Section B3
Erosion treatment techniques for hydraulic structures
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B3.1 INTRODUCTION

This section aims to assist engineers adapt erosion treatment techniques to common hydraulic structures. However, it is stressed that creek erosion adjacent to many hydraulic structures can introduce significant habitat diversity to a watercourse which is not necessarily ‘bad’ for the watercourse. Therefore, the first question to be answered is always:

Is the erosion really a problem, or is it a case of wanting to combat erosion just because it is there?

The first step to avoiding a problem is not to place structures (including bikeways and roads) within 15 metres of the top of any watercourse bank. If bank erosion occurs, many emergency bank protection measures can result in a significant loss of environmental values within the watercourse and possibly initiate further downstream bank erosion. As a general guide, no structure should be located within the zone defined by a 3(H):1(V) gradient from the toe of a watercourse bank, unless justified by geotechnical and hydraulic advice.

B3.2 OPEN CHANNEL DROP STRUCTURES

Introduction

There are many standard energy dissipator designs for dam spillways. These designs are normally grouped into categories, depending on the calculated Froude number and velocity at the toe of the spillway. However, one common misunderstanding is that these standard designs will eliminate downstream erosion.

The main objectives of a spillway energy dissipator are to dissipate energy, reduce the extent of erosion and transfer the remaining energy far enough downstream to avoid undermining the structure. This, of course, differs from the main aim of an open channel drop structure, which is to control upstream channel velocities.

Independent of the energy dissipator design, the possibility of downstream erosion should always be considered in any spillway or drop structure design.

Approach channel

Most of the problems in the operation of drop structures occur within the outlet or energy dissipation area, but problems can also occur within the approach channel.

Drop structures, unless designed with a suitable crest weir, will experience a drawdown effect as flow approaches the drop as shown on Figure B3.1.
In the case of trapezoidal channels, the approach velocity varies along the channel chainage, width and depth. High-flow velocities associated with the drawdown effect, and variations in flow velocity across the channel width, can cause significant bed erosion immediately upstream of the drop.

The solution to this problem can be the introduction of either scour protection works upstream of the drop or a suitably designed weir at the crest of the drop as shown on Figure B3.2.
The weir crest should be designed to maintain uniform approach flow velocities over as great a discharge range as possible. This can often be achieved by the use of a stepped profile on the crest weir.

A channel constriction, such as a transition from a wide trapezoidal channel to a rectangular section, can also be used to reduce the drawdown effects, but high-approach velocities will still occur in the immediate transition area.

**Bed erosion downstream of a drop structure**

Energy dissipation of a plunging jet, discharging from a drop structure, is usually achieved by using the standard hydraulic jump basin or with a modified stilling basin (with or without baffle blocks and end sill). However, hydraulic instabilities can arise when tailwater conditions drown out this free-falling jet. Such conditions normally occur when the downstream water level rises above the crest level of the drop structure.

As the tailwater level increases, the angle of trajectory of the falling jet decreases, and the point where submerged jets impact on the downstream bed moves further downstream. Erosion problems can occur when this jet begins to strike the bed downstream of the energy dissipator blocks or the protective lining of the stilling basin.

Placing a weir at the crest of a drop will cause critical flow to occur at the crest (rather than some distance upstream), reducing the drawdown effects and the brink (crest) velocity. For a given drop height, the lower the brink velocity, the greater the impact angle of the jet and the more efficient the localised energy dissipation.

**Bank erosion downstream of a drop structure**

When the tailwater level (TW) above the weir crest approaches a depth of 0.7\(y_c\) to 0.8\(y_c\), a surface jet will form instead of a plunging jet. If the downstream channel is straight, the resulting high-velocity surface jet may not be of concern. However, conditions can occur where this jet is deflected to one side of the channel by large surface eddies. In such cases, the surface jet can cause significant bank erosion.

**Energy dissipation downstream of a drop structure**

In a typical drop structure, the Froude number (\(F_1\)) at the base of the drop is relatively low (below 4.5) and the resulting hydraulic jump is described as undular, weak or oscillating and the energy loss within the jump can be low. If the hydraulic jump is weak and the energy loss low, channel velocities will exceed those predicted by a backwater analysis downstream of the hydraulic jump.

Unless designed as a permanent pool, a stilling basin should be free-draining for health and safety reasons. An open break in the end sill to allow free draining will have fewer siltation and debris blockage problems than a low-flow pipe. The break should be divergent (widen towards the outlet) to further decrease the chance of blockage.

All stilling basins within moveable bed channels should be designed with cut-off walls constructed to a depth representative of the expected level of scour, typically not less that 0.6 metres.
**B3.3 CAUSEWAYS**

Bed erosion downstream of road and pedestrian causeways is quite common in rural residential areas of Brisbane. In most cases, the eroded scour hole should not be looked upon as a problem, but as potential aquatic habitat. However, structural problems can arise when the scour hole begins to undermine the foundations of the causeway.

Suggested means of protecting the structural integrity of the causeway are in Figures B3.3 to B3.5.

*Figure B3.3 Log and rock protection*
B3.4 CULVERTS

The impact of a culvert on the local stream ecology can often be reduced by appropriate planning of high-level and low-level wildlife corridors and the control of – but not necessarily the elimination of – stream-bank erosion. When properly planned, a culvert can be used to increase the ecological diversity of a watercourse by introducing habitat diversity. As an example, minor downstream erosion can provide:

- re-aeration of stream water
- permanent or semi-permanent ponding
- shading of the scour pond by undercutting the outlet apron. Such aprons should be designed as cantilevered structures to avoid structural collapse upon the onset of scour. Deeply recessed cutoff walls may still be required on these outlets to provide adequate foundations for the apron.

Sediment/pollution traps

Culverts can be used as convenient locations for in-stream sediment collection because in-bank access may already be needed for culvert maintenance. Sediment trapping is usually more efficient on the upstream side of the culvert because:

- lower stream velocities usually exist, especially during high-discharge events
• downstream sediment traps may allow sediment build-up within the culvert
• maintenance access is usually already required upstream of the culvert for removal of debris blockages.

When sediment traps are downstream of culverts and within the area of disturbance of the culvert outlet, the trap should be cleaned before the wet season. If a reed bed establishes itself in the sediment trap (if ecologically sound), it can increase the efficiency of the trap during periods of low flow. However, well-established reed beds can also concentrate flow through weak sections of the reed bed, decreasing the efficiency of the sediment trap.

Loosely compacted sediment, especially if it has a high proportion of cohesive clay, can be a safety hazard. Establishing a reed bed within the sediment trap can reduce such hazards.

**Safety and maintenance aspects of in-stream sediment traps should always be considered.**

Ideally, de-silting of in-stream sediment traps should be done without introducing heavy machinery into the stream bed. Once full, the location and geometry of a sediment trap will be difficult to verify. This often makes excavation of the sediment difficult. Sediment traps constructed from gabions and rock mattresses are difficult to de-silt with an excavator without damaging the wire baskets.

### Drop inlet

Drop inlets are used on culverts for a variety of reasons. As a general rule, drop inlets are preferred to drop outlets because energy dissipation occurs within the culvert and extensive downstream erosion control structures are usually not needed. However, their design needs special consideration of a number of other issues.

As a result of surface water drawdown effects, high approach velocities can cause upstream bed erosion (similar to open channel drop structures), while severe pressure differentials around the inlet can cause structural failure of the inlet apron. See Figure B3.6.

![Figure B3.6 Uncontrolled drop inlet](image)

Avoid the erosion and safety issues associated with high approach velocities by constructing an open weir control at the inlet (Figure B3.7). These weirs should allow for near uniform-flow approach conditions during bank-full flow. The weirs should also have a full depth and an open, low-flow V-notch to avoid upstream ponding.

If ponding is created by the construction of a weir within a defined watercourse, a licence from the Department of Natural Resources and Mines (Qld) might be needed. However, with an open low-flow cut, ponding will not occur and the flow control acts as a low-flow choke and not a true weir.
Figure B3.7  Controlled drop inlet

Sediment control at inlet

Sediment deposits within culverts, especially multi-cell culverts, can cause significant operational and maintenance problems. Most design recommendations suggest that the culvert should be constructed at the same grade as the existing watercourse to avoid such sediment deposits. However, this recommendation seems illogical when there is more than one cell in the culvert or when the total culvert flow area is significantly different from the in-bank area of the natural watercourse.

If the sediment size is known, then the culvert grade may be designed to allow for self-cleaning velocities to occur during the 1-year or 2-year ARI design storm. Typical self-cleaning velocities range from 0.5 to 0.9 m/s (Concrete Pipe Association, 1986 and ASCE, 1992).

However, neither of the above design philosophies may be satisfactory for multi-cell culverts because low-flow conditions can cause a sediment build-up in a number of cells (usually outer cells) while the remaining cells remain adequately flushed. Sometimes, the sediment deposits compact or become reinforced by vegetation, so the cells do not flush clean, even during significant flood events.

In critical areas, or for long culverts where maintenance is extremely difficult, a small sediment trap/weir can be built at the inlet to divert low flows to just one or two culvert cells. Flows can enter the remaining cells only during periods of high flow. These sediment weirs should be fully drowned during major flood events so no adverse backwater effects occur. Access ramps can be integrated into the design to allow for quick removal of accumulated sediment as shown in Figure B3.8.
Outlet geometry

A culvert should always be designed assuming downstream erosion will occur. Erosion should be considered the ‘norm’, not the exception, even if an energy dissipator is installed.

Very few outlet structures can effectively control all forms of erosion. The most effective control of downstream erosion is velocity control through the culvert and not energy dissipation downstream of the culvert.

When designing an outlet structure, it is very important to distinguish between the control of bed scour and control of the outlet jet. Some standard outlet structures concentrate on control of bed scour and provide little control of a submerged outlet jet. Other structures concentrate solely on energy dissipation of a free-plunging jet or a submerged floating jet.

Bed scour is usually controlled to avoid damaging the culvert structure (undermining), while energy dissipation of the outlet jet is usually required when there is a need to avoid scour of a downstream bend or streambank. In either case, erosion control is only required if excessive flow velocities are likely to exist.

If significant bed or bank scour occurs only during the less frequent floods (1-in-10 year ARI events or greater) then it could be better to repair the scour after each erosive event rather than constructing a potentially dangerous, high debris maintenance and aesthetically unattractive energy dissipator outlet.

Scour holes

References such as Bohan (1970), McInnes & Argue (1987) and US Dept. of Transport (1983) can be used to estimate the dimensions of an outlet scour hole. In general, the scour hole has the following characteristics if discharging onto a uniform, non-cohesive bed material.

- Under high tailwater conditions (outlet submerged), there will be minimal scour depth immediately downstream of the apron as shown on Figure B3.9. Under low tailwater conditions, scour depth at the apron may be 70% of the maximum scour hole depth (Bohan 1970). Thus the lower the expected tailwater level, the greater the need for, and depth of, an apron cut-off wall.

- The greatest scour hole depth will generally occur when the tailwater depth is level with, or less than, the culvert centre line (i.e. TW < D/2).

- The most severe scour will occur over the first 60 to 70% of the scour hole length, with maximum scour depth occurring at around 40% of the scour hole length downstream of the outlet.
Sometimes, the shape of the scour hole is an indicator of actual tailwater conditions that occurred during a flood. However, as most culverts are subject to a wide range of tailwater depths during flood events, the shape of the scour hole can only be used as a general indicator of typical tailwater depths.

Bed scour can be caused by a number of factors including:

- high-velocity flow entrainment induced by the outlet jet
- the outlet jet striking the bed (usually somewhere well downstream of the outlet)
- poor boundary layer development within the culvert.

In the last example, a culvert may have a low-average outlet velocity, but bed scour can still occur because the velocity profile (variation of velocity with depth) on the smooth concrete apron is significantly different from that required on a natural stream bed. See Figure B3.10.

Expansion of outlet jet

Without the use of impact blocks or columns, flow expansion from a culvert outlet can be relatively slow. As a general rule, the following applies.

- To avoid flow separation, the maximum allowable wing wall expansion for an open channel outlet is 1 in 6 ($\theta = 9.5^\circ$ relative to the culvert centre line). The US Department of Transport (1983) indicates that a straight line open channel transition/expansion may be considered an abrupt transition if $\tan(\theta) > 1/(3F_1)$. Such mild expansions are generally not practical ($F_1 =$ outlet Froude number).

- A two-dimensional (2D) unconfined jet expansion from a slot is typically defined by a 1 in 4 expanding plume. Typically, culvert outlets act as 2D flow if there is only limited vertical expansion of the outlet jet (also see HECRAS manual – culvert analysis).

- A three-dimensional (3D) unconfined jet expansion from an orifice is typically defined by a 1 in 5 expanding plume (uncommon in culvert hydraulics and generally only encountered when the outlet is fully submerged and there is significant vertical and horizontal expansion of the jet).

- A single pipe with a low to medium velocity, free discharge (low tailwater and critical depth occurring at the outlet) will typically spill-out over approximately a 1 in 2 expansion.

As a jet expands from a fully submerged outlet, velocity reduction begins to occur on the outer circumference of the jet, while the centre core maintains its exit velocity for around 6 diameters (or slot
widths in 2D flow) from the outlet. At around 10 diameters (or slot widths) from the outlet, the centre velocity of the jet is around 60% to 70% of the exit velocity. If a scour hole is formed, its length can reach 10 to 13 times the effective outlet diameter.

**Cut-off walls**

Scour hole experiments have indicated that the lower the tailwater level, the greater the scour hole depth adjacent to the outlet apron. Since most floods usually start with near zero flow and low tailwater levels, the incidence of bed scour and the undermining of outlet aprons are quite common. Unless suitably designed, outlet aprons will be subject to structural damage if bed scour undermines the apron.

As discussed elsewhere in these guidelines, bed scour is not necessarily a problem requiring a solution. In some cases, bed scour and undermining outlet aprons can add to the creek’s habitat diversity. In cases where undermining is allowed, a recessed cut-off wall is still recommended. See Figure B3.11.

![Recessed cut-off wall](image)

**B3.11 Recessed cut-off wall**

**Outlet structures**

Outlet structures are used for:

- energy dissipation
- flow expansion
- boundary layer development – stream bed scour control
- controlling hydraulic jump location – location of bed scour
- supporting fish migration.

Control of the outlet jet and control of bed scour are two separate functions, often needing separate solutions. Both factors must be addressed separately. Energy dissipators should be introduced only if an erosion problem is considered to exist.

**B3.5 ENERGY DISSIPATORS**

Energy dissipator outlets can be:

- impact structures
- plunge pools
- bed friction
- hydraulic jump outlets.

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* Refer Brisbane City Council’s Stormwater Outlets in Parks and Waterways guideline.
In most cases, the need for, and use of, baffle blocks, impact columns and hydraulic jump energy dissipators on culvert outlets should be avoided for the safety of the public and aquatic-life.

**Impact structures**

Impact structures consisting of dissipator blocks or impact columns are effective in medium to high velocity outlets where control of the outlet jet is required. The control of bed scour immediately downstream of the outlet usually needs extra riprap protection and/or the introduction of an end sill at the end of the apron.

A review of the design philosophy of drop structure energy dissipators (Witheridge, 1994) has shown that the height of baffle blocks is usually equal to the height of the incoming jet. In the case of a culvert outlet, the height of the incoming jet is usually equal to the height of the culvert. Physical model studies of culvert outlets have also shown that, to be effective for culvert-full flow, impact columns need to be at least equal in height to the height of the culvert (AWACS, 1990 and Smith & Yu, 1966).

In the absence of any proven designs (model studies or field testing), the momentum equation can be used to give an initial estimate of the required total surface area of impact blocks/columns. However, the calculated impact surface area must confront the jet in order to be effective.

**Plunge pools**

Plunge pools are an effective way of dissipating energy and controlling bed scour. However, if these designs are to be effective, the outlet jet must be allowed to free-fall into the pool. This requires low tailwater conditions. Under high tailwater conditions (fully submerged outlet), plunge pool designs are relatively ineffective at controlling the outlet jet.

It is recommended that concrete or other impervious surface lined plunge pool dissipators be free-draining to avoid the formation of stagnant water bodies. Scour holes in natural streambeds on the other hand, often develop a balanced aquatic ecosystem which avoids many of the health problems associated with stagnant water.

**Bed friction**

Some dissipators use riprap or rows of small dissipator blocks to retard the plunging (or spilling) outlet flow. This artificial bed friction can help spread the flow, develop an effective boundary layer to reduce bed scour and/or induce a hydraulic jump if favourable tailwater conditions exist.

Bed friction energy dissipators are most effective at low tailwater conditions and have only minimal control over a fully submerged outlet jet.

**Hydraulic jumps**

Hydraulic jump dissipators are usually very effective for high velocity ‘sheet’ flow (spillway) outlets. They usually need well-controlled tailwater levels to prevent the hydraulic jump from being drowned or washed out of the basin. These structures generally have only limited value in culvert outlet design because suitable tailwater conditions cannot be guaranteed and outlet velocities are too small.

**Flow expansion**

Energy dissipation is usually associated with flow expansion. As flow velocity decreases, the flow area must expand to maintain continuity. Conversely, an effective way to dissipate energy is to force the
outlet jet to expand (Smith & Yu, 1966). Impact blocks and columns can be used to initially break-up or spread the outlet jet, increasing the rate of energy dissipation.

As a general rule, the greater the total jet circumference and the lower the tailwater level, the more localised energy dissipation will be with respect to the outlet. As reported by Seetharamaiah and Shashidhara (1965), energy dissipation in twin jets is much greater than in a corresponding single jet of the same total area and outlet velocity. Downstream of the outlet, the two jets eventually merge and the effective rate of energy dissipation decreases. Increasing the distance between the jets will delay their merging, but will also increase the width of the outlet.

**Boundary layer development**

The function of an outlet energy dissipator is not just to return the flow back to the required average velocity, but also to the required velocity distribution throughout the flow depth. That is, appropriate streambed-boundary layer conditions need to be achieved to minimise bed scour. See Figure B3.10.

Small roughness blocks, often used for boundary layer development or forced hydraulic jump development, should be placed in rows not closer than 6 to 12 times the block height (h). Results from “Forced Hydraulic Jump Basins”, US Department of Transport (1983), indicate that for slightly submerged roughness blocks (say h/y₁ < 0.9; where y₁ = outlet flow depth) the row spacing should be 6h, while for well-submerged blocks (say h/y₁ > 0.3) a row spacing of 12h is more appropriate. Closely spaced rows cause shadowing effects that decrease the efficiency of the roughness blocks, causing the outlet jet to pass over the blocks with only minor energy dissipation.

**Control of hydraulic jumps**

Some outlet structures introduced bed roughness to form the hydraulic jump and stabilise its position. Generally, these structures require specific tailwater conditions that are often difficult to guarantee at typical culvert locations.
**TYPICAL OUTLET STRUCTURES**

<table>
<thead>
<tr>
<th>Name</th>
<th>Gabion outlet</th>
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<tbody>
<tr>
<td>Function</td>
<td>Prevent bed scour undermining head wall, boundary layer control, energy dissipation</td>
</tr>
<tr>
<td>Form of energy loss</td>
<td>Plunge pool/bed friction</td>
</tr>
<tr>
<td>Tailwater conditions</td>
<td>Effective at low tailwater only</td>
</tr>
<tr>
<td>Jet control</td>
<td>Control of plunging jet, minimum control of high-velocity submerged jet</td>
</tr>
<tr>
<td>Bed scour control</td>
<td>Bed scour will still occur, but away from the head wall</td>
</tr>
<tr>
<td>Debris effects</td>
<td>Low debris hazard</td>
</tr>
<tr>
<td>Safety issues</td>
<td>Low safety hazard</td>
</tr>
</tbody>
</table>

* For further information, see Brisbane City Council’s - Stormwater Outlets in Parks and Waterways Guideline 2003
Name: Riprap outlet
Function: Energy dissipation, boundary layer development, control of bed scour location
Form of energy loss: Bed friction
Tailwater conditions: Designs for both high and low tailwater conditions
Jet control: Control of plunging jet only (low tailwater condition)
Bed scour control: Control of both location and extent of bed scour, but scour is not eliminated
Debris effects: Low debris hazard
Safety issues: Low safety hazard

Name: Rock lined plunge pool
Function: Energy dissipation
Form of energy loss: Plunge pool
Tailwater conditions: Effective at low tailwater conditions
Jet control: Control of plunging jet, minimum control of submerged outlet jet
Bed scour control: Bed scour caused by a high velocity submerged jet can still occur
Debris effects: Low debris hazard
Safety issues: Low safety hazard
### Riprap Basin

**Name:** Riprap Basin  
**Design reference:** U.S. Dept. of Transport (1983)  
**Function:** Energy dissipation, hydraulic jump control  
**Form of energy loss:** Plunge pool  
**Tailwater conditions:** Effective for tailwater less than 3/4 incoming jet depth  
**Jet control:** Jet control exists only for low tailwater conditions (plunging jet)  
**Bed scour control:** Bed scour control exists for low tailwater conditions  
**Debris effects:** Low debris hazard  
**Safety issues:** Low to medium safety hazard, ponding may occur  

### Single Pipe Outlet

**Name:** Single pipe outlet  
**Design reference:** Argue (1960), Queensland Transport (1975)  
**Function:** Energy dissipation, hydraulic jump control, flow expansion  
**Form of energy loss:** Plunge pool/hydraulic jump  
**Tailwater conditions:** Effective at low tailwater conditions (inlet control)  
**Jet control:** Minimal control of high velocity submerged jets, controls plunging jets  
**Bed scour control:** Riprap required if bed scour is to be controlled  
**Debris effects:** Low debris hazard  
**Safety issues:** Medium safety hazard
**Name:** Twin pipe outlet  
**Design reference:** O'Loughlin (1960), Queensland Transport (1975)  
**Function:** Energy dissipation, hydraulic jump control, flow expansion  
**Form of energy loss:** Plunge pool/hydraulic jump  
**Tailwater conditions:** Effective at low tailwater conditions (inlet control)  
**Jet control:** Minimum control of high-velocity submerged jets, controls plunging jets  
**Bed scour control:** Riprap required if bed scour is to be controlled  
**Debris effects:** Low debris hazard  
**Safety issues:** Medium safety hazard

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**Name:** Forced Hydraulic Jump Basin or CSU Rigid Boundary Basin  
**Design reference:** U.S. Dept. of Transport (1983)  
**Function:** Energy dissipation, boundary layer development, hydraulic jump  
**Form of energy loss:** Impact, bed friction, hydraulic jump  
**Tailwater conditions:** Tailwater requirements exist but are flexible, generally suitable for a range of tailwater conditions  
**Jet control:** Minimum jet control unless effective hydraulic jump forms  
**Bed scour control:** Relatively good control of bed scour  
**Debris effects:** Medium debris hazard  
**Safety issues:** Medium safety hazard

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**Name:** Hydraulic Jump Chambers  
**Design reference:** Korom, Sarikelle & Simon (1990)  
**Function:** Energy dissipation, hydraulic jump control  
**Form of energy loss:** Bed friction/hydraulic jump  
**Tailwater conditions:** Maximum tailwater requirements exist, no minimum tailwater condition
Jet control: Jet control exists if an effective hydraulic jump is formed, otherwise jet will wash through with minimum energy loss
Bed scour control: Minor bed scour may still occur
Debris effects: Low to medium debris hazard, but may be difficult to desilt
Safety issues: Medium safety hazard

Name: Hydraulic jump
Function: Energy dissipation
Form of energy loss: Hydraulic jump
Tailwater conditions: Strict tailwater requirements exist to control location of jump
Jet control: Jet control exists if an effective hydraulic jump forms, for typical culvert outlet, hydraulic jump is weak and jet control limited
Bed scour control: Minimal bed scour control
Debris effects: Low debris hazard
Safety issues: Low to medium safety hazard

Name: USBR Type II, III, IV, and SAF Stilling Basins
Function: Energy dissipation, hydraulic jump control
Form of energy loss: Impact/hydraulic jump
Tailwater conditions: Tailwater requirements exist, but generally can operate over a range of tailwater conditions
Jet control: Effective jet control if hydraulic jump if formed
Bed scour control: Limited control of location and extent of bed scour
Debris effects: Low debris hazard
Safety issues: High safety hazard
### Name: USBR Type VI Impact Basin


**Function:** Energy dissipation

**Form of energy loss:** Impact

**Tailwater conditions:** Although not necessary, basin performance will improve with the presence of some tailwater

**Jet control:** Control of high-velocity outlet jet

**Bed scour control:** Bed scour will still occur and may require riprap protection

**Debris effects:** High debris hazard

**Safety issues:** Extreme safety hazard

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### Name: Contra Costa Energy Dissipator

**Design reference:** Keim (1962), U.S. Dept. of Transport (1983)

**Function:** Energy dissipation, hydraulic jump control

**Form of energy loss:** Impact/hydraulic jump

**Tailwater conditions:** Flexible tailwater requirements, can operate with no tailwater

**Jet control:** Jet control exists if culvert flow is less than half full

**Bed scour control:** Bed scour will still occur and riprap may be required

**Debris effects:** Low to medium debris hazard

**Safety issues:** High safety hazard
Name: Impact column open channel expansion
Design reference: Smith & Yu (1966), Hydraulic investigation only, design procedure not supplied
Function: Energy dissipation, flow expansion
Form of energy loss: Impact type
Tailwater conditions: Suitable for high or low tailwater conditions
Jet control: Effective jet control
Bed scour control: Minimum bed scour control
Debris effects: Medium to high debris hazard
Safety issues: Extreme safety hazard

Name: Hook dissipator
Function: Energy dissipation, flow expansion (developed for large arch culverts)
Form of energy loss: Impact/hydraulic jump
Tailwater conditions: Effective for a range of tailwater conditions
Jet control: Effective control of outlet jet
Bed scour control: Bed scour may still occur, riprap protection may be required
Debris effects: Medium debris hazard
Safety issues: High safety hazard
B3.6 BIBLIOGRAPHY


