Overview](#).

Key takeaways

- HDS-5 designs for minimum performance: compute headwater for inlet and outlet control and use the higher value.
- Inlet control depends on headwater, inlet area, edge, shape and (slightly) slope. Barrel roughness, length and tailwater do not affect it.
- Outlet control adds barrel roughness, area, length, slope and tailwater. High tailwater alone can force outlet control.
- Outlet-control loss is $H = [1 + k_e + K_u n^2 L / R^{1.33}] V^2 / 2g$, with $K_u = 29$ (English units).
- Entrance loss coefficients in HDS-5 Table C.2 range from 0.2 (beveled, groove end, tapered) to 0.9 (projecting corrugated metal).
- Allowable HW/D criteria commonly range from 1.0 to 1.5, and the 100-year flood must be checked against the base flood elevation.
- Outlet velocity drives scour; HEC-14 covers scour estimates and energy dissipators, and HEC-20 covers degradation.
- Liners and repairs change hydraulics differently in inlet control than in outlet control.

References

1. FHWA, HDS-5 Hydraulic Design of Highway Culverts, 3rd Edition, FHWA-HIF-12-026, 2012
2. FHWA, HDS-5 Hydraulic Design of Highway Culverts, 3rd Edition, FHWA-HIF-12-026, April 2012 (Schall, Thompson, Zerges, Kilgore, Morris), Chapters 1-3, 5 and 6 and Appendix C, Table C.2.

Study text only; the final quiz is taken online. Verify all references against the edition your agency has adopted.