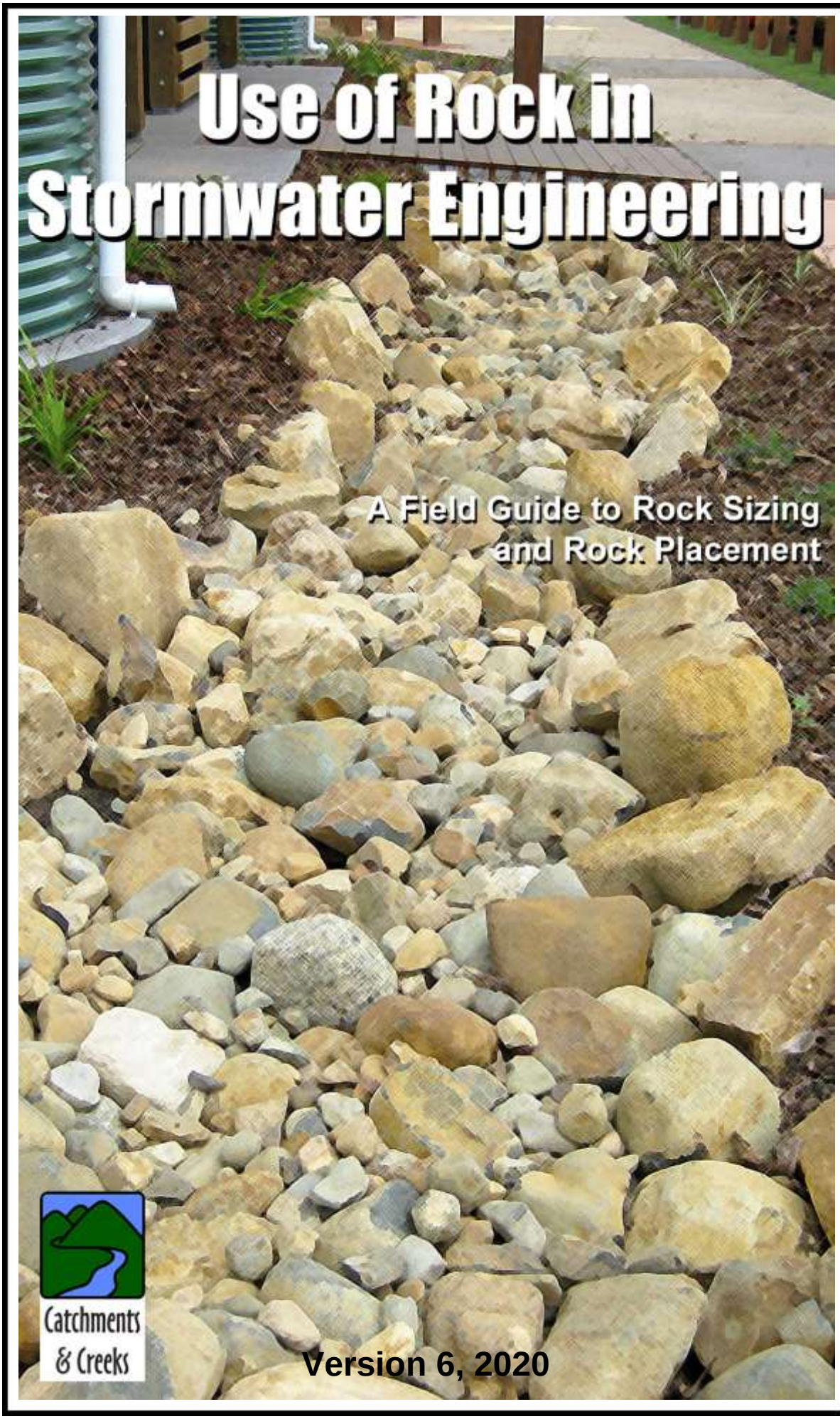
Use of Rock in Stormwater Engineering
A Field Guide to Rock Sizing and Rock Placement
Catchments & Creeks
Version 6, 2020

Use of Rock in Stormwater Engineering

Version 6, November 2021

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Published by: Catchments and Creeks Pty Ltd

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Witheridge 2021, *Use of Rock in Stormwater Engineering*. Catchments and Creeks Pty Ltd., Bargara, Queensland

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Disclaimer

Significant effort has been taken to ensure that this document is representative of current best practice with regards to the sizing and placement of rock within stormwater engineering. However, the author cannot and does not claim that the document is without error, or that the recommendations presented within this document will not be subject to future amendment.

The sizing and placement of rock is not an exact science. In general, the use of rock in stormwater engineering produces more 'natural' outcomes; however, these outcomes are also likely to be more susceptible to hydraulic failure.

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Specifically, adoption of the recommendations and procedures presented within this field guide will not guarantee:

- compliance with any statutory obligations
- avoidance of environmental harm or nuisance
- the design of engineering structures that will be stable in all flow conditions.

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Purpose of field guide

This field guide has been prepared specifically to:

- provide a general overview of engineering practices associated with the sizing and placement of rock within stormwater systems and constructed drainage channels
- assist engineers in understanding how the sizing of rock for engineered structures may vary from structure type to structure type
- assist engineers in understanding the most common failure modes of rock-lined engineering structures.

The photos presented within this document are intended to represent the current topic being discussed. These photos are presented for the purpose of depicting either a preferred or discouraged outcome (as the case may be). In some cases the photos may not represent current best practice, but are simply the best photos available to the author at the time of publication.

The caption and/or associated discussion should **not** imply that the actual site shown within the photograph represents either good or bad stormwater practice. The actual circumstances, site conditions and history of each site are not known, and may not be directly relevant to the current discussion. This means that there may be a valid, site-specific reason why the designer chose the design or layout depicted in the photo.

About the author

Grant Witheridge is a civil engineer with both Bachelor and Masters degrees from the University of NSW (UNSW). He has over 40 years experience in the fields of hydraulics, stormwater management, creek engineering and erosion & sediment control, during which time he has worked for a variety of federal, state and local governments, and private organisations.

Grant commenced his career at the UNSW Water Research Laboratory constructing and operating physical flood models of river floodplains. He later worked for Brisbane City Council on creek engineering and stormwater management issues. He currently works through his own company Catchments & Creeks Pty Ltd.

Grant is the principal author of the revised Queensland Urban Drainage Manual (2007, 2013 & 2016), Brisbane City Council's Natural Channel Design and Creek Erosion guidelines; the IECA (2008) Best Practice Erosion & Sediment Control documents, and the 2002 engineering guidelines on the Fish Passage Requirements for Waterway Crossings.

Introduction

Rock is a natural substance that can, in the right circumstances, bring a natural aesthetic appeal to stormwater systems. However, loosely placed rock can have significantly less structural stability than traditional engineering surfaces, such as concrete. Rock-lined surfaces can also be susceptible to weed invasion resulting in untidy, high-maintenance, drainage systems.

When used in an appropriate manner, rock can greatly enhance the 'natural' beauty of engineering structures. In general, rock-lined structures can age well if appropriate vegetation cover is incorporated into the structure during its initial construction. The filling of all voids with soil and the establishment of plants over the rocks also helps to increase the structural stability of these drainage systems.

Care and attention in rock placement can result in very good outcomes, while poor attention to minor surface level details can ultimately lead to structural failure.

Successful outcomes largely depend on:

- the experience of the designers that are applying the various rock-sizing equations
- the experience of those placing (constructing) the rock-lined structure
- the selection and placement of appropriate vegetation cover.

Introduction

Background to rock sizing equations

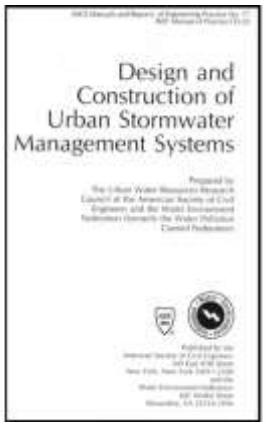
Fact Sheet: Rock sizing equations

- A report on the development of the rock sizing equations used within this document can be found on the 'Catchments and Creeks' web site.
- Fact sheet: https://www.catchmentsandcreeks.com.au/fact-sheets/esc_rock_sizing.html

Background to rock roughness equation

Fact Sheet: Rock roughness equation

- A report on the development of the rock roughness equation found within this document can be found on the 'Catchments and Creeks' web site.
- This reference document details the development of a new equation applicable to both shallow and deep water flow conditions.
- Fact sheet: https://www.catchmentsandcreeks.com.au/fact-sheets/esc_rock_sizing.html



ASCE (1992)

Design and Construction of Urban Stormwater Management Systems

- ASCE (1992) Manuals and Reports of Engineering Practice No. 77, and Water Environment Federation Manual of Practice FD-20, American Society of Civil Engineers, New York

Riprap Design and Construction Guide

Riprap Design and Construction Guide

- Public Safety Section, Water Management Branch, Province of British Columbia, Ministry of Environment, Lands and Parks

Use of rock in stormwater structures

Rock-lined stormwater drain (Qld)

Introduction

This document is divided into the following:

- Batter chutes
- Batter chute outlet structures
- Drainage channels
- Energy dissipaters
- Multi-pipe outlet structures
- Single pipe outlet structures
- Slope drain outlet structures
- Small dam spillways

Rock-lined batter chute (Qld)

Batter chutes

- A batter chute is a shallow drainage channel designed to convey concentrated storm runoff down the face of an embankment without causing erosion.
- The channel gradient is usually steeper than 10%.
- The hydraulics of batter chutes is similar to that of a waterway grade control structure, gully chute, or dam spillway.

Rock-lined drainage channel (Qld)

Drainage channels

- Rocks can be used as a surface lining within stormwater drainage channels for a variety of reasons, including:
  - scour protection
  - aesthetics (often using rounded river rock)
  - as a stable surface that can eventually incorporate vegetation.
- Weed control is often the greatest maintenance issue associated with rock-lined drains.

Pipe outlet energy dissipater basin (Qld)

Energy dissipaters

- Energy dissipaters generally contain two zones that may contain rock:
  - Zone 1 where energy losses and turbulence are the greatest
  - Zone 2 a region downstream of the main energy dissipation zone where flows are allowed to return to uniform flow conditions prior to entering the receiving channel.
- This section focuses on the rock placed in Zone 2.

Use of rock in stormwater structures

Multi-pipe outlet structure (Qld)

Multi-pipe stormwater outlet structures

- Similar hydraulic forces exist at the outlets of multi-pipe drainage systems and multi-cell culverts.
- The hydraulic forces generated by multiple pipe outlets are generally higher than those expected at single pipe outlets due to the convergence of adjacent jets.
- Consequently the rock sizing charts are different for multi and single pipe outlets.

Stormwater outlet scour protection (Qld)

Single pipe stormwater outlet structures

- Similar hydraulic forces exist at the outlets of single-pipe drainage systems and single-cell culverts.
- The rock sizing design charts and tables presented in this section are based on the acceptance that some degree of rock movement (rearrangement) will likely occur during the first few years following installation.
- Also, some degree of bed scour may also occur downstream of the rock pad during major discharges.

Slope drain outlet structure (Qld)

Slope drain outlet structures

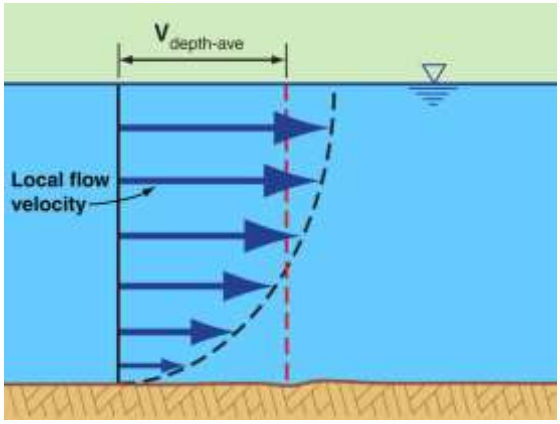
- A ‘slope drain’ is a prefabricated solid-wall or lay-flat pipe anchored to the side of an embankment to provide ‘temporary’ stormwater drainage.
- They are normally used as temporary drainage structures during the revegetation of an embankment, or as part of a temporary flow diversion system.
- The critical design parameters are the mean rock size (d_{50}) and length of the rock pad (L).

Sediment basin spillway (USA)

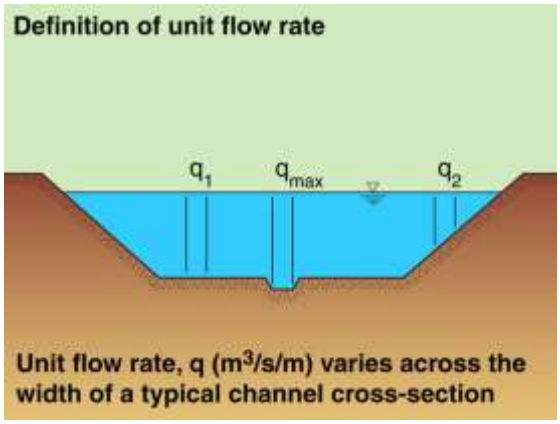
Small dam spillways

- A dam spillway is simply a drainage chute used to carry excess flows over or around a dam embankment.
- The hydraulics of a small dam spillway are very similar to that of drainage chutes.
- Selection of rock (size, density and shape) is critical for the design of a stable structure.

Background to the rock sizing equations



Depth-average flow velocity



Unit flow rate within an irregular channel

Rocks placed on a steep slope (Qld)

Whitewater flow conditions (Qld)

Use of 'average', 'depth-average' and 'local' flow velocity in sizing rock

- Rock displacement occurs as a result of local forces, local shear stresses, and local velocities.
- Logic would therefore suggest that rock size is best determined through use of the 'local' flow velocity, or local shear stress.
- However, the practicalities of fluid dynamics means that it is the average flow conditions measured over a vertical plane above the rock (i.e. the 'depth-average' value) that must be used.

Use of unit flow rate (q) as the preferred equation variable

- Using flow velocity to determine rock size introduces unnecessary 'errors' into the design procedure due to the problems of determining the Manning's roughness.
- These problems can be avoided by using the unit flow rate (q) instead of velocity.

Units of 'q' are $m^3/s/m$

$$q = (1/n) \cdot Y^{5/3} \cdot S^{1/2}$$

where: Y = water depth at given location, and S = hydraulic gradient of flow.

Problems associated with the use of shear stress and the Shield's equation in determining rock size

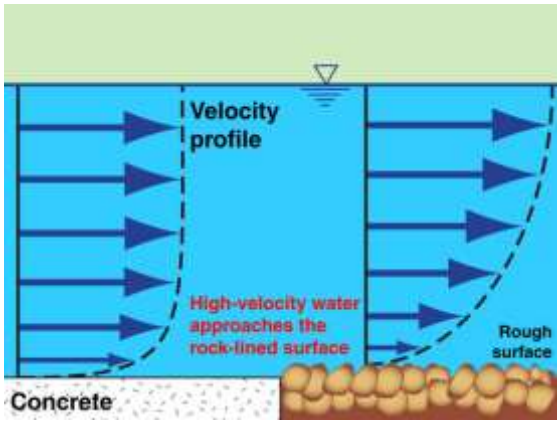
- Traditionally, rock sizing equations have used shear stress as the primary variable, which resulted in the development of the Shield's equation.
- However, the Shield's equation does not take into account the additional restraining forces associated with the weight of the upper rocks sitting on the lower rocks, which is a critical factor when rocks are placed on steep slopes.

The effects of air entrainment and whitewater flow conditions

- Air entrainment into the water causes a reduction in the density of the water passing over the rocks.
- As a result, the effective flow depth increases and the forces exerted on the rocks by the water decrease.
- In addition, rock stability can increase due to the reduced effects of buoyancy on the submerged rocks (lower water density).
- Thus the adopted rock-sizing equations can over-estimate the required rock size.

Critical design issues

Rock displaced at end of concrete channel



Changing flow conditions

Rock downstream of a concrete drain

Rock downstream of a 'smooth' bank

Caution!

- Flow velocity is obviously a critical parameter in the sizing of rock.
- Throughout this document there are numerous equations and tables presented to assist designers in the sizing of rock in different circumstances.
- In most cases these equations and tables **assume** the flow velocity above the rock is governed by the slope and roughness of the rock-lined surface; **however**, in some cases this will not be the case.

The assumed channel roughness

- Below many of the rock sizing equations and tables there will be a note similar to:
  - "The above equations are based on the Manning's 'n' roughness for a rock-lined surface determined from Equation 5."
- This note means that the flow conditions above the rock are assumed to be governed by uniform flow properties linked to the channel roughness generated by the exposed rock.

Flow velocity not influenced by the local rock roughness

- In some cases the flow velocity and boundary layer conditions above the rock will be governed by the channel roughness upstream of the placed rock.
- For example:
  - rock located immediately downstream of a concrete channel or chute
  - rock placed on a channel bank downstream of a long reach of grass-lined soil.

Sizing rock when the flow velocity is governed by other factors

- In circumstances where the flow conditions above the rock are governed by the channel slope or roughness external to the rock surface, then **always** check the rock size based on the simplified Isbash equation:

$$d_{50} = 0.04\ V^2$$

where:

- d_{50} = means rock size [m]
- V = approaching flow velocity [m/s]

Critical design issues

Low-risk batter chute (USA)

Safety factor (SF)

- For low risk structures, a safety factor (SF) of 1.2 is recommended.
- Examples of low-risk structures include:
  - structures that are likely to experience increased stability due to sediment deposition and vegetation growth
  - stormwater batter chutes.
- For high risk structures, for example some dam spillways, a safety factor of 1.5 is recommended.

Fractured rock (Qld)

Effects of rock shape (K_1)

- Crushed rock is generally more stable than natural rounded rock.
- Most rock sizing equations, including those presented within this document, are based on the use of fractured (angular) rock.
- A correction factor (K_1 = 1.36) must be applied if rounded rock is used.
- This means rounded rock needs to be 36% larger than angular rock.

Rock weir made from round natural stone

Use of rounded natural stone

- Rounded rock has a more 'natural' appearance, but in many cases the appearance/colour of the rock becomes irrelevant because vegetation eventually hides the rock.
- In waterway environments, such as batter chutes located on creek banks, any introduced rock should not dominate the landscape, rather the rock should integrate (disappear) into the landscape.

Individual placement of rocks (Qld)

Effects of rock placement on rock stability

- Rock-lined surfaces formed by the individual placement (stacking) of rocks are generally more stable than rock-lined surfaces produced by simply dumping the rock.
- Also, rocks dumped from a height, such as being dumped from a truck, will fall to a lower bank slope (angle of repose) than that which can be achieved through the gradual placement of the rocks.

Critical design issues

Rocks placed on a steep surface (SA)

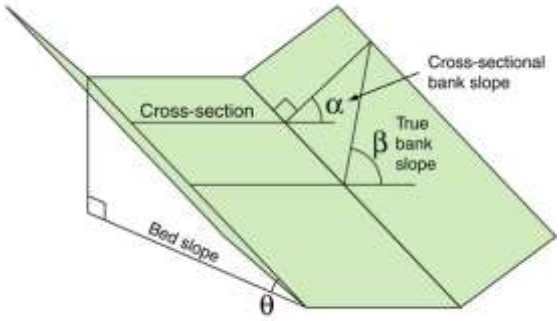


Diagram supplied by Catchments & Creeks Pty Ltd

Steep rock chute with steep banks

Well vegetated rock chute (Qld)

Vegetated rock stabilisation (Qld)

Effects of surface slope on rock stability

- The stability of rock-lined surfaces naturally decreases with the increasing slope of the rock-lined surface.
- However, these surfaces are more stable than would be suggested by the Shield's equation due to the increased friction between the rocks resulting from the upper rocks resting on the lower rocks.
- As previously discussed, the individual placement of rocks can also increase the effective stability of a rock-lined surface.

Assessment of complex bank slopes

- The 'effective' slope of the banks of a steep rock-lined chute relative to a horizontal plane can be significantly greater than the bank slope measured relative to the chute's cross-section.
- The gradient of this complex slope (β) is determined by the following equation.

$$\tan^2(\beta) = \tan^2(\alpha) + \tan^2(\theta) \qquad (1)$$

β = bank slope relative to the horizontal

α = bank slope relative to channel X-section

θ = slope of channel bed [degrees]

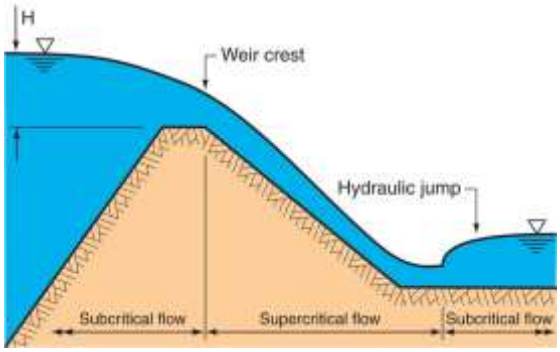
The aging of rock-lined surfaces

- The interflow of water through the open voids of rock-lined surfaces can play a significant role in the potential destabilisation of the rock.
- Observations by the author indicate that a majority of rock chute failures occurred within the first few years of their installation, i.e. the period during which these voids typically remain open.
- Once the voids become blocked with sediment and stabilised with vegetation, the stability of the structure increases.

Incorporation of vegetation over the rock

- Weed management can often be achieved through the promotion of the preferred plant species immediately after rock placement.
- Vegetating rock-lined structures can significantly increase the stability of these structures, but can also reduce their hydraulic capacity.
- Obtaining experienced, expert advice is always recommended before establishing vegetation within waterways, especially in flood risk areas.

Alignment of the weir crest



Dam spillway weir crest

Importance of weir crest geometry

- The design and alignment of the weir crest is critical in many hydraulic structures.
- The 'crest' of a weir or chute is the upper ridge of the inclined surface over which the water spills.
- Weir crests typically exist within the following hydraulic structures:
  - batter chutes
  - dam spillways
  - waterway and gully chutes
  - waterway riffles and rock weirs.

Rectangular weir with straight crest (Qld)

Grade control structure with curved crest

Straight, flat weir crest (NSW)

Use of 'straight' (rectangular) weir crests

- The weir crest should be straight and flat if it is desirable to achieve uniform flow across the full width of the chute, and energy dissipation is primarily achieved through the formation of a hydraulic jump.
- The weir crest must be perpendicular to the alignment of the chute.
- Straight flat crests are commonly used on:
  - most dam spillways
  - most fish-friendly, low-gradient chutes
  - most grade control structures.

Looking upstream to crest of rock chute

Dam spillway with flat, straight weir crest

Use of filter layers and filter cloth

Rocks placed over a geotextile filter

Conditions where a geotextile filter cloth should be used

- Filter cloth is typically used in the following structures:
  - some batter chutes
  - some drainage channels
  - non-vegetated bank stabilisation
  - energy dissipaters & outlet structures.
- The filter cloth must have sufficient strength (minimum 'bidim A24') and must be suitably overlapped to withstand the placement of the rock.

Bank stabilisation (Qld)

Conditions where filter cloth is <u>not</u> used

- The 'old' rule was that rock must always be placed over a filter layer made up of smaller rocks or geotextile filter cloth.
- The 'new' rule is that an underlying filter layer is usually not required **IF** the voids are filled with soil and pocket planted.
- In minor drainage channels, the use of filter cloth **may** be unnecessary if the soil is erosion-resistant and sediment flows are likely to fill the voids.

Rock filter layer (blue) under surface rock

The use of aggregate filters

- An alternative to the use of a geotextile filter cloth underlay is the use of an aggregate layer.
- Two or more layers of rock underlay may be required depending on the void size within the primary armour rock.
- Recommended rock size grading is:

$$d_{15c}/d_{85f} < 5 < d_{15c}/d_{15f} < 40$$

  where:
  - 'c' and 'f' refer to the coarse layer and fine rock underlay respectively.

Erosion under rocks on a dispersive soil

Filter cloth cannot be placed directly on a dispersive soil

- Dispersive soils contain highly mobile clay particles.
- Clay particles are so small in diameter that they readily pass through **<u>all</u>** forms of construction grade filter cloth.
- Dispersive soils **<u>must</u>** be sealed by a layer of non-dispersive soil prior to placement of the filter cloth.

Identification of dispersive and slaking soils

Collapse of a slaking soil in water

Dispersive and slaking soils

- Dispersive soils are structurally unstable when immersed in water, breaking down into their constituent particles (sand, silt and clay) thus allowing the dispersive clay fraction to disperse and cloud the water.
- 'Slaking' is the natural collapse of a soil aggregate in water when its mechanical strength is insufficient to withstand the swelling of clay and the expulsion of air from pore spaces—it does not include the effects of soil dispersion.

Fluting erosion in a dispersive soil (SA)

Identification of dispersive soils

- Ideally, dispersive and slaking soils should be identified through appropriate pre-construction soil testing, such as:
  - exchangeable sodium percentage > 6%
  - Emerson aggregate classes 1 to 5, note classes 3(2), 3(1) and 5 also have a slight risk of dispersive problems.
- The *'Aggregate Immersion Test'* is an on-site indicator of the soil properties.
- Dispersive soils may also be identified by their distinctive erosion patterns (left).

Dispersion of a dispersive soil

Aggregate immersion test

- At best, soil tests conducted on-site can only 'indicate' the existence of a potential soil problem.
- Such field tests are **not** a substitute for official soil sampling and testing.
- An aggregate immersion test (left) can be used as an indicator of potentially dispersive or slaking soils.
- Slaking soils (soils that readily collapse in water, but do not necessarily cloud the water) can be just as problematic.

Fluting erosion in a dispersive soil (Qld)

Stabilisation of dispersive soils

- Dispersive soils are highly susceptible to deep, narrow rilling (fluting) on slopes and along the invert of drains.
- Dispersive soils **must** be treated (with gypsum or the like), or buried under a minimum 100 mm layer of non-dispersive soil before placing any vegetation or erosion control measures.
- Thicker (200–300 mm) capping with non-dispersive soil may be required on steep slopes and on the banks of waterways.

The placement of rock over dispersive soils

Batter chute placed on a dispersive soil

Rock placed on dispersive or slaking soils

- Rocks should **not** be placed directly on a dispersive (sodic) or slaking soil.
- If the subsoils are dispersive/slaking, then the work area (e.g. a batter chute) should be over-excavated, then topped with a 100 to 300 mm (min) layer of non-dispersive soil covered with filter cloth prior to placement of the amour rock.
- The thickness of the non-dispersive soil layer depends on the likelihood of future bank disturbance.

Failure of rock-lined batter chute

Placement of rock on dispersive soils

- Even 'temporary' batter chutes placed directly on dispersive soils, such as this example, can experience significant damage during their short service life.

Erosion of a dam's bywash (spillway)

Grass-lined dam spillways

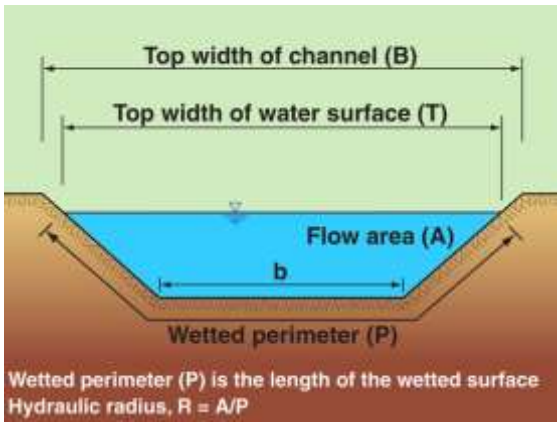
- Erosion in dispersive soils typically results in the formation of deep, steep-sided gullies that are usually deeper than they are wide.
- Dispersive soils are often the cause of the total failure of farm dam spillways.
- If the soil directly below the grass or rock is dispersive, then tunnel and rill erosion is likely to occur.

Grouted rock placed on dispersive soil

Placement of grouted rock over dispersive soils

- If loose or grouted rock is to be placed on a dispersive or sodic soil, then **prior** to placing the filter cloth, the exposed soil **must** first be covered with a layer of non-dispersive soil.
- It is noted that filter cloth, no matter how thick, cannot seal a dispersive soil, and thus should not be relied upon as the sole underlay for rock placed on a dispersive soil.

Manning's roughness of rock-lined surfaces



Channel geometry and flow conditions

Rock-lined drainage channel (Qld)

Deep water flow conditions (NSW)

Shallow water flow conditions (Qld)

Manning's equation

- The **average** channel flow velocity may be calculated using Manning's equation:

$$V = (1/n) \cdot R^{2/3} \cdot S^{1/2} \qquad (2)$$

where:

V = average flow velocity (m/s)

n = Manning's roughness coefficient

R = hydraulic radius (m) = A/P

A = effective flow area of channel (m^2)

P = wetted perimeter of flow (m)

S = channel slope (m/m)

Factors affecting the hydraulic roughness of rock-lined surfaces

- The effective Manning's roughness (n) of rock-lined surfaces depends on:
  - average rock size (d_{50})
  - the distribution of rock sizes, defined in this case by a ratio: d_{50}/d_{90}
  - the depth of water flow, defined by the hydraulic radius of flow (R)
  - the existence of vegetation
  - the occurrence of aerated 'whitewater' (not directly considered here).

Manning's roughness in deep water

- The Strickler equation for deep water may be presented in the modified form:

$$n = ((d_{50})^{1/6})/21.1 \qquad (3)$$

- An alternative equation was developed by Meyer-Peter & Muller:

$$n = ((d_{90})^{1/6})/26.0 \qquad (4)$$

  - d_{50} = rock size for which 50% of rocks (by weight) are smaller [m]
  - d_{90} = rock size for which 90% of rocks (by weight) are smaller [m]

Manning's roughness in shallow water

- The Manning's roughness (n) of rock-lined surfaces in both shallow-water and deep-water flow conditions is provided below.

$$n = \frac{d_{90}^{1/6}}{26(1 - 0.3593^{m})} \qquad (5)$$

  - $m = [(R/d_{90})(d_{50}/d_{90})]^{0.7}$
  - R = hydraulic radius of flow [m]
- The relative roughness (d_{50}/d_{90}) of rock extracted from streambeds is typically in the range 0.2 to 0.5; while quarried rock is commonly in the range 0.5 to 0.8.

Manning's roughness of rock-lined surfaces

The Manning's (n) roughness for rock-lined surfaces can be determined from Table 1 or Equation 5.

Table 1 – Manning's (n) roughness of rock-lined surfaces

	d_{50}/d_{90} = 0.5				d_{50}/d_{90} = 0.8			
d_{50} =	**200mm**	**300mm**	**400mm**	**500mm**	**200mm**	**300mm**	**400mm**	**500mm**
R (m)	Manning's roughness (n)				Manning's roughness (n)			
0.2	0.10	0.14	0.17	0.21	0.06	0.08	0.09	0.11
0.3	0.08	0.11	0.14	0.16	0.05	0.06	0.08	0.09
0.4	0.07	0.09	0.12	0.14	0.04	0.05	0.07	0.08
0.5	0.06	0.08	0.10	0.12	0.04	0.05	0.06	0.07
0.6	0.06	0.08	0.09	0.11	0.04	0.05	0.05	0.06
0.8	0.05	0.07	0.08	0.09	0.04	0.04	0.05	0.06
1.0	0.04	0.06	0.07	0.08	0.03	0.04	0.05	0.05

Equation 5 is considered to produce significantly better estimates of the Manning's roughness of rock-lined surfaces in shallow water flow compared to the use of traditional deep water equations such as the Strickler, Meyer-Peter & Muller or Limerinos equations.

Given the high variability of Manning's n and the wide range of variables that are believed to influence the hydraulic roughness of a rock-lined channel, Equation 5 is considered well within the limits of accuracy expected for Manning's n selection.

Data analysis during the development of Equation 5 indicated that the Meyer-Peter & Muller equation (Eqn 4) produced more reliable estimates of the deep water Manning's roughness values than the Strickler equation (Eqn 3). Possibly the choice between the two equations would come down to how reliable the determination of the d_{50} and d_{90} values were. If the estimate of d_{90} is not reliable, then it would be more appropriate to rely on the Strickler equation for the determination of the deep water Manning's n value, and vice versa.

Table 2 provides the range of data values used in the development of Equation 5. This table also contains the data range for the selected variables for which the calculated Manning's n value using Equation 5 fall within +/-10% of the observed Manning's n.

Table 2 – Data range used in determination of Equation 5

	d_{50} (mm)	d_{90} (mm)	R/d_{50}	R/d_{90}	n_o/n	d_{50}/d_{90}
Min (+/-10%)	16	90	2.31	0.73	0.284	0.080
Max (+/-10%)	112	350	55.6	12.0	1.080	0.661
Min (All data)	16	90	1.17	0.31	0.097	0.080
Max (All data)	397	1080	66.9	12.9	1.120	0.661

Maximum bank gradient

The recommended maximum desirable side slope of a large rock-lined chute is 1:2 (V:H); however, side slopes as steep as 1:1.5 can be stable if the rock is individually placed rather than dumped. Typical angles of repose for dumped rock are provided in Table 3.

Table 3 – Typical angle of repose for dumped rock

Rock shape	**Angle of repose (degrees)**	
	Rock size > 100 mm	**Rock size > 500 mm**
Very angular rock	41^o	42^o
Slightly angular rock	40^o	41^o
Moderately rounded rock	39^o	40^o

Typical properties of rock

Crushed rock is generally more stable than natural rounded rock; however, rounded rock has a more 'natural' appearance. A 36% increase in rock size is recommended if rounded rock is used (i.e. $K_1 = 1.36$).

The rock should be durable and resistant to weathering, and should be proportioned so that neither the breadth nor the thickness of a single rock is less than one-third of its length.

Maximum rock size generally should not exceed twice the nominal (d_{50}) rock size, but in some cases a maximum rock size of 1.5 times the average rock size may be specified.

Typical rock densities (s_r) are presented in Table 4.

Table 4 – Relative density (specific gravity) of rock

Rock type	Relative density (s_r)
Sandstone	2.1 to 2.4
Granite	2.5 to 3.1 (commonly 2.6)
Limestone	2.6
Basalt	2.7 to 3.2

Table 5 provides a suggested distribution of rock size for stormwater structures. The distribution of rock size can also be described by the coefficient of uniformity, $C_u = d_{60}/d_{10}$, which usually falls in the range 1.1 to 2.7, but typically around 2.1. Studies suggest that poorly graded rock ($C_u = 1.1$) has a critical discharge 8% greater than well-graded rock ($C_u = 2.2$).

Table 5 – Typical distribution of rock size (provided as a guide only)

Rock size ratio	Assumed distribution value
d_{100}/d_{50}	2.00
d_{90}/d_{50}	1.82
d_{75}/d_{50}	1.50
d_{65}/d_{50}	1.28
d_{40}/d_{50}	0.75
d_{33}/d_{50}	0.60
d_{10}/d_{50}	> 0.50

Thickness and height of rock layer

On dam spillways, the minimum height of the rock protection placed on the spillway banks should be equal to the critical flow depth (at the crest) plus 0.3 m.

The thickness of the armour layer should be sufficient to allow at least two overlapping layers of the nominal rock size. The thickness of rock protection must also be sufficient to accommodate the largest rock size. It is noted that increasing the thickness of the rock placement will **not** compensate for the use of undersized rock.

In order to allow at least two layers of rock, the minimum thickness of rock protection (T) can be approximated by the values presented in Table 6.

Table 6 – Minimum thickness (T) of rock lining

Min. thickness (T)	Size distribution (d_{50}/d_{90})	Description
1.4 d_{50}	1.0	Highly uniform rock size
1.6 d_{50}	0.8	Typical upper limit of quarry rock
1.8 d_{50}	0.67	Recommended lower limit of distribution
2.1 d_{50}	0.5	Typical lower limit of quarry rock

Note: d_X = nominal rock size (diameter) of which X% (by weight) of the rocks are smaller.

Sizing rock for stormwater chutes and minor dam spillways

Application of equation	**Primary rock sizing equation:**
• This is the preferred design equation • Applicable for uniform flow conditions only, $S_e = S_o$ • Batter slopes (S_o) less than 50% (1 in 2)	$$d_{50} = \frac{127.SF.K_1.K_2.S_o^{0.5}.q^{0.5}.y^{0.25}}{(s_r - 1)} \quad (6)$$

Tables 7 to 10 provide mean rock size (rounded up to the next 0.1 m unit) for angular rock, and a safety factor of both 1.2 and 1.5. These tables are based on Equation 6, and are best used in the design of long drainage chutes. Use of the 'unit flow rate' (q) as the primary design variable is preferred to the use of 'flow velocity' (V) because it avoids errors associated with the selection of Manning's roughness.

Alternatively, tables 11 and 12 provide mean rock size for angular rock and a safety factor of 1.2 and 1.5, based on Equation 6 with flow velocity presented as the primary variable. These tables are best used in the design of short drainage chutes where uniform flow conditions are unlikely to be achieved down the face of the chute.

Definition of equation symbols

d_X = nominal rock size (diameter) of which X% (by weight) of the rocks are smaller [m]

d_{15c} = rock size of 'coarse' layer of which 15% of the rocks are smaller [m]

d_{85f} = rock size of 'fine' underlay of which 85% of the rocks are smaller [m]

A & B = equation constants

K = equation constant based on flow conditions

= 1.1 for low-turbulent deep water flow, 1.0 for low-turbulent shallow water flow, and 0.86 for highly turbulent and/or supercritical flow

K_1 = correction factor for rock shape

= 1.0 for angular (fractured) rock, 1.36 for rounded rock (i.e. smooth, spherical rock)

K_2 = correction factor for rock grading

= 0.95 for poorly graded rock ($C_u = d_{60}/d_{10} < 1.5$), 1.05 for well graded rock ($C_u > 2.5$), otherwise $K_2 = 1.0$ ($1.5 < C_u < 2.5$)

n_o = Manning's roughness value for deepwater conditions [dimensionless]

q = flow per unit width down the embankment [$m^3/s/m$]

s_r = specific gravity of rock (e.g. sandstone 2.1–2.4; granite 2.5–3.1, typically 2.6; limestone 2.6; basalt 2.7–3.2)

S_e = slope of energy line [m/m]

S_o = bed slope = tan(θ) [m/m]

SF = safety factor

V = actual depth-average flow velocity at location of rock [m/s]

V_o = depth-average flow velocity based on **uniform** flow down a slope, S_o [m/s]

y = depth of flow at a given location [m]

θ = slope of channel bed [degrees]

Table 7 – Uniform flow depth [1], y (m) and mean rock size, d_{50} (m) for SF = 1.2

Safety factor, SF = 1.2			Specific gravity, s_r = 2.4		Size distribution, d_{50}/d_{90} = 0.5			
Unit flow rate ($m^3/s/m$)	Bed slope = 1:2		Bed slope = 1:3		Bed slope = 1:4		Bed slope = 1:6	
	y (m)	d_{50}	y (m)	d_{50}	y (m)	d_{50}	y (m)	d_{50}
0.1	0.09	**0.20**	0.09	**0.20**	0.09	**0.10**	0.09	**0.10**
0.2	0.14	**0.30**	0.14	**0.20**	0.14	**0.20**	0.15	**0.20**
0.3	0.18	**0.30**	0.19	**0.30**	0.19	**0.20**	0.20	**0.20**
0.4	0.22	**0.40**	0.23	**0.30**	0.23	**0.30**	0.24	**0.20**
0.5	0.26	**0.40**	0.26	**0.40**	0.27	**0.30**	0.27	**0.30**
0.6	0.29	**0.50**	0.30	**0.40**	0.30	**0.40**	0.31	**0.30**
0.8	0.35	**0.60**	0.36	**0.50**	0.37	**0.40**	0.37	**0.40**
1.0	0.41	**0.70**	0.42	**0.60**	0.42	**0.50**	0.44	**0.40**
1.2	0.46	**0.70**	0.47	**0.60**	0.48	**0.50**	0.49	**0.50**
1.4	0.51	**0.80**	0.52	**0.70**	0.53	**0.60**	0.54	**0.50**
1.6	0.56	**0.90**	0.57	**0.70**	0.58	**0.70**	0.60	**0.50**
1.8	0.60	**1.00**	0.62	**0.80**	0.63	**0.70**	0.64	**0.60**
2.0	0.65	**1.00**	0.66	**0.90**	0.67	**0.70**	0.69	**0.60**
3.0	0.85	**1.30**	0.87	**1.10**	0.88	**1.00**	0.90	**0.80**
4.0	1.02	**1.60**	1.05	**1.30**	1.07	**1.20**	1.10	**1.00**
5.0	1.19	**1.80**	1.22	**1.50**	1.24	**1.30**	1.27	**1.10**

[1] Flow depth is expected to be highly variable due to whitewater (turbulent) flow conditions.

Table 8 – Uniform flow depth [1], y (m) and mean rock size, d_{50} (m) for SF = 1.2

Safety factor, SF = 1.2			Specific gravity, s_r = 2.4		Size distribution, d_{50}/d_{90} = 0.5			
Unit flow rate ($m^3/s/m$)	Bed slope = 1:10		Bed slope = 1:15		Bed slope = 1:20		Bed slope = 1:30	
	y (m)	d_{50}	y (m)	d_{50}	y (m)	d_{50}	y (m)	d_{50}
0.1	0.10	**0.10**	0.10	**0.10**	0.10	**0.05**	0.11	**0.05**
0.2	0.15	**0.10**	0.16	**0.10**	0.16	**0.10**	0.17	**0.10**
0.3	0.20	**0.20**	0.21	**0.20**	0.21	**0.10**	0.22	**0.10**
0.4	0.25	**0.20**	0.25	**0.20**	0.26	**0.20**	0.27	**0.10**
0.5	0.28	**0.20**	0.29	**0.20**	0.30	**0.20**	0.31	**0.20**
0.6	0.32	**0.30**	0.33	**0.20**	0.34	**0.20**	0.35	**0.20**
0.8	0.39	**0.30**	0.40	**0.30**	0.41	**0.20**	0.43	**0.20**
1.0	0.45	**0.30**	0.47	**0.30**	0.48	**0.30**	0.50	**0.20**
1.2	0.51	**0.40**	0.53	**0.30**	0.54	**0.30**	0.56	**0.20**
1.4	0.56	**0.40**	0.58	**0.30**	0.60	**0.30**	0.62	**0.30**
1.6	0.62	**0.40**	0.64	**0.40**	0.65	**0.30**	0.68	**0.30**
1.8	0.67	**0.50**	0.69	**0.40**	0.71	**0.30**	0.73	**0.30**
2.0	0.72	**0.50**	0.74	**0.40**	0.76	**0.40**	0.79	**0.30**
3.0	0.94	**0.60**	0.97	**0.50**	0.99	**0.50**	1.03	**0.40**
4.0	1.14	**0.80**	1.17	**0.60**	1.20	**0.60**	1.25	**0.50**
5.0	1.32	**0.90**	1.36	**0.70**	1.40	**0.60**	1.45	**0.50**

[1] Flow depth is expected to be highly variable due to whitewater (turbulent) flow conditions.

Table 9 – Uniform flow depth [1], y (m) and mean rock size, d_{50} (m) for SF = 1.5

Safety factor, SF = 1.5			Specific gravity, s_r = 2.4		Size distribution, d_{50}/d_{90} = 0.5			
Unit flow rate ($m^3/s/m$)	Bed slope = 1:1		Bed slope = 1:3		Bed slope = 1:4		Bed slope = 1:6	
	y (m)	d_{50}	y (m)	d_{50}	y (m)	d_{50}	y (m)	d_{50}
0.1	0.10	**0.20**	0.10	**0.20**	0.10	**0.20**	0.10	**0.10**
0.2	0.15	**0.30**	0.15	**0.30**	0.16	**0.20**	0.16	**0.20**
0.3	0.20	**0.40**	0.20	**0.30**	0.21	**0.30**	0.21	**0.30**
0.4	0.24	**0.50**	0.25	**0.40**	0.25	**0.40**	0.26	**0.30**
0.5	0.28	**0.50**	0.28	**0.50**	0.29	**0.40**	0.30	**0.30**
0.6	0.31	**0.60**	0.32	**0.50**	0.33	**0.40**	0.34	**0.40**
0.8	0.38	**0.70**	0.39	**0.60**	0.40	**0.50**	0.41	**0.40**
1.0	0.44	**0.80**	0.45	**0.70**	0.46	**0.60**	0.47	**0.50**
1.2	0.50	**0.90**	0.51	**0.80**	0.52	**0.70**	0.53	**0.60**
1.4	0.55	**1.00**	0.57	**0.90**	0.58	**0.80**	0.59	**0.60**
1.6	0.60	**1.10**	0.62	**0.90**	0.63	**0.80**	0.64	**0.70**
1.8	0.65	**1.20**	0.67	**1.00**	0.68	**0.90**	0.70	**0.70**
2.0	0.70	**1.30**	0.72	**1.10**	0.73	**0.90**	0.75	**0.80**
3.0	0.92	**1.70**	0.94	**1.40**	0.96	**1.20**	0.98	**1.00**
4.0	1.11	**2.00**	1.14	**1.70**	1.16	**1.50**	1.19	**1.20**
5.0	1.29	**2.30**	1.32	**1.90**	1.34	**1.70**	1.38	**1.40**

[1] Flow depth is expected to be highly variable due to whitewater (turbulent) flow conditions.

Table 10 – Uniform flow depth [1], y (m) and mean rock size, d_{50} (m) for SF = 1.5

Safety factor, SF = 1.5			Specific gravity, s_r = 2.4		Size distribution, d_{50}/d_{90} = 0.5			
Unit flow rate ($m^3/s/m$)	Bed slope = 1:10		Bed slope = 1:15		Bed slope = 1:20		Bed slope = 1:30	
	y (m)	d_{50}	y (m)	d_{50}	y (m)	d_{50}	y (m)	d_{50}
0.1	0.11	**0.10**	0.11	**0.10**	0.11	**0.10**	0.11	**0.05**
0.2	0.17	**0.20**	0.17	**0.20**	0.18	**0.10**	0.18	**0.10**
0.3	0.22	**0.20**	0.23	**0.20**	0.23	**0.20**	0.24	**0.10**
0.4	0.26	**0.20**	0.27	**0.20**	0.28	**0.20**	0.29	**0.20**
0.5	0.31	**0.30**	0.32	**0.20**	0.32	**0.20**	0.34	**0.20**
0.6	0.35	**0.30**	0.36	**0.30**	0.37	**0.20**	0.38	**0.20**
0.8	0.42	**0.40**	0.43	**0.30**	0.44	**0.30**	0.46	**0.20**
1.0	0.49	**0.40**	0.50	**0.30**	0.51	**0.30**	0.53	**0.30**
1.2	0.55	**0.50**	0.57	**0.40**	0.58	**0.30**	0.60	**0.30**
1.4	0.61	**0.50**	0.63	**0.40**	0.64	**0.40**	0.67	**0.30**
1.6	0.67	**0.50**	0.69	**0.50**	0.70	**0.40**	0.73	**0.30**
1.8	0.72	**0.60**	0.74	**0.50**	0.76	**0.40**	0.79	**0.40**
2.0	0.77	**0.60**	0.80	**0.50**	0.82	**0.50**	0.85	**0.40**
3.0	1.01	**0.80**	1.04	**0.70**	1.07	**0.60**	1.11	**0.50**
4.0	1.23	**1.00**	1.27	**0.80**	1.30	**0.70**	1.34	**0.60**
5.0	1.43	**1.10**	1.47	**0.90**	1.50	**0.80**	1.56	**0.70**

[1] Flow depth is expected to be highly variable due to whitewater (turbulent) flow conditions.

Table 11 – Velocity-based design table for mean rock size, d_{50} (m) for SF = 1.2

Safety factor, SF = 1.2			Specific gravity, s_r = 2.4			Size distribution, d_{50}/d_{90} = 0.5		
Local velocity (m/s)	**Bed slope (V:H)**							
	1:2	**1:3**	**1:4**	**1:6**	**1:10**	**1:15**	**1:20**	**1:30**
0.5	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
0.8	0.10	0.10	0.05	0.05	0.05	0.05	0.05	0.05
1.0	0.20	0.10	0.10	0.10	0.10	0.10	0.05	0.05
1.3	0.20	0.20	0.20	0.20	0.10	0.10	0.10	0.10
1.5	0.30	0.30	0.20	0.20	0.20	0.20	0.20	0.10
1.8	0.40	0.30	0.30	0.30	0.20	0.20	0.20	0.20
2.0	0.50	0.40	0.40	0.30	0.30	0.30	0.20	0.20
2.3	0.60	0.50	0.50	0.40	0.30	0.30	0.30	0.30
2.5	0.70	0.60	0.60	0.50	0.40	0.40	0.30	0.30
2.8	0.80	0.70	0.70	0.60	0.50	0.40	0.40	0.40
3.0	1.00	0.90	0.80	0.70	0.60	0.50	0.50	0.40
3.5	1.30	1.10	1.00	0.90	0.80	0.70	0.60	0.60
4.0	1.70	1.50	1.30	1.20	1.00	0.90	0.80	0.70
4.5	2.10	1.90	1.70	1.50	1.20	1.10	1.00	0.90
5.0				1.80	1.50	1.30	1.20	1.10
6.0						1.90	1.70	1.60

[1] Based on uniform flow conditions, **safety factor = 1.2**, rock specific gravity of 2.4, and a rock size distribution such that the largest rock is approximately twice the size of the mean rock size.

Table 12 – Velocity-based design table for mean rock size, d_{50} (m) for SF = 1.5

Safety factor, SF = 1.5			Specific gravity, s_r = 2.4			Size distribution, d_{50}/d_{90} = 0.5		
Local velocity (m/s)	**Bed slope (V:H)**							
	1:2	**1:3**	**1:4**	**1:6**	**1:10**	**1:15**	**1:20**	**1:30**
0.5	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
0.8	0.10	0.10	0.10	0.10	0.05	0.05	0.05	0.05
1.0	0.20	0.20	0.20	0.20	0.10	0.10	0.10	0.10
1.3	0.30	0.30	0.20	0.20	0.20	0.20	0.20	0.10
1.5	0.40	0.30	0.30	0.30	0.20	0.20	0.20	0.20
1.8	0.50	0.50	0.40	0.40	0.30	0.30	0.30	0.20
2.0	0.70	0.60	0.50	0.50	0.40	0.40	0.30	0.30
2.3	0.80	0.70	0.60	0.60	0.50	0.40	0.40	0.40
2.5	1.00	0.90	0.80	0.70	0.60	0.50	0.50	0.40
2.8	1.20	1.00	0.90	0.80	0.70	0.60	0.60	0.50
3.0	1.40	1.20	1.10	1.00	0.80	0.70	0.70	0.60
3.5	1.90	1.70	1.50	1.30	1.10	1.00	0.90	0.80
4.0			1.90	1.70	1.40	1.30	1.10	1.00
4.5					1.80	1.60	1.40	1.30
5.0						1.90	1.80	1.60
6.0								2.20

[1] Based on uniform flow conditions, **safety factor = 1.5**, rock specific gravity of 2.4, and a rock size distribution such that the largest rock is approximately twice the size of the mean rock size.

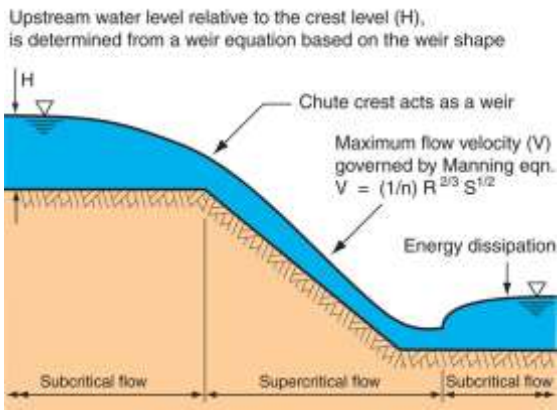
1. Batter Chutes

Introduction

Rock-lined batter chute fact sheet

Rock-lined batter chute (USA)

Inflows fail to enter drainage channel



Batter chute hydraulics

Introduction

- A batter chute is a steep drainage channel formed down the face of an embankment or slope.
- Also known as 'drainage chutes'.
- The term 'chute' can also apply to the sloping face of a grade control structure used in waterway bed stabilisation.
- Relevant fact sheet: https://www.catchmentsandcreeks.com.au/fact-sheets/esc_rock_sizing.html

Critical design and operational issues

- Critical **design issues** are:
  - flow entry into the chute
  - maximum allowable flow velocity down the face of the chute, and
  - energy dissipation at the base of chute.
- The critical **operational issues** are:
  - controlled flow entry into the chute
  - ensuring flows do not undermine or spill/splash out of the chute, and
  - control of erosion at base of chute.

Common failure modes

- Most drainage chute failures are associated with inflows not entering the batter chute properly, and as a result, passing around the edges of the chute.
- It is critical to control flow entry, and to ensure inflows have smooth, unrestricted entry into the middle of the chute.
- This essentially requires the top of the rocks to be level with the invert of the inflow channel.

Hydraulic design

- Drainage chutes are hydraulic structures that need to be designed for a specified 'design' storm using standard hydraulic equations.
- The hydraulic design can be broken down into three components:
  - design of the chute **inlet** using an appropriate weir equation
  - sizing rock for the **face of the chute** based on the maximum flow velocity
  - sizing rock for the **outlet structure**.

Sizing rock for the face of a batter chute

The recommended design equations for sizing rock placed on the face of batter chutes (not within the energy dissipater zone) are provided below.

Tables 7 to 10 provide mean rock size (rounded up to the next 0.1 m unit) for angular rock, and for a safety factor of both 1.2 and 1.5. These tables are based on Equation 1.1 (below) and are best used in the design of long chutes where the flow will achieve its maximum velocity. Use of the 'unit flow rate' (q) as the primary design variable is preferred to the use of 'flow velocity' (V) because it avoids errors associated with the selection of Manning's roughness.

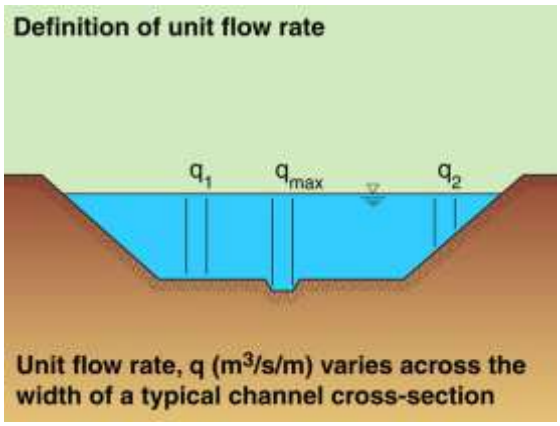
Alternatively, tables 11 and 12 provide mean rock size for angular rock and a safety factor of 1.2 and 1.5, also based on Equation 1.1; however, flow velocity is presented as the primary variable. These tables are best used in the design of short drainage chutes where uniform flow conditions are unlikely to be achieved down the face of the chute.

Application of Equation 1.1	**Equation 1.1**
• Preferred design equation • Applicable for uniform flow conditions only, i.e. the chute is long enough to achieve terminal flow velocity, i.e. the energy slope (S_e) equals the batter slope (S_o) • Batter slopes (S_o) less than 50% (1 in 2)	$$d_{50} = \frac{127.SF.K_1.K_2.S_o^{0.5}.q^{0.5}.y^{0.25}}{(s_r - 1)}$$
Application of Equation 1.2	**Equation 1.2**
• A simplified equation that is independent of flow depth • Applicable to uniform flow conditions only, i.e. $S_e = S_o$ • Batter slopes (S_o) less than 50% (1 in 2)	$$d_{50} = \frac{SF.K_1.K_2.S_o^{0.47}.q^{0.64}}{(s_r - 1)}$$
Application of Equation 1.3	**Equation 1.3**
• A simplified velocity-based equation • Applicable to uniform flow conditions only, i.e. $S_e = S_o$ • Batter slopes (S_o) less than 33% (1 in 3)	$$d_{50} = \frac{SF.K_1.K_2.V^2}{(A - B.\ln(S_o)).(s_r - 1)}$$ For SF = 1.2: A = 3.95, B = 4.97 For SF = 1.5: A = 2.44, B = 4.60

where:

- d_X = nominal rock size (diameter) of which X% (by weight) of the rocks are smaller [m]
- A & B = equation constants
- K = equation constant based on flow conditions
  - = 1.1 for low-turbulent deep water flow, 1.0 for low-turbulent shallow water flow, and 0.86 for highly turbulent and/or supercritical flow
- K_1 = correction factor for rock shape
  - = 1.0 for angular (fractured) rock, 1.36 for rounded rock (i.e. smooth, spherical rock)
- K_2 = correction factor for rock grading
  - = 0.95 for poorly graded rock ($C_u = d_{60}/d_{10} < 1.5$), 1.05 for well graded rock ($C_u > 2.5$), otherwise $K_2 = 1.0$ ($1.5 < C_u < 2.5$)
- ln = log to base 'e'
- q = flow per unit width down the embankment [$m^3/s/m$]
- s_r = specific gravity of rock (e.g. sandstone 2.1–2.4; granite 2.5–3.1, typically 2.6; limestone 2.6; basalt 2.7–3.2)
- S_o = bed slope = tan(θ) [m/m]
- SF = factor of safety
- V = actual depth-average flow velocity at location of rock [m/s]
- y = depth of flow at a given location [m]
- θ = slope of channel bed [degrees]

Sizing rock for the face of a batter chute



Unit flow rate (q)

Adopted flow conditions

- Wherever practical, the unit flow rate 'q' (m^3/s/m), flow velocity 'V' (m/s), and flow depth 'y' (m) used to determine the rock size should be based on the flow conditions (q or V) found directly above the rock being sized.
- This means that the maximum rock size will usually be based on the depth-average flow conditions at deepest section of the channel.

Stormwater batter chute (Qld)

Selection of safety factor (SF)

- For low risk structures, a safety factor of 1.2 is recommended.
- Examples of low risk structures include:
  - batter chutes where failure of the structure is likely to result in easily repairable soil erosion
  - batter chutes that are likely to achieve significant vegetation growth before experiencing high flows.
- For high risk structures, a safety factor of 1.5 is recommended.

Batter chute with well-defined banks

Sizing rock placed on the chute's banks

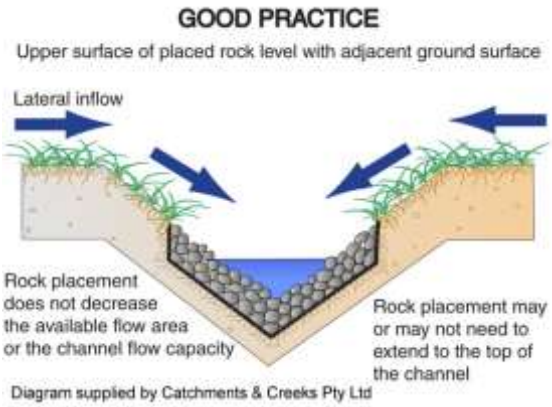
- Rocks should be extended up the banks each side of the batter chute such that the spilling water is fully contained.
- The same equations can be used for sizing rock placed on the banks for slopes equal to or less than 1:2 (V:H), but a 25% increase in rock size should be applied for bank slopes of 1:1.5.

Vegetated batter chute (Qld)

Placement of vegetation over rocks

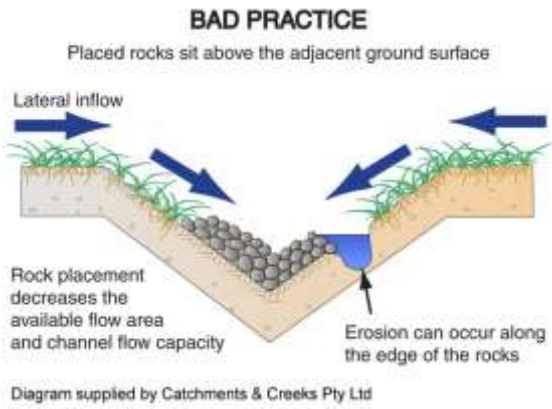
- Vegetating rock-lined drainage chutes can significantly increase the stability of these drainage structures, but can also reduce their hydraulic capacity.
- Obtaining expert advice is always recommended before establishing vegetation within shallow drainage structures.

Placement of rock on batter chutes



Placement of rock

- The minimum recommended batter chute depth is 300 mm.
- A minimum design freeboard of 150 mm is suggested.
- A greater freeboard may be required if it is necessary to contain the splash generated within steep, rough, batter chutes.



Placement of rock

- It is important to ensure that the top of the rock surface is level with, or slightly below, the surrounding land to allow the free entry of water, including lateral inflows (if such inflows are possible).
- If the rocks sit above the ground surface, then inflows may be directed along the edges of the rocks causing erosion.

Erosion caused by insufficient chute depth

Control of splash

- Chutes must have sufficient depth and/or side-edge scour controls to prevent the generation of soil erosion along the sides of the batter chute.
- In general, energy dissipation should primarily occur at the base of the batter chute, not down the face of the chute.
- Rocks should **not** be embedded into concrete chutes unless so directed within the design plans.

Shallow, curved batter chute

Alignment of batter chutes

- Supercritical flow conditions exist down the face of most batter chutes.
- Unpredictable surface waves can be generated if supercritical flows are forced to change direction while passing down a batter chute.
- Therefore, batter chutes must be straight while descending the batter slope (i.e. no bends or curves).

Common construction problems

Newly established rock chute

Flow spills around rocks

- A rock-lined drainage chute should **not** be formed by simply filling an eroded gully with rock such that the upper surface of the rock sits above the adjacent ground level.
- In this case (left) soil erosion would be expected along each side of the recently placed rocks.
- Also, weeds will likely grow among the rocks, and these weeds will be difficult to manage.

Rocks sitting above the soil profile

Flow spills around rocks

- In this case, the rocks have not been recessed into the bank, but instead sit above the adjacent land surface.
- Inflows are likely to move to the edge of the rocks causing rilling down the edges of the batter chute.

Rock-lined stormwater drain

Insufficient cross-sectional depth

- This rock-lined drainage channel has insufficient flow depth or cross-sectional area.
- In such cases, water flow is expected to spill out of the channel and pass along the outer edges of the rocks causing erosion.

Grouted rock batter chute

Insufficient cross-sectional depth

- This batter chute does not have any scour-resistant banks that will be able to contain the spilling flows.
- Erosion is likely to occur on each side of the batter chute.
- Also, the scour protection does not extend to the base of the embankment.

Common construction problems

Rocks slipping down batter chute

Rocks slip down smooth filter cloth

- These rocks have been placed as a single layer, on a steep slope, over filter cloth.
- The filter cloth effectively acts as a 'slippery dip' or 'slide', and the rocks are slowly slipping down the slope.
- If rocks need to be placed on a steep slope, then the rocks should be 'keyed' into the slope.
- Keying can be done by 'stair-stepping' the bank prior to placing the filter cloth.

Rounded river stone placed on steep slope

Rounded rock placed on steep slopes

- Rounded rock can be significantly less stable than angular fractured rock, especially when placed on steep slopes.
- Minimal aesthetic value is achieved through the use of round river rocks if the rocks will shortly be covered by weeds and grasses.
- Also, the use of round river rocks and gravels can promote environmental harm through their extraction from river beds.

Batter chute placed on a dispersive soil

Rock placed on dispersive or slaking soils

- Rocks should **not** be placed directly onto an untreated dispersive, sodic or slaking soil.
- If the subsoils are dispersive/slaking, then the batter chute should be over-excavated, then topped with a minimum 200 mm layer of non-dispersive soil, then covered with filter cloth prior to placement of the amour rock.

Failure of a fine-rock batter chute

Complex energy dissipation down the face of batter chutes

- Energy dissipation should primarily occur at the base of batter chutes, not down the face of the chute.
- 'Rock check dams' (which are velocity control structures) should not be placed on the face of batter chutes.
- Also, the placement of a few large anchor rocks down a steep slope will not help to 'compensate' for the use of under-sized rocks.

2. Batter Chute Outlet Structures

Introduction

Batter chute outlet fact sheet

Batter chute rock pad outlet structure

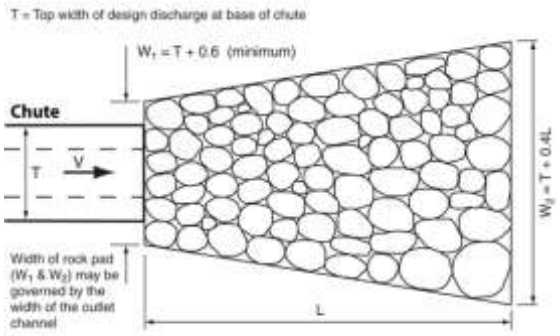


Diagram supplied by Catchments & Creeks Pty Ltd

Rock pad outlet structure

Rocks displaced by high velocity flows

Introduction

- The term 'outlet structure' refers to a wide range of scour control devices constructed at the outlet of stormwater systems.
- These structures aim to control soil erosion adjacent to the outlet and to help dissipate the flow energy.
- Outlet structures typically consist of rock pads, rock mattress aprons and various types of concrete energy dissipaters.
- Relevant fact sheet: https://www.catchmentsandcreeks.com.au/fact-sheets/esc_rock_sizing.html

Limitation of these design procedures

- Energy dissipaters (outlet structures) are required at the end of numerous hydraulic structures such as:
  - stormwater outlets
  - batter chutes
  - dam spillways.
- The adopted design procedure for sizing an outlet structure varies with the type of hydraulic structure the outlet structure is attached to.

Critical design parameters

- The critical design parameters are the mean rock size (d_{50}) and length of rock protection (L).
- The width of the outlet structure generally depends on the width of the approaching flow (i.e. the chute width) and the length of the rock pad.

Ongoing shifting of rocks

- The following rock sizing design tables are based on the acceptance that some degree of rock movement will occur during the first few years.
- The issue relates to the fact that flows passing over a smooth surface (such as water spilling down a concrete batter chute) generate a thin boundary layer that causes high shear stresses to exist close to the smooth surface—these same high shear stresses then pass directly onto the surface of the rock pad.

Sizing rock for batter chute outlet structures

Recommended mean (d_{50}) rock sizes and length (L) of rock protection for batter chutes are presented in tables 2.1 and 2.2. These rock sizes are based on information presented within ASCE (1992) rounded up to the next 100 mm increment, with a minimum size set as 100 mm.

Table 2.1 – Mean rock size, d_{50} (mm) for batter chute outlet protection [1]

Depth of approach flow (mm) [2]	Flow velocity at base of chute (m/s)						
	2.0	3.0	4.0	5.0	6.0	7.0	8.0
50	100	100	100	200	200	200	300
100	100	100	200	200	300	300	400
200	100	200	300	300	400	[3]	[3]
300	200	200	300	400	[3]	[3]	[3]

[1] For velocities at the base of the chute not exceeding 1.5 m/s, and where growing conditions allow, loose 100 mm rock may be replaced with 75 mm rock stabilised with a good cover of grass.

[2] This is the flow depth at the base of the chute as it approaches the outlet structure. The flow depth is based on the maximum depth, not the average flow depth.

[3] Consider using 400 mm grouted rock pad, or a rock-filled mattress outlet.

The rock pad lengths presented in Table 2.2 will not necessarily fully contain all energy dissipation and flow turbulence; therefore, some degree of scour may still occur downstream of the outlet structure. Extending the length of the rock pad will reduce the risk of this downstream soil erosion.

Table 2.2 – Recommended length, L (m) of rock pad for batter chute outlet protection

Depth of approach flow (mm)	Flow velocity at base of chute (m/s)						
	2.0	3.0	4.0	5.0	6.0	7.0	8.0
50	1.0	1.5	2.1	2.6	3.1	3.6	4.2
100	1.3	2.0	2.7	3.4	4.1	4.8	5.5
200	2.1	2.7	3.4	4.3	5.2	6.1	7.0
300	2.7	3.6	4.3	4.8	5.8	6.8	7.9

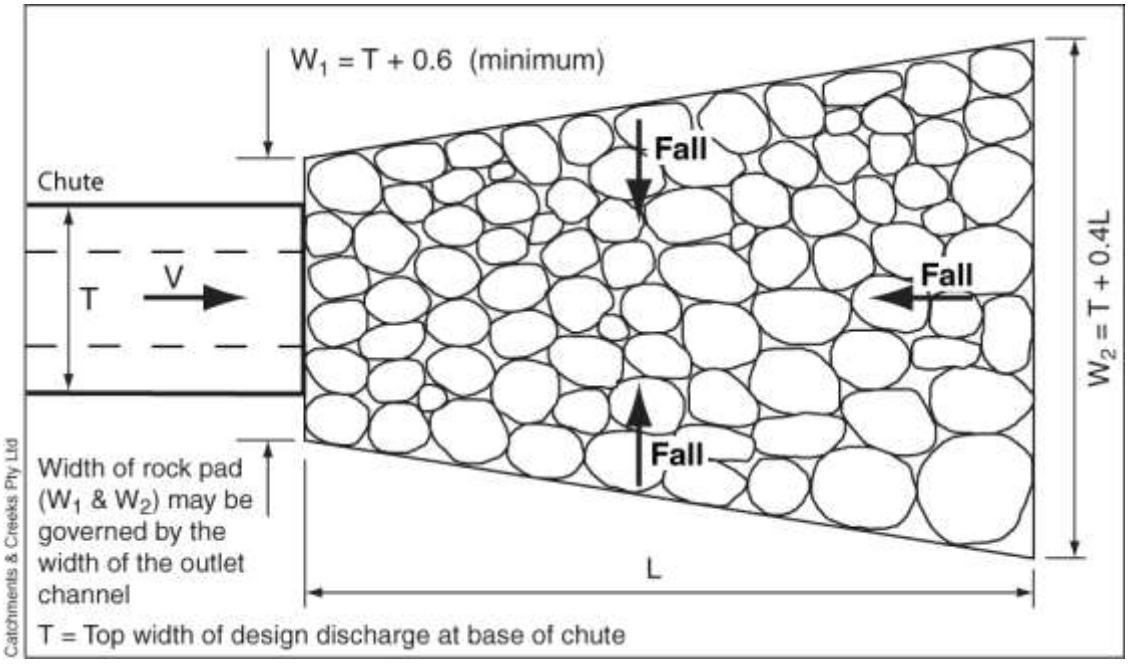


Figure 2.1 – Typical layout of a recessed rock pad for a chute (plan view)

As indicated in figures 2.1, 2.2 and 2.3, rock pad outlet structures for batter chutes should ideally be recessed below the surrounding ground level to promote effective energy dissipation. Recessing the rock pad helps to ensure suitable tailwater conditions are achieved. The recommended recess depth (Z) can be determined from Table 2.3.

In circumstances where it is not practical to recess the rock pad (e.g. for safety or mosquito breeding reasons), appropriate steps should be taken to increase the depth of flow (i.e. tailwater conditions) at the base of the chute.

Table 2.3 – Recommended recess depth, Z (m) for batter chute outlet protection

Depth of approach flow (mm)	Flow velocity at base of chute (m/s)						
	2.0	3.0	4.0	5.0	6.0	7.0	8.0
50	0.13	0.20	0.28	0.36	0.43	0.50	0.60
100	0.14	0.23	0.32	0.42	0.50	0.60	0.70
200	0.12	0.21	0.31	0.42	0.50	0.60	0.70
300	0.07	0.16	0.25	0.35	0.44	0.55	0.65

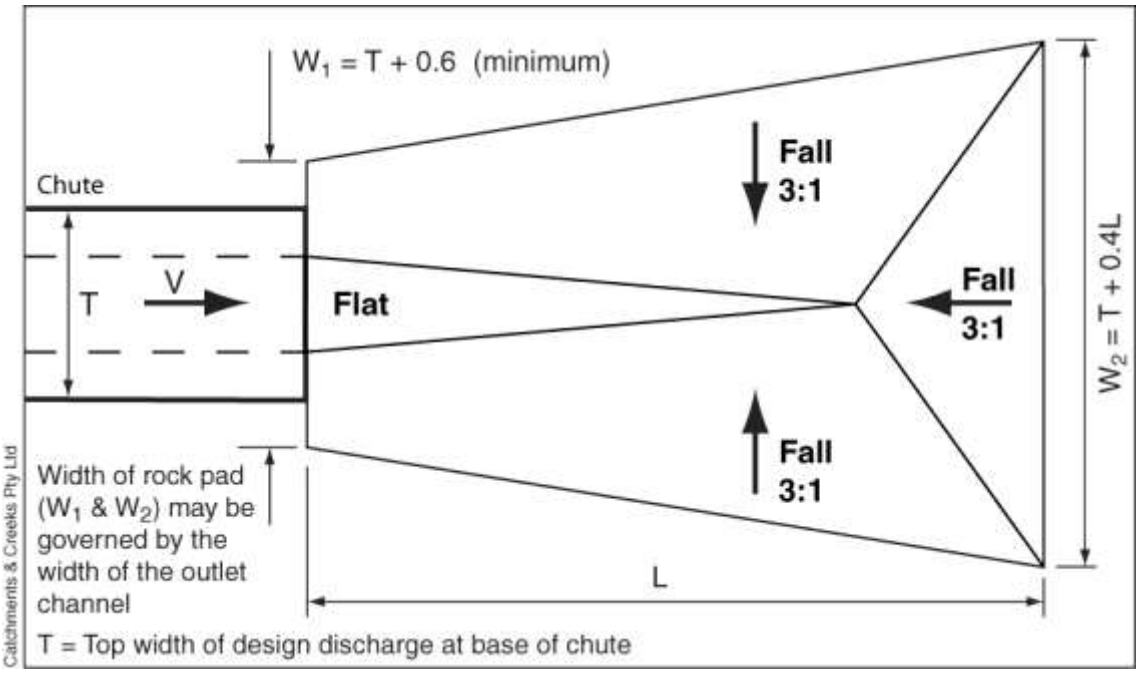


Figure 2.2 – Typical arrangement of a recessed outlet structure (plan view)

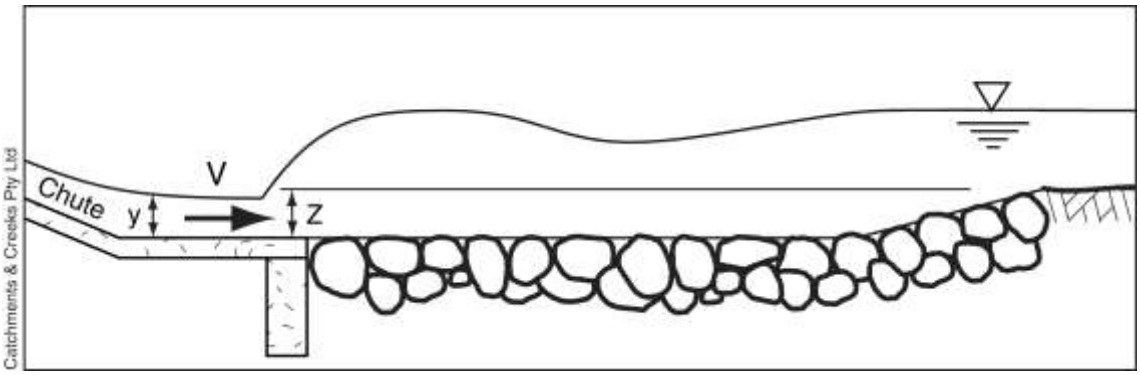


Figure 2.3 – Typical profile of a recessed outlet structure (side view)

ASCE 1992, *Design and Construction of Urban Stormwater Management Systems*. ASCE Manuals and Reports of Engineering Practice No. 77, and Water Environment Federation Manual of Practice FD-20, American Society of Civil Engineers, New York.

3. Drainage Channels

Introduction

Rock-lined drainage channel fact sheet

Rock-lined drainage channel (Qld)

Steep-sided rock-lined stormwater drain

Grouted rock placed on dispersive soil

Introduction

- Rock can be used as a surface lining within stormwater drainage channels for a variety of reasons, including:
  - scour protection
  - aesthetics (often incorporating round river cobbles)
  - as a stable surface that can eventually incorporate vegetation.
- Relevant fact sheet: https://www.catchmentsandcreeks.com.au/fact-sheets/esc_rock_sizing.html

Critical design parameters

- Rock size is primarily dependent on the flow velocity (V), rock shape (round or angular), and rock density (s_r).
- In most situations the nominal (d_{50}) rock size is between 100 mm to 450 mm.
- For rock sizes greater than 450 mm, the placement of two layers of rock may become impractical, thus alternative channel linings are generally considered.

Minimum channel dimensions

- Recommended minimum drain depth is 300 mm.
- A minimum freeboard of 150 mm is suggested, but may not be appropriate for all drains.
- The recommended maximum side slopes for large drainage channels is 1:2 (V:H); however, side slopes as steep as 1:1.5 can be stable if the rocks are individually placed rather than dumped.

Placement of rock over dispersive soils

- If the rock is placed on a dispersive (sodic) soil, then **prior** to placing the filter cloth, the exposed soil **must** first be covered with a layer of non-dispersive soil, typically minimum 200 mm thickness.
- The minimum thickness depends on site conditions and soil placement method.
- It is noted that filter cloth cannot seal a dispersive soil, and thus should not be relied upon as the sole underlay for rock placed on a dispersive soil.

Sizing of rock used in the lining of drainage channels

The recommended design equations for sizing rock used in drainage channels are presented below. These same equations can be used to size rock placed on the banks of large drainage channels provided the bank slope does not exceed 1:2 (V:H). For a bank slope of 1:1.5 (V:H) the rock size should be increased by 25%.

Table 3.2 provides mean rock size (rounded up to next 50/100 mm unit) based on Equation 3.1.

A 36% increase in rock size is recommended for rounded rock (i.e. $K_1 = 1.36$).

Application of Equation 3.1	**Equation 3.1**
• Applicable to uniform flow conditions only, i.e. $S_e = S_o$ • Low channel gradients, $S_o < 10\%$	$$d_{50} = \frac{K_1 . V^{3.9}}{C . y^{0.95} (s_r - 1)} \quad (3.1)$$ C = 120 for SF = 1.2 C = 68 for SF = 1.5
Application of Equation 3.2	**Equation 3.2**
• Simplified velocity-based equation suitable for uniform and non-uniform flow conditions • Low channel gradients, $S_o < 5\%$	$$d_{50} = \frac{K_1 . V^{2}}{2 . g . K^{2} (s_r - 1)} \quad (3.2)$$ K = 1.1 for low-turbulent deep water flow K = 1.0 for low-turbulent shallow water flow K = 0.86 for highly turbulent flow (Table 3.1)

Note: Equation 3.2 represents a modification of the equation originally presented by Isbash (1936).

Table 3.1 provides values of the constant 'K' required in Equation 3.2 to produce the equivalent rock sizes determined from Equation 3.1. This table suggests that as the channel slope increases and the flow becomes more turbulent, the required K-values decrease, which is consistent with the recommendations of Isbash (1936).

Table 3.1 – Values of 'K' required for Equation 3.2 to achieve the same rock size as achieved by Equation 3.1 in uniform flow conditions

Bed slope (%)	**1.0**	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**8.0**	**10.0**
K =	1.09	1.01	0.96	0.92	0.89	0.86	0.83	0.80
Flow conditions	Low turbulence ™ ™ ™ ™ ™ ™ ™ ™ ™ Highly turbulent (whitewater)							

Note: Tabulated vales are applicable to uniform flow conditions, and Manning's n based on Equation 5.

where:

d_{50} = nominal rock size (diameter) of which 50% (by weight) of the rocks are smaller [m]

g = acceleration due to gravity [m/s^2]

K = equation constant based on flow conditions

= 1.1 for low-turbulent deep water flow, 1.0 for low-turbulent shallow water flow, and 0.86 for highly turbulent and/or supercritical flow (also refer to Table 3.1)

K_1 = correction factor for rock shape

= 1.0 for angular (fractured) rock, 1.36 for rounded rock (i.e. smooth, spherical rock)

S_o = channel slope [m/m]

s_r = specific gravity of rock (e.g. sandstone 2.1–2.4; granite 2.5–3.1, typically 2.6; limestone 2.6; basalt 2.7–3.2)

V = actual depth-average flow velocity at location of rock [m/s]

y = depth of flow at a given location [m]

Table 3.2 – Rock sizing selection table, d_{50} (mm) based on uniform flow velocity [1]

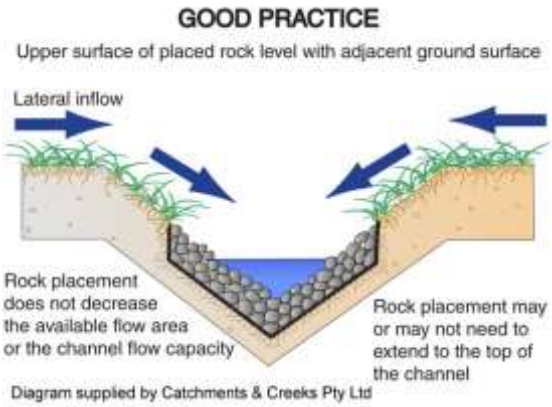
Uniform flow conditions	Angular rock (K_1 = 1.0)				Specific gravity, s_r = 2.4			
Uniform velocity (m/s)	**Bed slope (%)**							
	1.0	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**	**8.0**	**10.0**
0.5	100	100	100	100	100	100	100	100
0.8	100	100	100	100	100	100	100	100
1.0	100	100	100	100	100	100	100	100
1.3	100	100	100	100	100	100	100	100
1.5	100	100	100	150	150	150	150	150
1.8	100	150	150	150	150	200	200	200
2.0	150	150	200	200	200	300	300	300
2.3	150	200	300	300	300	300	300	300
2.5	200	300	300	300	400	400	400	400
2.8	300	300	400	400	400	400	500	500
3.0	300	400	400	500	500	500	500	600
3.5	400	500	600	600	600	700	700	800
4.0	500	700	700	800	800	900	900	1000
4.5	600	800	900	1000	1000	1100	1200	1200
5.0	800	1000	1100	1200				

[1] Tabulated results are applicable to uniform flow conditions based on Manning's roughness determined from Equation 5.

Reference

Isbash, S.V. 1936, *Construction of Dams by Depositing Rock in Running Water*, Transactions, Second Congress on Large Dams, Washington, D.C. USA.

Placement of rock within drainage channels



Rock recessed into channel earth

Placement of rock

- It is important to ensure that the top of the rock surface is level with, or slightly below, the surrounding land to allow the free entry of water, including lateral inflows if required.
- In general, rock should be recessed into the ground, not sit on the ground.

Rock-lined drainage channel (Qld)

Use of rounded river stone

- The aesthetics of non-vegetated drainage channels can be improved through the use of rounded river stone.
- However, minimal aesthetic value is achieved if the rocks will eventually be covered by weeds and grasses—assess each situation on a case-by-case basis.
- Also, in some locations, the use of rounded river stone increases the demand for potentially damaging in-stream rock extraction.

Rock-lined drainage drain

Vegetating rock-lined drains

- Vegetating rock-lined drains can significantly increase the stability of the rock; however, it can also reduce the drain's hydraulic capacity.
- Issues to be considered include:
  - impact on the channel's flow capacity
  - practicality of controlling weed growth and the mowing of grasses
  - the likelihood of bank erosion caused by excessive vegetation growth along the channel invert.

Above drain with excessive weed growth

Control of vegetation on rock-lined drains

- Rock-lined drains can be difficult to mow.
- Weed control can be very problematic and labour-intensive.
- Excess vegetation is often best managed through the placement of a top cover of gravel and soil, then seeding with grasses—this effectively forms a 'structural soil' that can be mown.

Common construction problems

Drain dimensions reduced by rock

Reduced channel flow capacity

- Most failures of rock-lined hydraulic structures are considered to occur as a result of inappropriate placement of the rock, either due to inadequate design detailing, or poorly supervised construction practices.
- Inadequate channel excavation and excess rock fill has reduced the flow capacity under this footpath bridge (left) causing flows to regularly spill from the drain.

Flows passing around rock lining

Rocks placed above the adjacent ground level

- Once placed, the top of the rock-lined surface should allow the free entry of water into the drain.
- In this case (left) rocks were placed in an eroding table drain to stop the erosion; however, the rocks sit higher than the road shoulder, thus flows are simply diverted along the edge of the rocks, and the erosion continues.

Inflow prevented from entering drain

Restricted flow entry into a drain

- The rocks placed in the upstream end of this drain (left) are higher than the adjacent ground.
- This type of rock placement will prevent the free entry of water.
- Drainage channels need to be ‘over-excavated’ such that, once the rock-lining has been placed, the final channel invert levels and dimensions match those presented within the design drawings.

Rock-lined stormwater drain

Insufficient cross-sectional depth

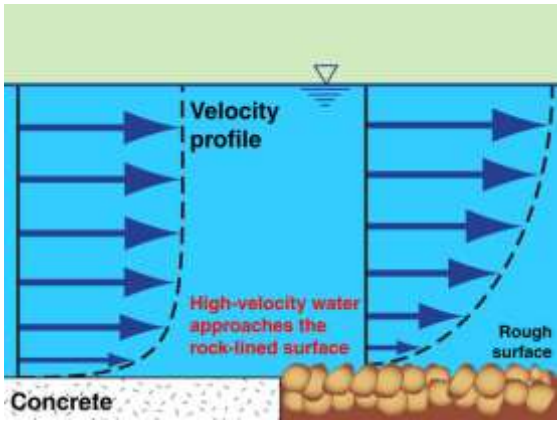
- This rock-lined drainage channel has insufficient flow depth or cross-sectional area.
- In such cases, water flow is expected to spill out of the channel and pass along the outer edges of the rocks causing erosion.

Rock placed downstream of concrete drainage channels

Rock displaced at end of concrete channel

The problem

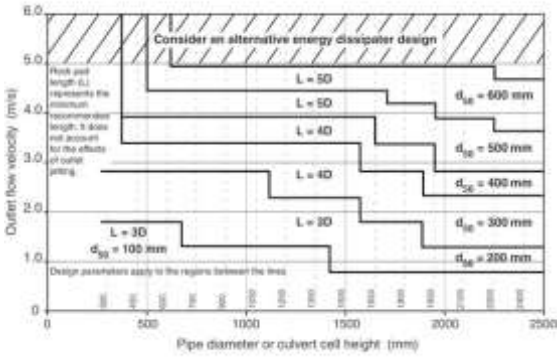
- Rocks are often displaced if placed immediately downstream of concrete channels.
- One of the primary reasons for this rock movement is the thin boundary layer that is formed when flows pass over smooth surfaces, such as concrete.
- This thin boundary layer allows high shear stresses to exist close to the concrete surface.



Changing flow conditions

Development of boundary layer conditions

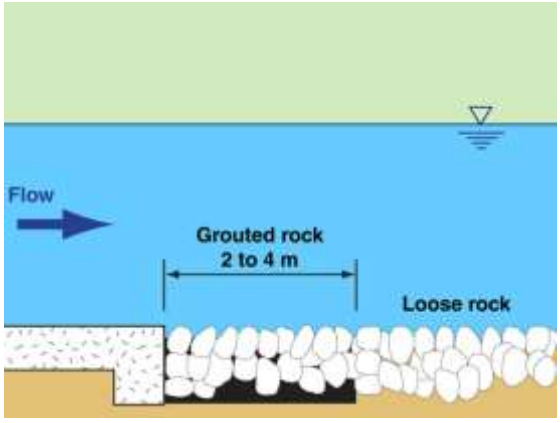
- Rock pads placed downstream of hydraulic structures, such as concrete drainage channels, perform several tasks, including:
  - energy dissipation
  - prevention of soil scour that could undermine the hydraulic structure
  - development of a thicker boundary layer within the flow before the water enters a vegetated channel.



Rock sizing at culvert outlets

Consider using the rock size specified for culvert outlets

- One option for the sizing of rock placed downstream of concrete channels is to adopt the equivalent rock specified for culvert outlets.
- The recommendations for rock placement downstream of waterway culverts can be found in the partner *Catchments and Creeks* field guide:
  - *'Use of Rock in Waterway Engineering'*



Grouted rock pad

Consider the use of grouted rock

- An additional design option is to heavily grout the first few metres of the rock pad to reduce the risk of rocks being displaced.
- This grouting must allow the exposed rock surface to be left in a 'rough' condition in order to help in the formation of a thick boundary layer.
- Warning; grouted rock is not durable, and will likely need to be repaired or replaced at some stage.

4. Energy Dissipaters

Introduction

Rock-lined energy dissipater fact sheet

Rock stabilisation of a drop structure

Rock stabilisation of an outlet structure

Rock stabilisation of a high-energy outlet

Introduction

- Energy dissipaters generally contain two zones that may contain rock:
  - Zone 1 where energy losses and turbulence are the greatest
  - Zone 2 where flows are allowed to return to normal 'uniform' flow before entering the receiving channel
- **This section focuses on rock in <u>Zone 2</u>.**
- Relevant fact sheet: https://www.catchmentsandcreeks.com.au/fact-sheets/esc_rock_sizing.html

Treatment of Zone 1 (upstream of end sill)

- Zone 1 is where energy dissipation is the greatest.
- Concrete is more commonly used within Zone 1, however rock has been used on occasions.
- In some cases the stability of the rock is increased by filling all voids with grout (e.g. a grouted boulder energy dissipater).
- Only angular, fractured angular rock should be placed within high energy areas (i.e. not rounded rock).

Sizing rock for placement downstream of the end sill (i.e. in Zone 2)

- Bos, Reploge, and Clemmens (1984) recommended the following equation for sizing rock placed downstream of energy dissipaters.

$$d_{40} = 0.038\, V^{2.26} \qquad (4.1)$$

- If it is assumed the above equation is based on $s_r = 2.6$, and $d_{40}/d_{50} = 0.75$, then:

$$d_{50} = \frac{0.08\, V^{2.26}}{(s_r - 1)} \qquad (4.2)$$

Alternative equation for sizing rock placed downstream of stilling basins (Zone 2)

- The following equation is based on Isbash, (1936) and includes rock density as a variable.

$$d_{50} = \frac{K_1 . V^2}{14.5 (s_r - 1)} \qquad (4.3)$$

- V = the depth-average flow velocity at the location of rock in Zone 2 [m/s]
- It is strongly recommended that the rock is highly angular, thus $K_1 = 1.0$.

5. Multi-Pipe Stormwater Outlet Structures

Introduction

Multi-pipe and culvert outlet fact sheet

Introduction

- Similar hydraulic forces exist at the outlets of multi-pipe drainage systems and multi-cell culverts.
- The hydraulic forces generated by multiple pipe outlets are generally higher than those expected at single pipe outlets, consequently the rock sizing charts are different for multi and single pipe outlets.
- Relevant fact sheet: https://www.catchmentsandcreeks.com.au/fact-sheets/esc_rock_sizing.html

Multi-pipe outlet structure (Qld)

Critical design parameters

- The critical design parameters for multi-pipe outlet structures are the mean rock size (d_{50}) and length of rock protection (L).
- The primary performance objectives are to:
  - minimise the risk of soil erosion downstream of the outlet, and
  - prevent soil erosion adjacent to the outlet that could potentially undermine the headwall.

Multi-pipe 'drop' outlet (Qld)

Length of the rock pad

- The specified minimum pad length (L) is based on practicality issues and will not necessarily prevent all bed scour.
- During high tailwater conditions, bed and bank erosion can occur well downstream of the rock pad.
- When the outlet is fully or partially drowned (i.e. high tailwater), 'jetting' from the outlet can transfer flow energy well downstream of the rock pad.

Partial movement of rock (Qld)

Ongoing shifting of rocks

- The following rock sizing design tables are based on the acceptance that some degree of rock movement will likely occur during the first few years.
- The problem relates to the fact that flows passing over a smooth surface (such as concrete pipe) generate a thin boundary layer that causes high shear stresses to exist close to the pipe invert—these same high shear stresses then pass directly onto the surface of the rock pad causing movement of some rocks.

Sizing rock downstream of multi-pipe stormwater outlets

Recommended mean (d_{50}) rock sizes are presented in tables 5.2 and 5.3. These values have been rounded up to the next 100 mm increment in consideration of the limited availability of rock sizes and the high variability of expected outcomes.

Mean rock sizes are also presented graphically in Figure 5.1. Some minor variations should be expected between Figure 5.1 and the tabulated values.

A 36% increase in rock size is recommended if rounded rocks are used instead of angular rock.

The recommended minimum length of rock protection (L) is presented in tables 5.4 and 5.5. A typical layout of the rock pad is shown in Figure 5.2. The rock pad should be straight and aligned with the direction of outflow.

The recommended minimum width of the rock pad, W = B + 0.6 (Figure 5.2) is presented as a guide only. In most cases the width of rock protection is likely to be limited by the width of the receiving channel.

In circumstance where the width of the rock pad is governed by the width of the receiving channel, then the rock protection may need to extend partially up the banks of the channel if suitable vegetation cannot be established on the channel banks.

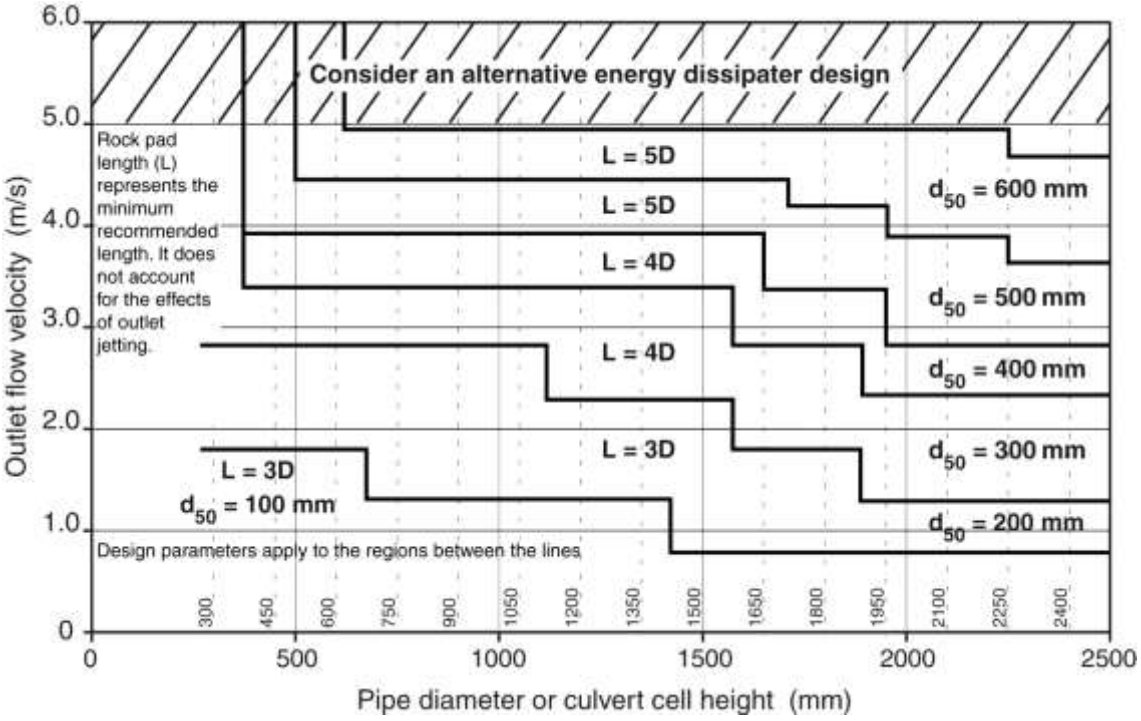


Figure 5.1 – Sizing of rock pad outlet structures for multi-cell/pipe outlets

The thickness of the rock pad should be based on at least two layers of rock. This typically results in an overall pad thickness as presented in Table 5.1.

Table 5.1 – Minimum thickness (T) of rock pad

Min. thickness (T)	Size distribution (d_{50}/d_{90})	Description
1.4 d_{50}	1.0	Highly uniform rock size
1.6 d_{50}	0.8	Typical upper limit of quarry rock
1.8 d_{50}	0.67	Recommended lower limit of distribution
2.1 d_{50}	0.5	Typical lower limit of quarry rock

Note: d_X = nominal rock size (diameter) of which X% (by weight) of the rocks are smaller.

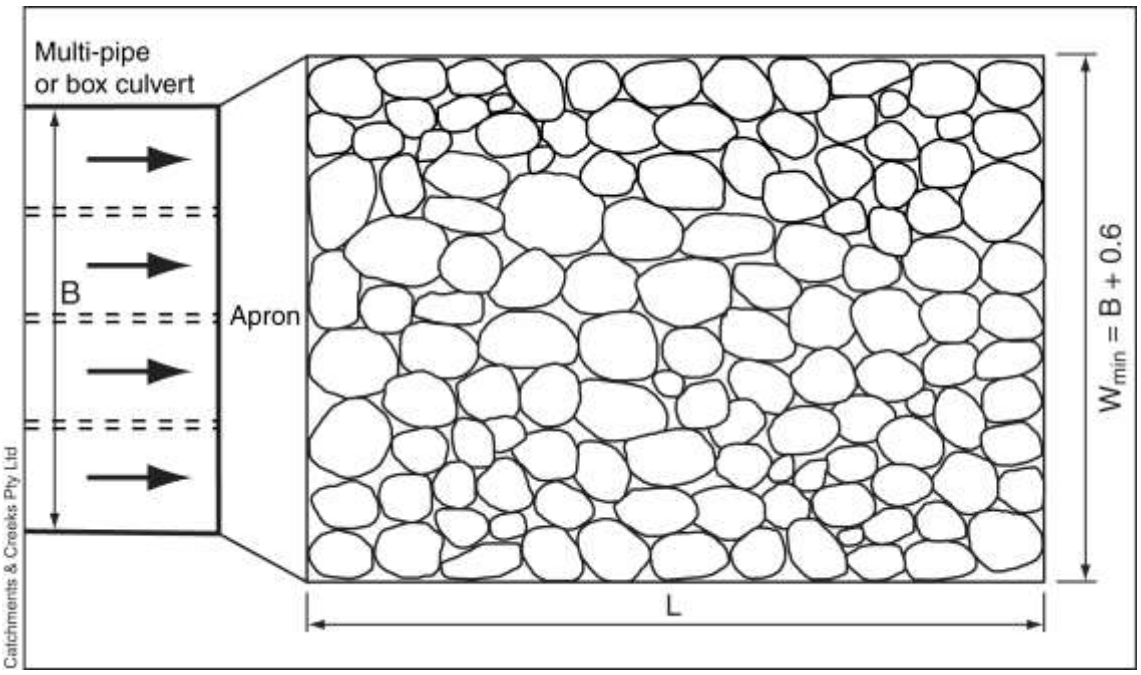


Figure 5.2 – Typical layout of a rock pad for multiple pipe and box culverts (plan view)

The surface elevation of the downstream end of the rock pad should be level with the invert of the receiving channel, i.e. the rocks should be recessed into the outlet channel (Figure 5.3) to minimise the risk of erosion around the edges of the rock pad.

The placement of filter cloth under the rock pad is generally considered mandatory for all permanent structures; however, if heavy sedimentation is expected within the rock voids, then the 'need' for the filter cloth is reduced. The placement of filter cloth is essential in circumstances where it is only practical to place a single layer of rock.

Selecting the appropriate length of rock protection

In circumstances where it is essential to minimise the risk of bed scour downstream of the outlet, then the length of the rock pad should be twice that presented in tables 5.4 and 5.5; however, little value is gained from extending the rock protection any further.

When the outlet is submerged (TW > H) a floating outlet 'jet' can pass over the rock pad with minimal energy loss. In such cases the rock pad still provides essential scour protection adjacent to the outlet, but extending the rock protection beyond the nominated minimum length may not necessarily provide any significant increase in energy dissipation or scour protection.

High velocity outlet jets can cause bank erosion problems if the outlet is aimed at a downstream embankment. Typically, such problems only occur if an unprotected embankment is less than 13 times the pipe diameter away from the outlet (based on a twin-pipe outlet).

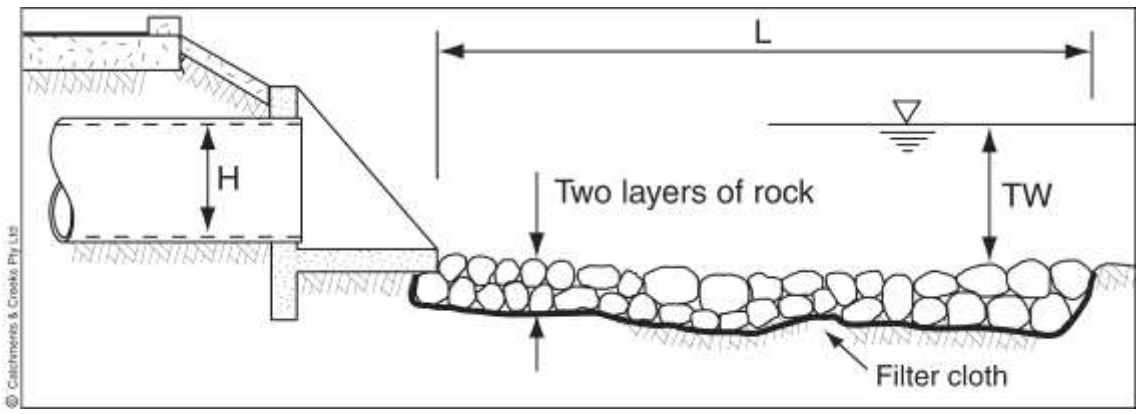


Figure 5.3 – Rock pad recessed into the receiving channel

Table 5.2 – Mean rock size, d_{50} (mm) for multi-pipe outlet scour protection

Outflow velocity (m/s)	Culvert height or pipe diameter (mm)						
	300	**375**	**450**	**525**	**600**	**750**	**900**
0.50	100	100	100	100	100	100	100
1.00	100	100	100	100	100	100	100
1.50	100	100	100	100	100	200	200
2.00	200	200	200	200	200	200	200
2.50	200	200	200	200	200	200	200
3.00	300	300	300	300	300	300	300
3.50	300	400	400	400	400	400	400
3.75	300	400	400	400	400	400	400
4.00	300	400	500	500	500	500	500
4.25	300	400	500	500	500	500	500
4.50	300	400	500	600	600	600	600
4.75	300	400	500	600	600	600	600
5.00	300	400	500	600	600	700	700
5.25	300	400	500	600	600	800	800
5.50	300	400	500	600	600	800	800
5.75	300	400	500	600	600	800	900
6.00	300	400	500	600	600	800	900

Table 5.3 – Mean rock size, d_{50} (mm) for multi-pipe outlet scour protection

Outflow velocity (m/s)	Culvert height or pipe diameter (mm)						
	1050	**1200**	**1350**	**1500**	**1800**	**2100**	**2400**
0.50	100	100	100	100	100	100	100
1.00	100	100	200	200	200	200	200
1.50	200	200	200	200	200	300	300
2.00	200	200	200	200	300	300	300
2.50	200	300	300	300	300	400	400
3.00	300	300	300	300	400	500	500
3.50	400	400	400	400	500	500	500
3.75	400	400	400	400	500	500	600
4.00	500	500	500	500	500	600	600
4.25	500	500	500	500	600	600	600
4.50	600	600	600	600	600	600	600
4.75	600	600	600	600	600	600	700
5.00	700	700	700	700	700	700	700
5.25	900	900	900	900	900	900	900
5.50	900	900	900	900	900	900	900
5.75	900	900	900	900	900	900	900
6.00	1000	1000	1000	1000	1000	1000	1000

Table 5.4 – Minimum length (L) of rock pad relative to cell height (H) for multi-pipe outlet protection [1,2]

Outflow velocity (m/s)	Culvert height or pipe diameter (mm)						
	300	375	450	525	600	750	900
0.50	3	3	3	3	3	3	3
1.00	3	3	3	3	3	3	3
1.50	3	3	3	3	3	3	3
2.00	3	3	3	3	3	3	3
2.50	3	3	3	3	3	3	3
3.00	3	3	3	3	3	3	3
3.50	3	3	3	3	3	4	4
3.75	3	3	3	3	4	4	4
4.00	3	3	3	4	4	4	4
4.25	3	3	4	4	4	4	4
4.50	3	4	4	4	4	4	4
4.75	3	4	4	4	4	4	5
5.00	4	4	4	4	4	4	5
5.25	4	4	4	4	4	5	5
5.50	4	4	4	6	6	6	6
5.75	4	4	6	6	6	6	6
6.00	4	6	6	6	6	6	6

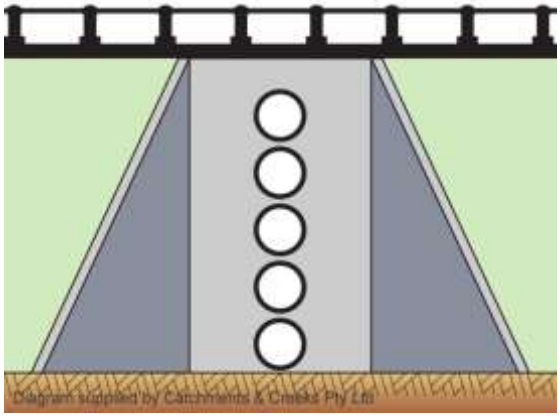
Table 5.5 – Minimum length (L) of rock pad relative to cell height (H) for multi-pipe outlet protection [1,2]

Outflow velocity (m/s)	Culvert height or pipe diameter (mm)						
	1050	1200	1350	1500	1800	2100	2400
0.50	3	3	3	3	3	3	3
1.00	3	3	3	3	3	3	4
1.50	3	3	3	3	3	4	4
2.00	3	3	3	3	4	4	4
2.50	3	4	4	4	4	4	4
3.00	4	4	4	4	4	4	4
3.50	4	4	4	4	5	5	5
3.75	4	4	4	4	5	5	5
4.00	4	4	5	5	5	5	5
4.25	4	5	5	5	5	5	5
4.50	5	5	5	5	5	5	5
4.75	5	5	5	5	5	5	5
5.00	5	5	5	5	6	6	
5.25	6	6	6	6	6	6	
5.50	6	6	6	6	6		
5.75	6	6	6	6	6		
6.00	6	6	6	6	6		

[1] Values represent the recommended minimum length of rock protection to prevent significant scour; however, some degree of soil erosion should be expected downstream of the rock protection.

[2] Under high tailwater conditions (TW > D/2) outlet jetting may extend beyond the rock protection during high tailwater conditions resulting in bed and/or bank erosion downstream of the rock protection. Extending the length of the rock protection will not necessarily reduce the risk of downstream bank erosion under high tailwater conditions.

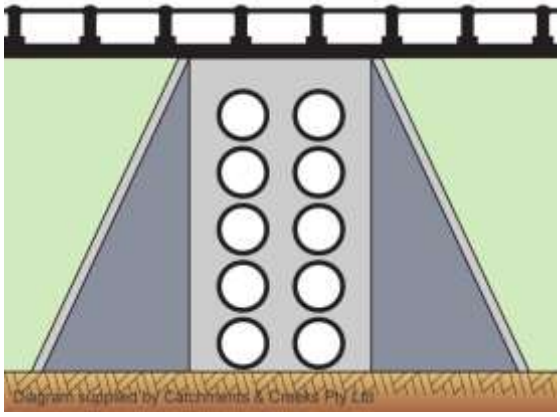
Multiple pipe detention/retention basin outlets



Five pipes stacked vertically

Multiple pipes stacked in a single column

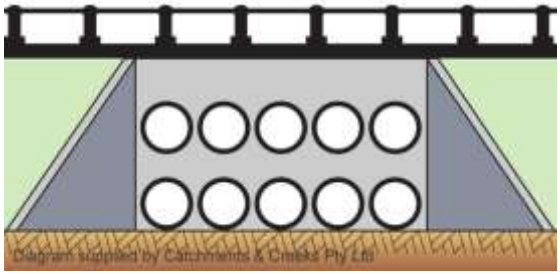
- If a stormwater detention basin has a multi-pipe outlet with the pipes stacked along a vertical column, then such an outlet should be treated as for a single pipe outlet.
- Therefore, rock sizing (d_{50}) and the length of scour protection (L) for 5 x 375 mm pipes stacked in a single column should be based on a **single-pipe** 375 mm outlet.
- The 'equivalent' pipe diameter remains as 375 mm in this case.



Ten pipes stacked in two columns

Multiple pipes stacked in two columns

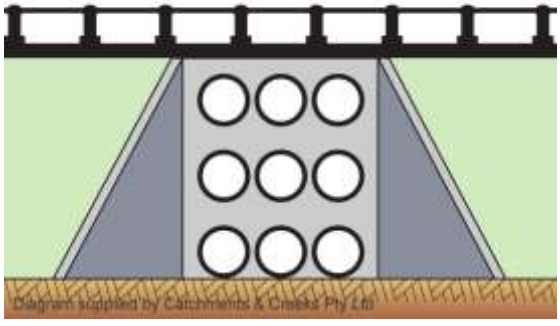
- If two or more pipes are stacked in vertical columns, the individual outlet jets will join to form a single outlet jet with energy dissipation governed by the 'width' of this outlet jet (the smaller dimension).
- Thus for 10 x 375 mm pipes stacked in two columns, adopting a **multi-pipe** 375 mm outlet will provide the lower limit for rock sizing, while adopting the equivalent pipe diameter of a square block of 4 x 375 mm pipes (i.e. 750 mm) based on a **single-pipe** outlet will provide the upper limit for the rock size and pad length.



Ten pipes stacked in two rows

Multiple pipes stacked in multiple columns

- In the case shown left, energy dissipation downstream of the outlet will be dictated by the 'depth' of the combined outlet jet.
- Thus for 10 x 375 mm pipes stacked in two rows, adopting a **multi-pipe** 375 mm outlet will provide the lower limit for the rock size and pad length, while adopting the equivalent pipe diameter of a square block of 4 x 375 mm pipes (i.e. 750 mm), and using a **multi-pipe** outlet, will provide the upper limit for the rock size and pad length.



Nine pipes stacked in three columns

Multiple pipes stacked in a group such that the effective depth and width of the outlet jet are similar

- In the case shown left, the individual outlet jets will combine to form a single circular outlet jet with a diameter equivalent to the combined flow area of the pipes.
- Thus, for 9 x 375 mm pipes, the equivalent pipe diameter = $(9 \times 375^{2})^{0.5}$ = 1125 mm.
- Therefore, rock sizing (d_{50}) and the length of scour protection (L) for 9 x 375 mm pipes should be based on a **single-pipe** 1125 mm outlet.

Common construction problems

Displacement of rock pad

Inadequate rock size

- Rock of inadequate size can readily be displaced downstream of the outlet causing erosion to threaten the structure.

Placement on dispersive soils (below)

- Outlet scour protection often fails when placed directly on a dispersive soil.
- The formation of a cut-off wall at the downstream end of the concrete apron can reduce the risk of structural failure, especially if placed on dispersive soils.

Undermining of outlet

Same outlet eight years later

Inappropriate rock placement

Poor placement of rock

- If the rocks sit above the invert of the outlet, then:
  - sediment is likely to collect within the pipes, and
  - the outlet 'jet' may be deflected towards the creek banks.
- The rocks need to be recessed such that the upper surface of the rocks is level with the concrete apron.

Outlet too close to opposite bank

Outlet jetting

- During periods of high tailwater, the outlet jet can float along the water surface with minimal energy dissipation.
- Floating outlet jets can travel at excessive speed for a distance of around 10 to 15 times the jet diameter (depending on the exit velocity and the spacing between the pipes).

6. Single Pipe Stormwater Outlet Structures

Introduction

Single pipe outlet structure fact sheet

Introduction

- Similar hydraulic forces exist at the outlets of single-pipe drainage systems and single-cell culverts.
- For advice on the design of multi-pipe outlets refer to the previous section (Section 5) of this document.
- Relevant fact sheet: https://www.catchmentsandcreeks.com.au/fact-sheets/esc_rock_sizing.html

Stormwater outlet scour protection (Qld)

Critical design parameters

- The critical design parameters for single pipe outlets are the mean rock size (d_{50}) and length of rock protection (L).
- The primary performance objectives are to:
  - minimise the risk of soil erosion downstream of the outlet, and
  - prevent soil erosion adjacent the outlet that could potentially undermine the structure.

Stormwater outlet scour protection (Qld)

Length of the rock pad

- The specified minimum pad length (L) is based on practicality issues and will not necessarily prevent all bed scour.
- During high tailwater conditions, bed and bank erosion can occur well downstream of the rock pad.
- When the outlet is fully or partially drowned (high tailwater) then 'jetting' from the outlet can transfer energy well downstream of the rock pad.

Movement of rocks within rock pad

Ongoing shifting of rocks

- The following rock sizing design charts/tables are based on the acceptance of some degree of rock movement (rearrangement) during the first few years.
- The problem relates to the fact that flows passing over a smooth surface (such as concrete pipe) generate a thin boundary layer that causes high shear stresses to exist close to the pipe invert—these same high shear stresses then pass directly onto the surface of the rock pad causing the displacement of some rocks.

Hydraulics of stormwater outlets

Pipe discharge with very low tailwater

Outlet flow conditions

- The hydraulics of stormwater outlets change with changing tailwater conditions.
- Some design guidelines provide different rock pad outlet dimensions for low tailwater conditions and high tailwater conditions.
- The different hydraulic conditions of low and high tailwater are discussed below.

Pipe discharge with low tailwater (Qld)

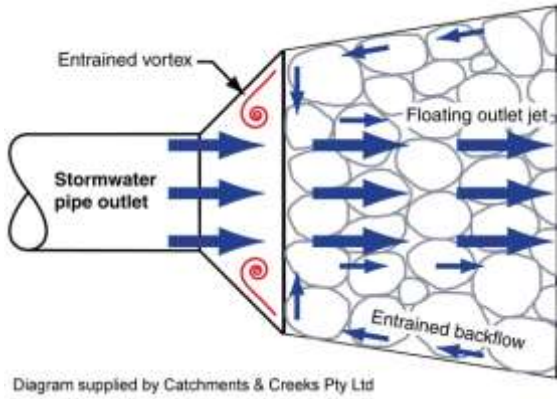
Low tailwater flow conditions

- During low tailwater conditions, discharges tend to 'spill' from stormwater pipes spreading the flow energy over a wider pathway than during high tailwater.
- Energy dissipation is much more efficient and the required length of the rock pad is smaller than is required during high tailwater conditions.
- The rock pad lengths (L) presented within the following pages typically reflect this low tailwater condition.

Outlet jetting during high tailwater (NSW)

High tailwater flow conditions

- During high tailwater conditions, discharges from pipes tend to 'float' along the surface of the water.
- During these conditions it is common for high velocity outlet jets to travel a distance of between 10 and 15 times the jet depth (i.e. approx twice the nominal rock pad length, L) before there is a significant reduction in the central core flow velocity.
- The existence of a rock pad may not necessarily enhance energy dissipation.



Example of entrained outlet vortices

Purpose of headwalls on pipe outlets

- Headwalls can provide the following benefits:
  - reduce the risk of erosion undermining the outlet (if a cut-off wall is included)
  - reduce the risk of rock displacement within outlet structures
  - reduce the risk of 'entrained vortices' eroding the channel banks adjacent the outlet.
- Headwalls are generally only 'essential' on high velocity stormwater outlets.

Sizing rock for single pipe outlet structures

Recommended minimum mean (d_{50}) rock sizes are presented in tables 6.2 and 6.3. These values have been rounded up to the next 100 mm increment in recognition of the limited availability of rock sizes and the high variability of expected outcomes. Mean rock sizes are also presented graphically in Figure 6.1. Some minor variations should be expected between Figure 6.1 and the tabulated values.

A 36% increase in rock size is recommended if rounded rocks are used instead of angular rock.

The recommended minimum length of rock protection (L) may be determined from tables 6.4 and 6.5. A typical layout of the rock pad is shown in Figure 6.2. The rock pad should be straight and aligned with the direction of the discharge.

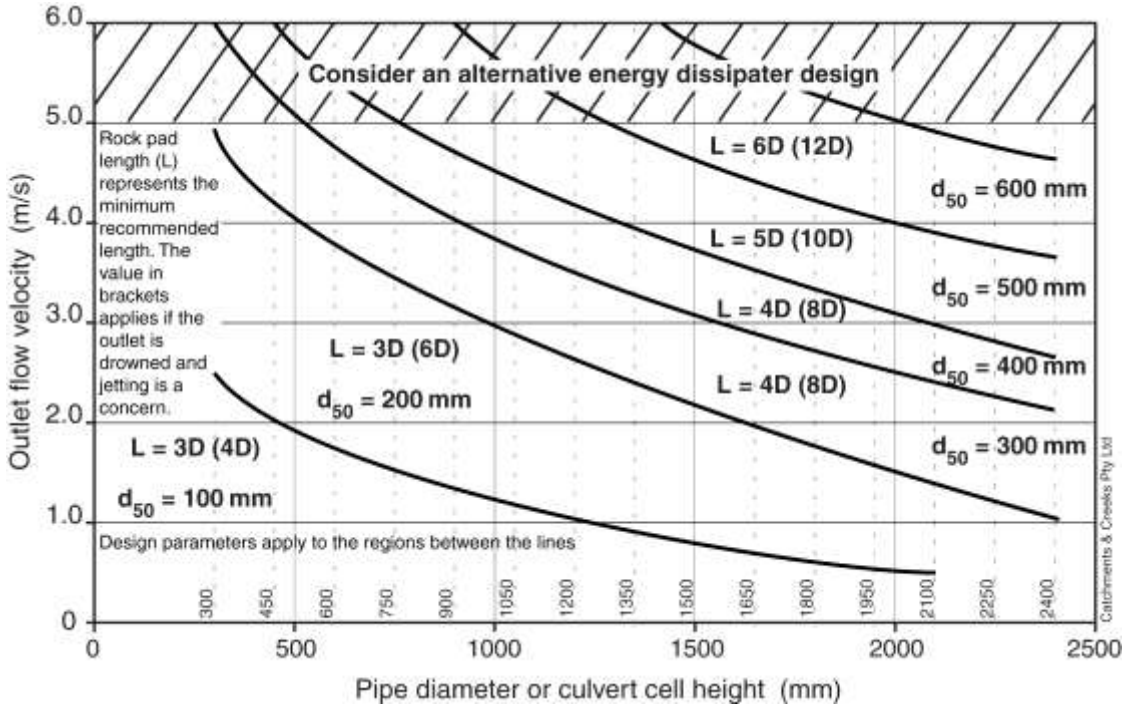


Figure 6.1 – Sizing of rock pad outlet structures for single pipe outlets

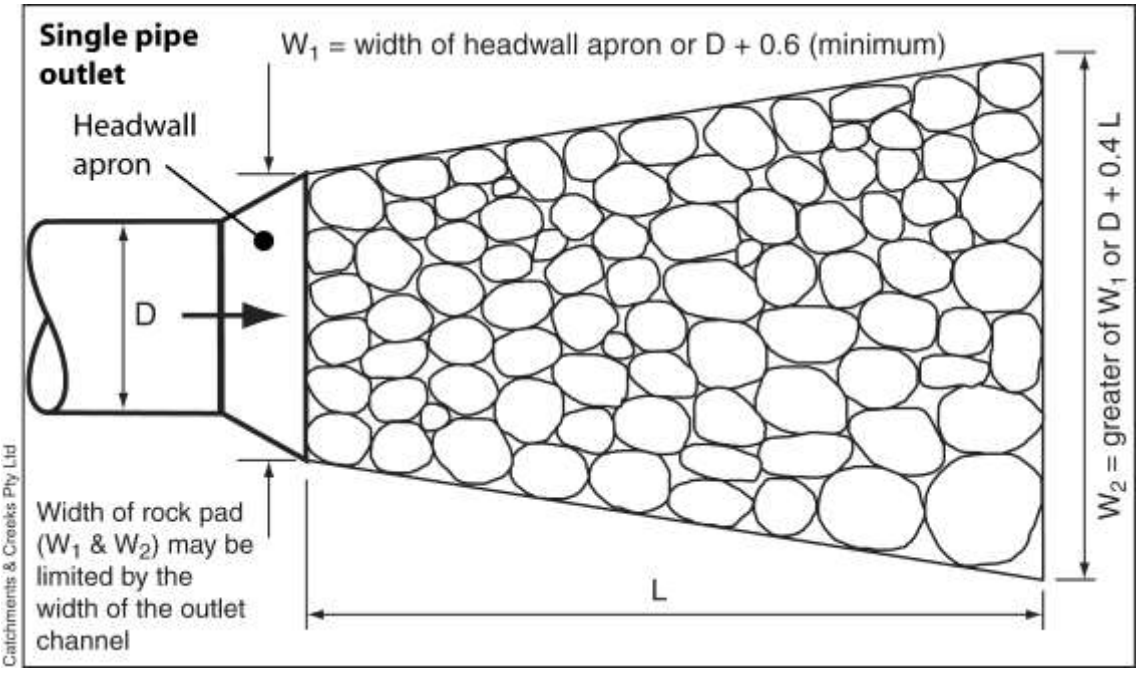


Figure 6.2 – Typical layout of a rock pad for single pipe outlet (plan view)

The recommended width of the rock pad (as shown in Figure 6.2) depends on whether or not a headwall and apron is attached to the outlet.

In circumstance where the width of the rock pad is governed by the width of the receiving channel, then the rock protection may need to extend partially up the banks of the channel. Alternatively, appropriate erosion-control vegetation may be established on the channel banks.

The thickness of the rock pad should be based on at least two layers of rock. This typically results in an overall pad thickness as presented in Table 6.1.

The surface elevation of the downstream end of the rock pad should be level with the invert of the receiving channel, i.e. the rocks should be recessed into the outlet channel (Figure 6.3) to minimise the risk of erosion around the outer edges of the rock pad.

The placement of filter cloth under the rock pad is generally considered mandatory for all permanent structures; however, if heavy sedimentation is expected within the rock voids, then the 'need' for the filter cloth is reduced. The placement of filter cloth is essential in circumstances where it is only practical to place a single layer of rock.

Table 6.1 – Minimum thickness (T) of rock pad

Min. thickness (T)	Size distribution (d_{50}/d_{90})	Description
1.4 d_{50}	1.0	Highly uniform rock size
1.6 d_{50}	0.8	Typical upper limit of quarry rock
1.8 d_{50}	0.67	Recommended lower limit of distribution
2.1 d_{50}	0.5	Typical lower limit of quarry rock

Selecting the appropriate length of rock protection

During low tailwater conditions (TW < D/2) flow exiting the pipe will normally spread rapidly unless confined within the receiving channel. Under such tailwater conditions the rock pad provides scour control benefits as well as energy dissipation. Typically the nominated minimum length of rock protection is considered adequate under these conditions.

As tailwater levels increase in elevation (D/2 < TW < D) energy dissipation as a direct result of the rock pad begins to decrease causing more flow energy to pass over the rocks. In such cases the length of the rock pad may be doubled (i.e. 2L), but only if it is essential to minimise soil erosion downstream of the rock pad.

When the outlet is submerged (TW > D) an outlet 'jet' can pass over the rock pad with minimal energy dissipation. In such cases the rock pad still provides essential scour protection adjacent to the pipe outlet, but extending the rock protection beyond the nominated minimum length may not necessarily provide any significant increase in energy dissipation or scour control.

Outlet jetting occurs when the outlet is submerged and outlet velocity is significantly greater than the receiving water velocity. High velocity jets can cause bank erosion problems if the outlet is aimed at a downstream embankment. Typically, such problems only occur if an unprotected embankment is less than 10 times the pipe diameter away from the outlet.

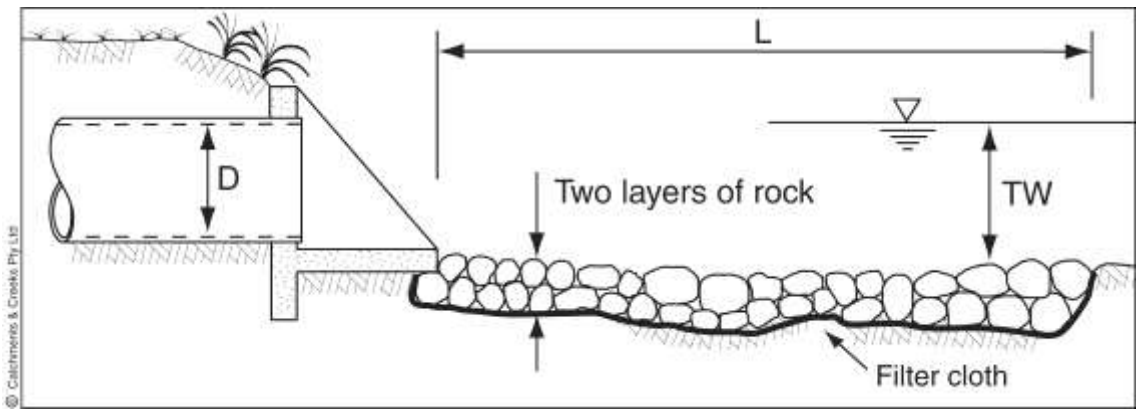


Figure 6.3 – Rock pad recessed into the receiving channel

Table 6.2 – Mean rock size, d_{50} (mm) for single pipe outlet protection

Outflow velocity (m/s)	Culvert height or pipe diameter (mm)						
	300	375	450	525	600	750	900
0.50	100	100	100	100	100	100	100
1.00	100	100	100	100	100	100	100
1.50	100	100	100	100	100	200	200
2.00	100	100	200	200	200	200	200
2.50	100	200	200	200	200	200	200
3.00	200	200	200	200	200	200	200
3.50	200	200	200	200	200	300	300
3.75	200	200	200	200	300	300	300
4.00	200	200	200	300	300	300	400
4.25	200	200	300	300	300	300	400
4.50	200	300	300	300	300	400	400
4.75	200	300	300	300	300	400	500
5.00	300	300	300	300	400	400	500
5.25	300	300	300	400	400	500	500
5.50	300	300	300	400	500	500	500
5.75	300	300	400	500	500	500	500
6.00	300	400	500	500	500	500	600

Table 6.3 – Mean rock size, d_{50} (mm) for single pipe outlet protection

Outflow velocity (m/s)	Culvert height or pipe diameter (mm)						
	1050	1200	1350	1500	1800	2100	2400
0.50	100	100	100	100	100	100	100
1.00	100	100	200	200	200	200	200
1.50	200	200	200	200	200	300	300
2.00	200	200	200	200	300	300	300
2.50	200	300	300	300	300	400	400
3.00	300	300	300	300	400	500	500
3.50	300	400	400	400	500	500	500
3.75	400	400	400	400	500	500	600
4.00	400	400	500	500	500	600	600
4.25	400	500	500	500	600	600	600
4.50	500	500	500	500	600	600	600
4.75	500	500	500	600	600	600	700
5.00	500	500	600	600	600	700	700
5.25	500	600	600	600	600	700	700
5.50	600	600	600	600	700	700	900
5.75	600	600	600	600	700	900	900
6.00	600	600	600	700	700	900	900

Table 6.4 – Minimum length (L) of rock pad relative to cell height (H) for single pipe outlet protection [1,2]

Outflow velocity (m/s)	Culvert height or pipe diameter (mm)						
	300	375	450	525	600	750	900
0.50	3	3	3	3	3	3	3
1.00	3	3	3	3	3	3	3
1.50	3	3	3	3	3	3	3
2.00	3	3	3	3	3	3	3
2.50	3	3	3	3	3	3	3
3.00	3	3	3	3	3	3	3
3.50	3	3	3	3	3	4	4
3.75	3	3	3	3	4	4	4
4.00	3	3	3	4	4	4	4
4.25	3	3	4	4	4	4	4
4.50	3	4	4	4	4	4	4
4.75	3	4	4	4	4	4	5
5.00	4	4	4	4	4	4	5
5.25	4	4	4	4	4	5	5
5.50	4	4	4	6	6	6	6
5.75	4	4	6	6	6	6	6
6.00	4	6	6	6	6	6	6

Table 6.5 – Minimum length (L) of rock pad relative to cell height (H) for single pipe outlet protection [1,2]

Outflow velocity (m/s)	Culvert height or pipe diameter (mm)						
	1050	1200	1350	1500	1800	2100	2400
0.50	3	3	3	3	3	3	3
1.00	3	3	3	3	3	3	4
1.50	3	3	3	3	3	4	4
2.00	3	3	3	3	4	4	4
2.50	3	4	4	4	4	4	4
3.00	4	4	4	4	4	4	4
3.50	4	4	4	4	5	5	5
3.75	4	4	4	4	5	5	5
4.00	4	4	5	5	5	5	5
4.25	4	5	5	5	5	5	5
4.50	5	5	5	5	5	5	5
4.75	5	5	5	5	5	5	5
5.00	5	5	5	5	6	6	6
5.25	6	6	6	6	6	6	
5.50	6	6	6	6	6		
5.75	6	6	6	6	6		
6.00	6	6	6	6	6		

[1] Values represent the recommended minimum length of rock protection to prevent significant scour; however, some degree of soil erosion should be expected downstream of the rock protection.

[2] Under high tailwater conditions (TW > D/2) outlet jetting may extend beyond the rock protection during high tailwater conditions resulting in bed and/or bank erosion downstream of the rock protection. Extending the length of the rock protection will not necessarily reduce the risk of downstream bank erosion under high tailwater conditions.

Common construction problems

Insufficient rock placement

Insufficient quantity or poor placement of rock

- Erosion is common on stormwater outlets where insufficient rock has been placed, or the rock has been placed in a manner that encourages the flow to pass around the outside of the rocks.

Use of concrete rubble

Use of concrete rubble

- The use of concrete rubble can cause the flow to spill to the outer edge of the rubble or be deflected towards the channel banks.

Rock sits above adjacent land surface

Poor placement of rock

- If the rock pad sits above the adjacent land surface, then the outflow will likely spill off the rock pad causing erosion along the edges of the rock pad.

Excessive quantity of rock

Excessive use of rock

- The excessive use of rock at stormwater outlets can be both a waste of resources and an eyesore.

7. Slope Drain Outlet Structures

Introduction

Slope drain outlet structure fact sheet

Introduction

- A ‘slope drain’ is a prefabricated solid-wall or lay-flat pipe anchored to the side of an embankment and used to provide temporary stormwater drainage.
- They are normally used as temporary drainage systems during the revegetation of an embankment or as part of flow diversion on a construction site.
- Relevant fact sheet: https://www.catchmentsandcreeks.com.au/fact-sheets/esc_rock_sizing.html

Temporary slope drain on road works

Difference between slope drain outlets and single pipe stormwater outlets

- The flow conditions within a ‘slope drain’ are usually different from those experienced within most stormwater pipes.
- Flows normally approach the outlet of a slope drain in a partial-full, supercritical flow condition.
- This means slope drain outlets normally experience higher flow velocities, but shallower flow conditions.

Slope drain outlet structure (Qld)

Critical design parameters

- The primary performance objectives of a slope drain outlet structure are to minimise the risk of soil erosion at the outlet, spread the released flow, and to dissipate excessive flow energy.
- The critical design parameters are the mean rock size (d_{50}) and length of rock pad (L).

Inappropriate outlet structure

Common construction problems

- Common construction problems include:
  - inadequate rock size
  - poorly placed rock that causes the redirection of the outflow
  - the outlet structure located on the batter slope (i.e. up-slope of the batter toe) thus causing erosion down the batter
  - use of an inappropriate energy dissipater such as straw bales (left).

Rock sizing for slope drain outlet structures

The following information is appropriate for the design of loose-rock outlet structures for temporary **slope drains up to 375 mm diameter**.

The thickness of the rock pad should be based on at least two layers of rock. This typically results in a minimum thickness as presented in Table 7.1.

Tables 7.2 and 7.3 provide the recommended mean (d_{50}) rock sizes and length (L) of rock protection for slope drain outlets for smooth and rough internal sidewall pipes respectively. These design tables are based on the acceptance that some degree of rock movement and minor soil erosion will likely occur following the initial storm events.

The typical layout of a rock pad for a slope drain is shown in Figure 7.1. The rock pad should be straight and align with the direction of outflow.

If the width of the rock pad is governed by the width of the receiving channel, then the rock protection should extend up the banks of the channel.

Slope drain outlet structures should be constructed at a level grade, or a gradient equal to that of the receiving channel (if any).

The surface level of the downstream end of the rock pad should be level with the invert of the receiving channel (if any) i.e. the rocks should be recessed into the outlet channel to minimise the risk of erosion around the outer edges of the rock pad.

The placement of filter cloth under the rock pad is generally considered optional for temporary outlet structures placed at the end of slope drains.

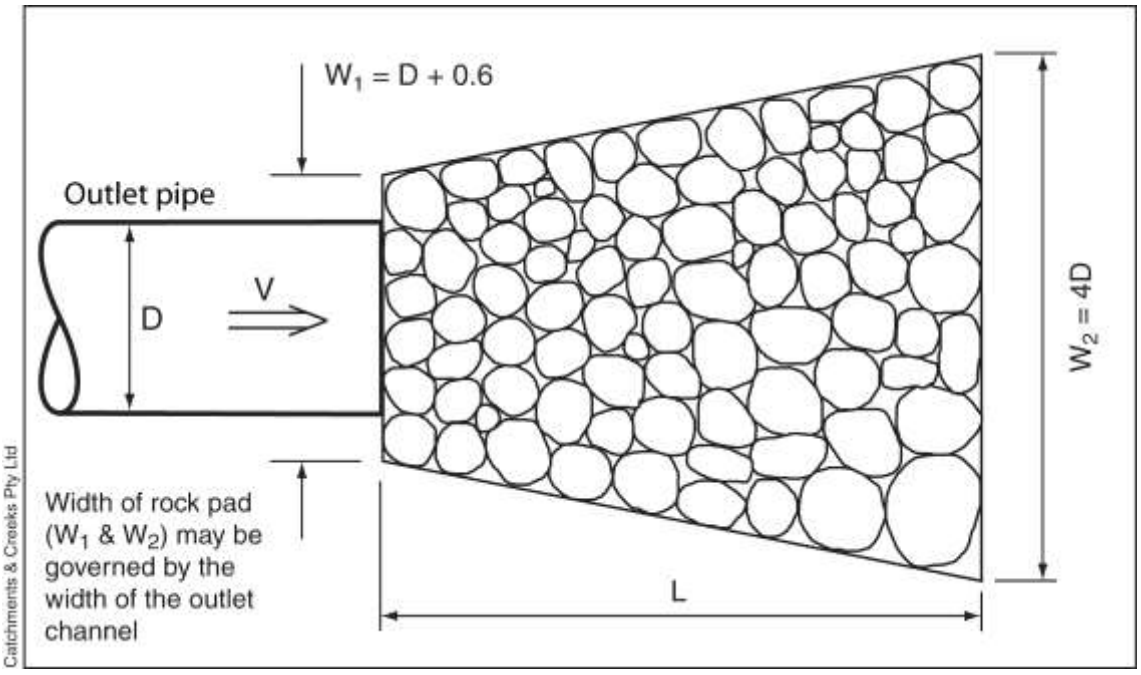


Figure 7.1 – Typical layout of a rock pad for a slope drain outlet (plan view)

Background to rock sizing tables

The rock sizes and pad lengths presented in tables 7.2 and 7.3 have been determined by firstly determining the partial-full, supercritical flow velocity expected at the base of a slope drain for a given discharge, internal pipe roughness, and slope gradient. Then an equivalent pipe diameter was determined that would have a full-pipe discharge and velocity equivalent to that determined above.

Using this equivalent pipe diameter, and the actual discharge velocity, the design charts presented within Bohan (1970) for low tailwater conditions were then used to determine the required mean rock size and length of rock protection. The rock sizes where finally rounded up to the nearest 100 mm rock size, with a minimum rock size set as 150 mm.

Table 7.1 – Minimum thickness (T) of rock pad

Min. Thickness (T)	Size distribution (d_{50}/d_{90})	Description
1.4 d_{50}	1.0	Highly uniform rock size
1.6 d_{50}	0.8	Typical upper limit of quarry rock
1.8 d_{50}	0.67	Recommended lower limit of distribution
2.1 d_{50}	0.5	Typical lower limit of quarry rock

Note: d_X = nominal rock size (diameter) of which X% (by weight) of the rocks are smaller.

Table 7.2 – Mean rock size (mm) and length (m) of rock pad outlet structure for smooth internal sidewall slope drain

Pipe diameter: 300 and 375mm						Smooth internal sidewall: Manning's n = 0.01						
Pipe slope (X:1)	Pipe discharge (L/s)											
	30	40	50	60	70	80	100	120	140	160	180	200	220
10	150	150	150	150	150	150	200	200	200	200	200	300	300
8	150	150	150	150	150	150	200	200	200	200	300	300	300
7	150	150	150	150	150	150	200	200	200	300	300	300	300
6	150	150	150	150	150	200	200	200	300	300	300	300	300
5	150	150	150	150	200	200	200	200	300	300	300	300	300
4	150	150	150	200	200	200	200	300	300	300	300	300	300
3	150	150	200	200	200	200	300	300	300	300	300	300	300
2	150	200	200	200	200	300	300	300	300	300	400	400	400
1	200	200	300	300	300	300	300	400	400	400	400	400	400
L [1]	**1.1**	**1.2**	**1.5**	**1.5**	**1.5**	**1.5**	**1.7**	**2.0**	**2.0**	**2.0**	**2.1**	**2.1**	**2.5**

[1] Recommended minimum length (m) of rock pad outlet structure.

Table 7.3 – Mean rock size (mm) and length (m) of rock pad outlet structure for rough internal sidewall slope drain

Pipe diameter: 300 and 375mm						Rough internal sidewall: Manning's n = 0.03						
Pipe slope (X:1)	Pipe discharge (L/s)											
	30	40	50	60	70	80	100	120	140	160	180	200	220
10	150	150	150	150	150	150	150	150	150	150	150	150	150
8	150	150	150	150	150	150	150	150	150	150	150	150	150
7	150	150	150	150	150	150	150	150	150	150	150	150	150
6	150	150	150	150	150	150	150	150	150	150	150	150	150
5	150	150	150	150	150	150	150	150	150	150	150	150	150
4	150	150	150	150	150	150	150	150	150	150	150	150	200
3	150	150	150	150	150	150	150	150	150	150	200	200	200
2	150	150	150	150	150	150	150	150	200	200	200	200	200
1	150	150	150	150	150	150	200	200	200	200	300	300	300
L [1]	**1.6**	**1.8**	**1.9**	**2.1**	**2.2**	**2.3**	**2.5**	**2.6**	**2.8**	**2.9**	**3.1**	**3.2**	**3.3**

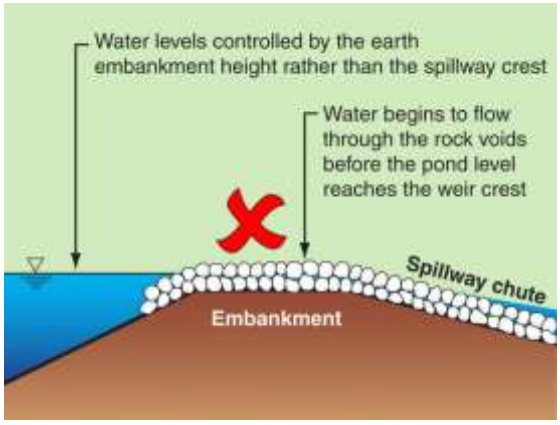
[1] Recommended minimum length (m) of rock pad outlet structure.

8. Small Dam Spillways

Introduction

Small dam spillway fact sheet

Sediment basin spillway (USA)



Flow leakage through rock voids

Poorly constructed spillway

Introduction

- In simple hydraulic terms, a dam spillway is just a large drainage chute used to carry excess flows over or around a dam embankment.
- The design procedures and rock sizing are similar to that used for batter chutes, but more care must be applied due to the possible severe consequences of structural failure.
- Relevant fact sheet: https://www.catchmentsandcreeks.com.au/fact-sheets/esc_rock_sizing.html

Critical design and operational issues

- Critical **design issues** for a spillway are:
  - the flow entry into the spillway
  - the maximum allowable flow velocity down the face of the spillway
  - energy dissipation at the base of the spillway.
- The critical **operational issues** are:
  - control of seepage flows through the rock voids at the spillway crest
  - control of splash
  - control of erosion at the base.

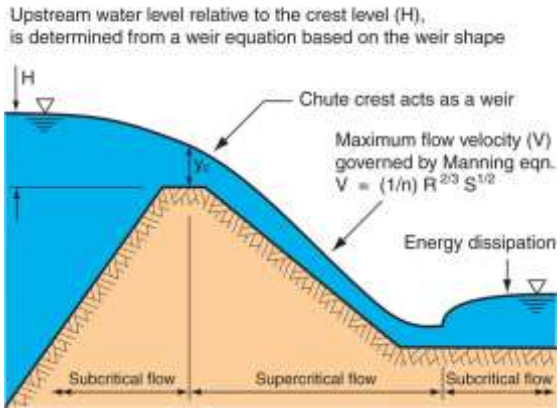
Common 'design' problems

- Common design problems include:
  - voids not sealed at the spillway crest, which causes water to leak from the dam (through the voids) before water levels reach the specified top water level
  - failure to judge the height of splash as the water spills down the spillway
  - specifying a curved spillway chute that causes supercritical flows to spill out of the spillway.

Common 'construction' problems

- Common construction problems include:
  - placement of rock that is smaller than the specified rock size
  - use of rounded rock instead of angular rock
  - flows spilling around the rock caused by inadequate height of rock placement along the sides (banks) of the spillway
  - inappropriate construction of a spillway within a dispersive soil.

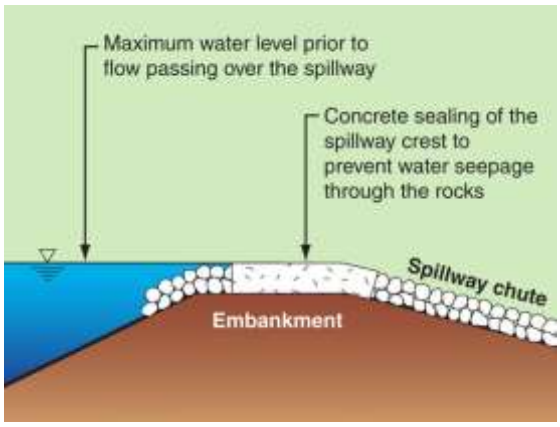
Spillway design



Dam spillway hydraulics

Hydraulic design

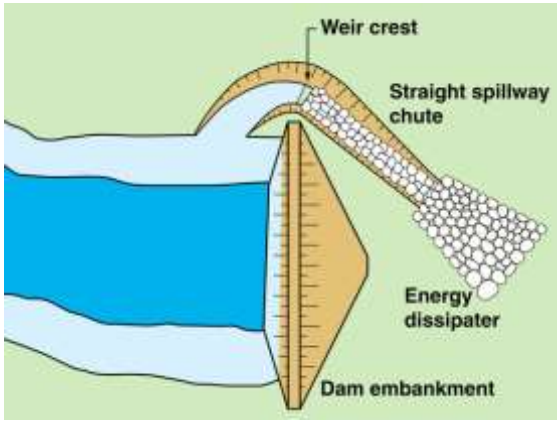
- Dam spillways are hydraulic structures that need to be designed for a specified design storm using standard hydraulic equations.
- The hydraulic design can be broken down into three components:
  - design of the spillway inlet using an appropriate weir equation
  - sizing rock for the face of the spillway based on Manning's equation velocity
  - sizing rock for the spillway outlet.



Sealing of spillway crest

Design of spillway crest

- Flow conditions at the spillway crest may be determined using an appropriate weir equation.
- It is important to ensure that the maximum potential water level within the dam at peak discharge will be fully contained by the dam embankments.
- The sealing of the spillway crest is necessary to maximise dam storage and prevent leakage through the rock voids.



Dam spillway cut into virgin soil

Design of spillway chute

- Determination of rock size on the spillway is based on either the maximum unit flow rate (q) or the maximum flow velocity (V) down the spillway.
- The upstream segment of the spillway's inflow channel can be curved (i.e. that section upstream of the spillway crest).
- Once the spillway descends down the embankment (i.e. where the flow is supercritical) the spillway **must** be straight.

Energy dissipation pond (Qld)

Design of energy dissipater

- A suitable energy dissipater or outlet structure is required at the base of the spillway.
- The design of the energy dissipater **must** be assessed on a case-by-case basis.
- It may or may not always be appropriate to use the standard rock sizing design charts presented elsewhere in this document.

Sizing of rock for use down the face of spillways

The recommended design equations for sizing rock placed on the face of spillway chutes (not within the energy dissipater) are provided below.

Tables 7 to 10 provide mean rock size (rounded up to the next 0.1 m unit) for angular rock, for a factor of safety of both 1.2 and 1.5. These tables are based on Equation 8.1 (below) and are best used in the design of long spillway chutes. Use of the 'unit flow rate' (q) as the primary design variable is preferred to the use of flow velocity (V) because it avoids errors associated with the selection of Manning's roughness.

Alternatively, tables 11 and 12 provide mean rock size for angular rock and a safety factor of 1.2 and 1.5. These tables are also based on Equation 8.1 but with flow velocity as the primary variable. These tables are best used in the design of small narrow spillways that have a cross-section similar to a batter chute, rather than a traditional wide shallow spillway.

Application of Equation 8.1	**Equation 8.1**
• Preferred design equation • Applicable for uniform flow conditions only, i.e. the chute is long enough to achieve terminal flow velocity where the energy slope (S_e) equal the batter slope (S_o) • Suitable for batter slopes less than 50%, (1 in 2)	$$d_{50} = \frac{127.SF.K_1.K_2.S_o^{0.5}.q^{0.5}.y^{0.25}}{(s_r - 1)}$$
Application of Equation 8.2 • A simplified equation that is independent of flow depth • Applicable to uniform flow conditions only, i.e. $S_e = S_o$ • Batter slopes (S_o) less than 50% (1 in 2)	**Equation 8.2** $$d_{50} = \frac{SF.K_1.K_2.S_o^{0.47}.q^{0.64}}{(s_r - 1)}$$
Application of Equation 8.3 • A simplified velocity-based equation • Applicable to uniform flow conditions only, i.e. $S_e = S_o$ • Batter slopes (S_o) less than 33% (1 in 3)	**Equation 8.3** $$d_{50} = \frac{SF.K_1.K_2.V^2}{(A - B.\ln(S_o)).(s_r - 1)}$$ For SF = 1.2: A = 3.95, B = 4.97 For SF = 1.5: A = 2.44, B = 4.60
Application of Equation 8.4 • A simplified equation for use on partially drowned spillway chutes • Steep gradient, non-uniform flow conditions, $S_e \neq S_o$, but $S_o < 50\%$	**Equation 8.4** $$d_{50} = \frac{127.SF.K_1.K_2.S_o^{0.5}.V^{2.5}.y^{0.75}}{V_o^{2.0}(s_r - 1)}$$

Note: The above equations, with the exception of Equation 8.2, are based on the Manning's 'n' roughness for a rock-lined surface determined from Equation 5.

Minimum dimensions, freeboard and vegetation

Recommended absolute minimum spillway depth is 300 mm.

A freeboard of 150 mm should exist. A greater freeboard may be required if it is necessary for the spillway to fully contain any splash.

The descending spillway chute must be straight from its crest to outlet (i.e. no bends or curves).

Vegetating rock-lined spillways can significantly increase the spillway's long-term stability. Flexible, mat-forming grasses (non-woody plants) must be used. Stiff grasses, such as *Lomandra* or *Vetiveria zizanioides,* are **not** recommended for dam spillways.

where:

d_X = nominal rock size (diameter) of which X% (by weight) of the rocks are smaller [m]

A & B = equation constants

K = equation constant based on flow conditions

= 1.1 for low-turbulent deep water flow, 1.0 for low-turbulent shallow water flow, and 0.86 for highly turbulent and/or supercritical flow

K_1 = correction factor for rock shape

= 1.0 for angular (fractured) rock, 1.36 for rounded rock (i.e. smooth, spherical rock)

K_2 = correction factor for rock grading

= 0.95 for poorly graded rock ($C_u = d_{60}/d_{10} < 1.5$), 1.05 for well graded rock ($C_u > 2.5$), otherwise $K_2 = 1.0$ ($1.5 < C_u < 2.5$)

ln = log to base 'e'

q = flow per unit width down the embankment [$m^3/s/m$]

s_r = specific gravity of rock (e.g. sandstone 2.1–2.4; granite 2.5–3.1, typically 2.6; limestone 2.6; basalt 2.7–3.2)

S_e = slope of energy line [m/m]

S_o = bed slope = tan(θ) [m/m]

SF = safety factor (refer to Table 8.1)

V = actual depth-average flow velocity at location of rock [m/s]

V_o = depth-average flow velocity based on **uniform** flow down a slope, S_o [m/s]

y = depth of flow at a given location [m]

θ = slope of channel bed [degrees]

Table 8.1 – Recommended safety factor for use in determining rock size

Safety factor (SF)	Recommended usage	Example site conditions
1.2	• Low risk structures. • Failure of structure is most unlikely to cause loss of life or irreversible property damage. • Permanent rock chutes with all voids filled with soil and pocket planted.	• Dam spillways where failure of the structure is likely to result in easily repairable soil erosion. • Dam spillways that are likely to experience significant sedimentation and vegetation growth before experiencing high flows. • Temporary (< 2 yrs) spillways with a design storm of 1 in 10 years or greater.
1.5	• High risk structures. • Failure of structure may cause loss of life or irreversible property damage. • Temporary structures that have a high risk of experiencing the design discharge while the voids remain open (i.e. prior to sediment settling within and stabilising the voids between individual rocks).	• Dam spillways where failure of the structure may cause severe gully erosion. • Dam spillways located up-slope of a residential area or busy roadway where an embankment failure could cause property flooding or loss of life. • Spillways designed for a storm frequency less than 1 in 10 years.

Common design and construction problems

Poorly defined spillway crest

Inadequate spillway crest profile

- A poorly defined spillway crest profile can result in flows bypassing the spillway.
- In such cases (left) damage to the earth embankment is likely to occur.

Insufficient scour protection at outlet

Insufficient scour control at base of spillway

- Rock protection should extend beyond the embankment toe to form a suitable energy dissipater (outlet structure).

Rocks sit above the embankment height

Spillway crest not recessed below the embankment crest

- It is essential to ensure that the crest of the rock-lined spillway is set well below the crest of the adjacent earth embankment.
- In such cases (left) damage to the earth embankment is likely to occur.

Inadequate rock size

Inadequate rock size

- Selection of appropriate rock (size, density and shape) is critical.
- If sufficient quantities of the specified rock size cannot be obtained, then an alternative spillway design will be required.

Common failure conditions in dispersive soils

Failed dam spillway

Curved farm dam bywash

- Dam spillways should be straight, not curved.
- If a spillway is formed on dispersive soils, then the spillway chute should be over-excavated, then topped with a minimum 200 to 300 mm layer of compacted non-dispersive soil, then covered with filter cloth prior to placement of the armour rock.
- The thickness of the non-dispersive soil layer depends on the likelihood of future erosion or disturbance by cattle.

Incised spillway in dispersive soil

Grass-lined dam spillway on dispersive soil

- Erosion in dispersive soils typically results in the formation of deep, steep-sided gullies that are usually deeper than they are wide.

Head-cut erosion on a dam spillway

Grass-lined dam spillway on dispersive soil

- An unstable bywash outlet can cause the formation of a gully-head (i.e. head-cut erosion) that then migrates along the bywash back towards the dam.

Severe gully erosion along dam bywash

Wide, grass-lined dam bywash located on dispersive soil

- In extreme cases, the gully erosion resulting from an unstable dam bywash can cause the total failure of the dam.

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