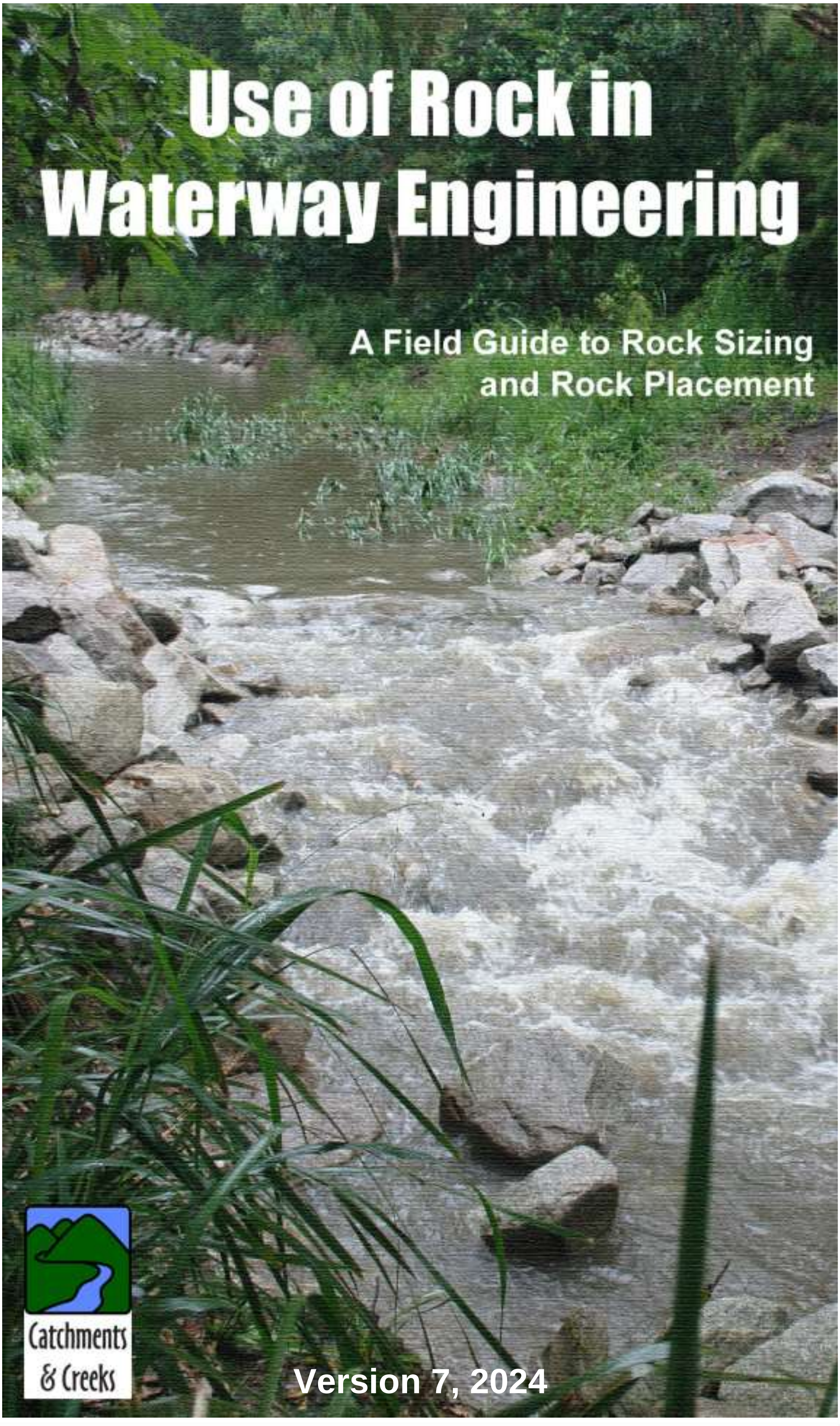

Use of Rock in Waterway Engineering

A Field Guide to Rock Sizing and Rock Placement

Catchments & Creeks

Version 7, 2024

Use of Rock in Waterway Engineering

Version 7, February 2024

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Published by: Catchments and Creeks

Diagrams by: Grant Witheridge, Catchments and Creeks

Photos by: Catchments and Creeks, and Ross Coventry

This document should be referenced as:

Witheridge 2024, *Use of Rock in Waterway Engineering*. Catchments and Creeks, Bargara, Queensland

Key words: rock stabilisation, rock placement, rock pads, rock beaching, bank stabilisation, rock-lined channels.

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 waterway 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 waterway engineering produces more 'natural' outcomes; however, these outcomes are also likely to be more susceptible to hydraulic failure.

As such, no warranty or guarantee, express, implied, or statutory is made as to the accuracy, reliability, suitability, or results of the methods or recommendations.

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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.

Contents

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 waterways and constructed channels
- assist engineers in understanding how the sizing of rock 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 and 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, however, this does not mean that the placement of rock within waterways will always be deemed ‘natural’. At best, engineers should aim to ensure the use of rock within waterways is done in a manner that demonstrates natural aesthetics, but with the degree of structural stability that is considered necessary.

When used in an appropriate manner, rock can greatly enhance the natural appearance of many engineered structures; however, rock stabilisation may not have the same degree of structural stability as some other forms of hard engineering. Rock-lined waterway structures can be more susceptible to structural failure, especially during the first few years following their installation.

In general, rock-lined structures age well. The filling of all voids with soil and the establishment of plants over the rocks generally helps to increase the structural stability of these systems.

Care and attention in rock placement can result in very good outcomes, while poor attention to what may appear to be just a minor design detail can ultimately lead to structural failure.

Successful outcomes largely depend on:

- the experience of those designers applying the various rock-sizing equations
- the experience of those persons placing (constructing) the rock-lined structure
- the weather and flow conditions experienced during the vegetation establishment phase.

Possibly more than most other areas of waterway engineering, the appropriate use of rock depends on the local site conditions.

Introduction


Background to Rock Sizing and Rock Roughness Equations

Background to Rock Sizing Equations

Background to Rock Sizing and Rock Roughness Equations.

Catchments & Creeks, 2023, Bargara Queensland.

Version 1, 2023


Use of Rock in Stormwater Engineering

Use of rock in stormwater engineering

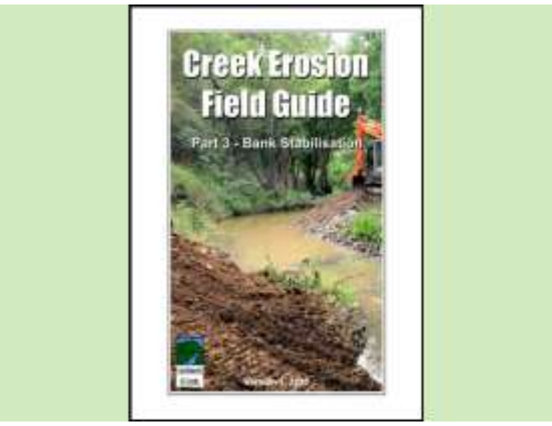
Use of Rock in Stormwater Engineering

Catchments & Creeks Pty Ltd, 2014, Brisbane Queensland.

68 pages (colour) PDF-file

Version 3, 2017

Version 4, 2020


Creek Erosion Field Guide

Part 3 - Bank Stabilisation

Creek Erosion, parts 1, 2, 3 & 4

Creek Erosion Field Guide

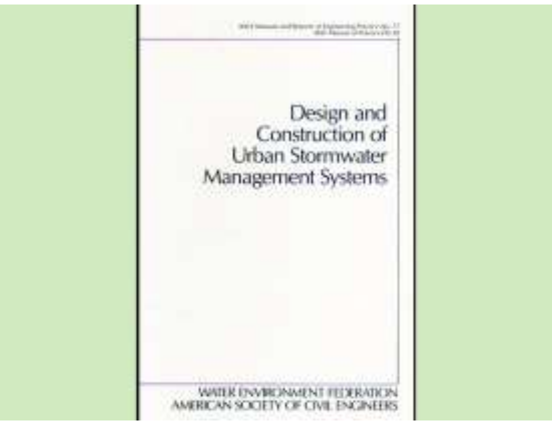
Catchments & Creeks, 2020, Bargara Queensland.

Part 1 – Types of waterways and causes of waterway erosion

Part 2 – Bed stabilisation

Part 3 – Bank stabilisation

Part 4 – Bank treatment options


Design and Construction of Urban Stormwater Management Systems

WATER ENVIRONMENT FEDERATION
AMERICAN SOCIETY OF CIVIL ENGINEERS

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

Use of rock in waterway channels

Rock-lined bank stabilisation (Qld)

Channel bank stabilisation

- Rock stabilisation has been one of the most widely adopted techniques for the control of waterway bank erosion.
- Historically this technique consisted of loosely placed rock with open voids.
- However, modern practice has seen a greater use of fully vegetated installations where all voids are filled with soil and pocket planted.

Culvert outlet scour control (Qld)

Culvert outlets and bed roughness

- Similar hydraulic forces exist at the outlets of multi-cell culverts and multi-pipe drainage systems, consequently the rock sizing charts used in culvert design are similar to those for multi-pipe outlets.
- To enhance fish passage conditions through culverts it is becoming common for rock to be placed, either loose or grouted, within the ‘wet’ cells to mimic natural bed conditions, and this rock must join with the apron rock.

Waterway chute (NSW)

Waterway and gully chutes

- A ‘waterway chute’ is a stabilised section of a waterway bed used to control bed erosion while maintaining desirable fish passage conditions in a manner similar to a natural riffle.
- A ‘gully chute’ is a steep drainage chute, typically of uniform cross-section, used to stabilise head-cut erosion and/or flow into, or out of, a drainage gully.
- In effect, gully chutes are just larger versions of a drainage batter chute.

Waterway riffle (Qld)

Waterway riffles

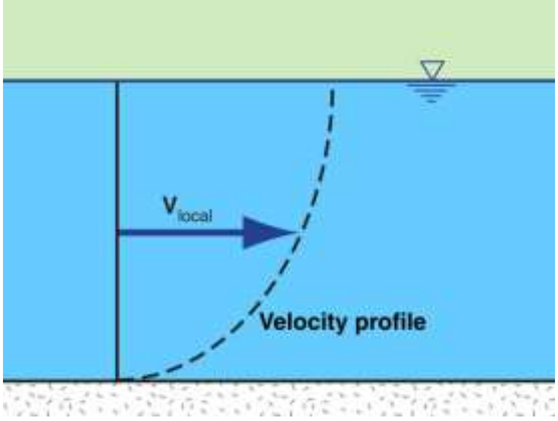
- A riffle is an isolated section of channel bed where the steepness of the bed allows for a local acceleration of flows and the possible exposure of the bed rocks during periods of low flow.
- In pure hydraulic terms, riffles are the same as rock chutes and rock ramps; however, their small size and low gradient means the design procedures used for sizing the rock are different from those used in the design of some drainage chutes.

Defining flow velocity

High-velocity stream flow (Qld)

Flow velocity

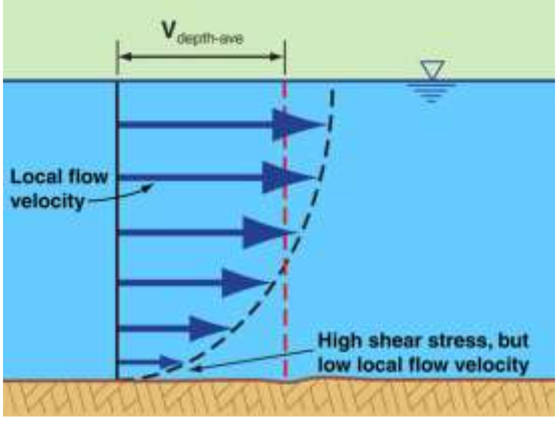
- There are several different ways to measure flow velocity, including:
  - local flow velocity (measured at a point)
  - depth-average velocity
  - average velocity (full cross-section)
  - critical velocity (special flow condition)
- Flow velocities can vary significantly across the depth and width of a stream, consequently the ‘average flow velocity’ is often much less than the maximum flow velocity within a waterway.



Local flow velocity

Local flow velocity

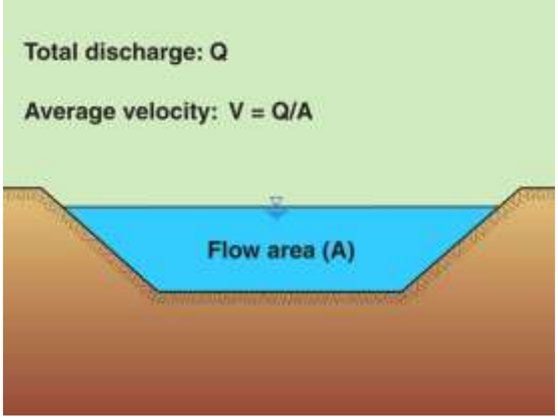
- The local flow velocity is the flow velocity at a specific point within a cross-section.
- The local flow velocity is the velocity of most importance to fish because it is this velocity that they confront when swimming upstream.
- In creek engineering, the local flow velocity is rarely used because it is so hard to calculate mathematically, even though it is relatively easy to measure in a creek.



Depth-average flow velocity

Depth-average flow velocity

- The depth-average velocity is the average of the local flow velocities measured down through a vertical plane.
- The depth-average velocity typically varies across the width of a channel.
- This flow velocity is used by creek engineers in the design of some scour protection measures, such as rock.
- It is noted that some engineers refer to the depth-average velocity as the ‘local velocity’ (which can cause confusion).



Cross-sectional flow parameters

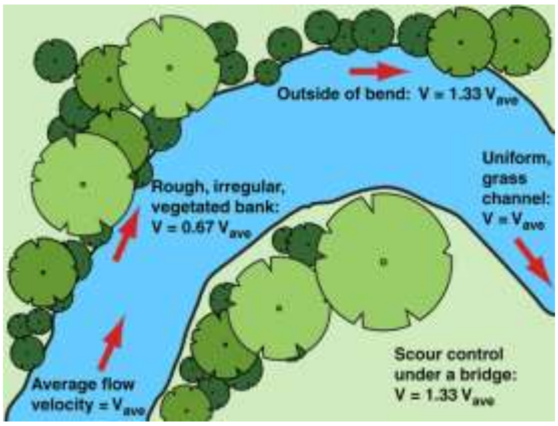
Average flow velocity

- The average flow velocity is defined as the total discharge (Q) divided by the total flow area (A).

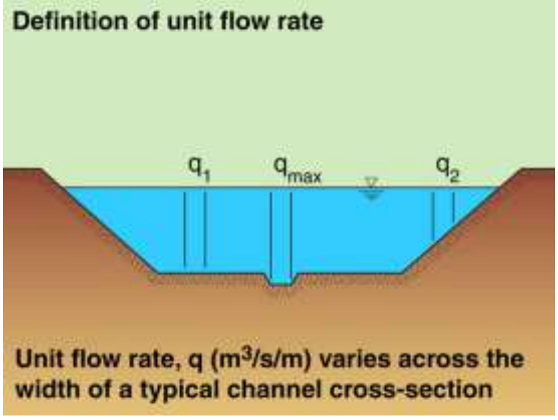
$$V = Q/A \quad [\text{m/s}]$$

- In complex cross-sections there may be areas of zero flow due to flow isolation; in such cases these areas may be excluded from the total flow area.
- The symbol for velocity is normally a lower case ‘v’, but an upper case ‘V’ is often used in publications to highlight its importance.

Defining flow conditions



Velocity multipliers for design purposes



Unit flow rate within an irregular channel

Stacked rocks on a creek bank (Qld)

Whitewater flow conditions (Qld)

Average flow velocity

- The average flow velocity of a stream is easy to calculate in a computer model, but hard to measure within a real creek.
- Because of the ease of calculating the average flow velocity in a computer model, creek engineers often use this term as the main variable in the design of scour control measures.
- To account for the variations in flow velocity across a creek, the average velocity is often multiplied by a nominated design factor.

Use of unit flow rate (q) instead of velocity 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 $m^3/s/m$

$$q = (1/n) \,.\, Y^{5/3} \,.\, S^{½}$$

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.

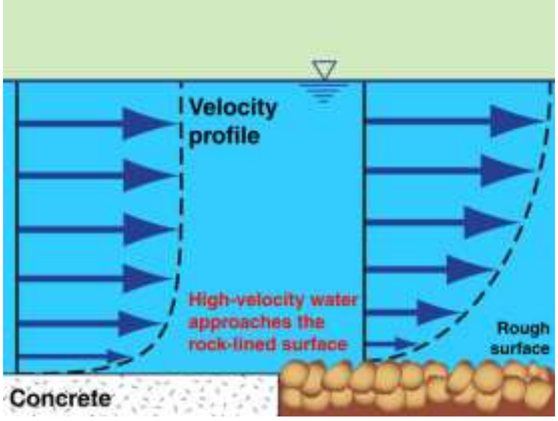
Critical design issues


Photo supplied by Catchments & Creeks Pty Ltd

Rock displaced at end of concrete channel

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.



Changing flow conditions

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.

Photo supplied by Catchments & Creeks Pty Ltd

Rock downstream of a concrete drain

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.

Photo supplied by Catchments & Creeks Pty Ltd

Rock downstream of a 'smooth' bank

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 (Qld)

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
  - some waterway and gully chutes.
- For high risk structures, such as some bed stabilisation structures, a safety factor of 1.5 is recommended.

Fractured rock (Qld)

Effects of rock shape (K_1)

- Angular rock is generally more stable than natural rounded rock.
- Most rock sizing equations, including those presented within this document, are primarily 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, introduced rock should not dominate the landscape, rather the rock should be incorporated (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.
- Rocks dumped from a height, such as being dumped from a truck, will fall to a lower bank slope (angle of repose) than can be achieved through the selective placement of the rocks.

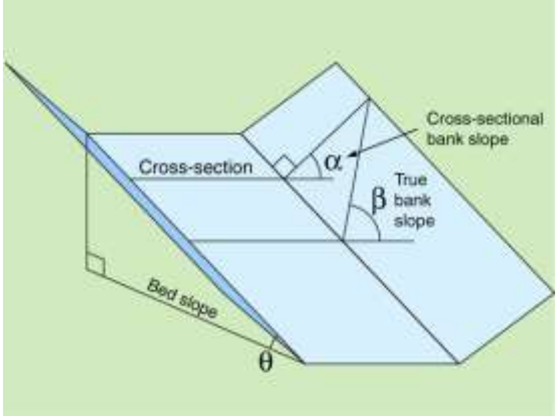
Critical design issues


Photo supplied by Catchments & Creeks Pty Ltd

Rocks placed on a steep surface (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 the rock-lined surface.



Steep rock chute with steep banks

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.

$$\tan^2(\beta) = \tan^2(\alpha) + \tan^2(\theta) \tag{1}$$

β = bank slope relative to the horizontal

α = bank slope relative to channel X-section

θ = slope of channel bed [degrees]


Photo supplied by Catchments & Creeks Pty Ltd

Well vegetated rock chute (Qld)

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.

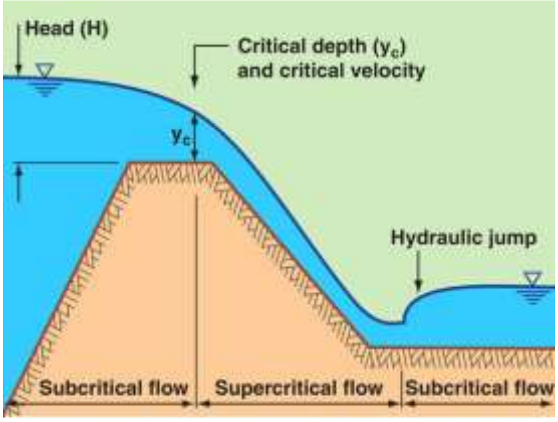

Photo supplied by Catchments & Creeks Pty Ltd

Vegetated rock stabilisation (Qld)

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 waterway and gully chutes
  - most fish-friendly, low-gradient chutes
  - most grade control structures.

Looking upstream to crest of rock chute

Dam spillway with flat, straight weir crest

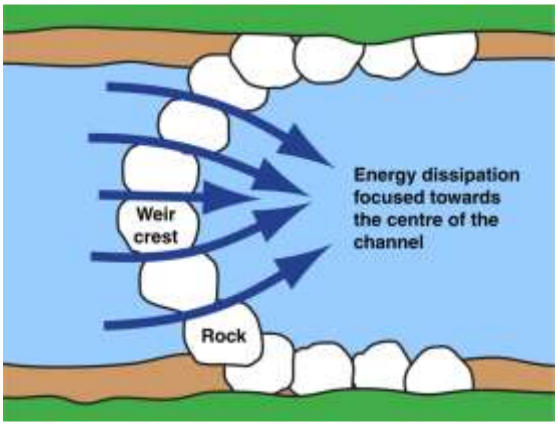
Alignment of the weir crest

Curved rock weir and plunge pool (Qld)

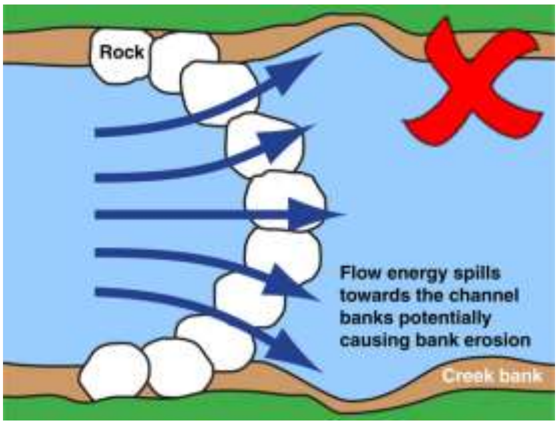
Use of 'curved' weir crests

- The weir crest should be curved in both the horizontal and vertical planes if the chute length is short and energy dissipation is primarily achieved through the water spilling into a central energy dissipation pool.
- Curved weir crests are commonly used on:
  - small pool/riffle systems
  - rock weirs
  - some grade control (drop) structures.

Curved weir crest on a drop structure



Flow conditions for curved weir crest



Problems caused by reverse crest shape

Undesirable weir flow conditions

- If the weir crest is curved and 'pointing downstream', then the curved weir crest will cause low flows to spill towards the creek banks, rather than directing the flow towards the centre of the channel.
- In extreme cases this can cause bank erosion, which can erode around the ends of the weir causing a weir failure.
- In the example below (both left and right) the uneven rock weir crest is the primary cause of the downstream bank erosion.

Flows spill unevenly over the rock weir

Weir crest is 'perpendicular' to the creek channel, but the crest dips adjacent the creek bank causing the stream flow to change its flow direction and angle towards the creek bank

Bank erosion produced from weir (left)

Use of filter layers and filter cloth


Photo supplied by Bruce Carey

Rocks placed over a geotextile filter (Qld)

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.


Photo supplied by Catchments & Creeks Pty Ltd

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.
- Fully vegetated rock-lined waterway banks usually do not require filter cloth to be placed under the rock.


Photo supplied by Catchments & Creeks Pty Ltd

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.


Photo supplied by Catchments & Creeks Pty Ltd

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


Photo supplied by Catchments & Creeks Pty Ltd

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.


Photo supplied by Catchments & Creeks Pty Ltd

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).


Photo supplied by Catchments & Creeks Pty Ltd

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.


Photo supplied by Catchments & Creeks Pty Ltd

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, and then 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

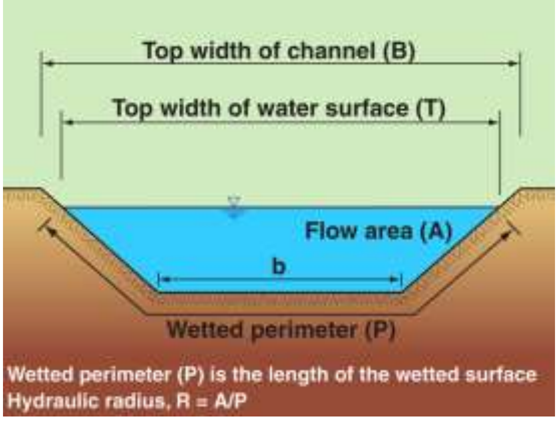
- Erosion in dispersive soils typically results in the formation of deep, steep-sided gullies that are usually deeper than they are wide.
- Dispersive soils are often the cause of the total failure of farm dam spillways.
- If the soil directly below the grass or rock is dispersive, then tunnel and rill 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 rock, the exposed soil **must** first be covered with a layer of non-dispersive soil.
- Grouted rock will always crack, and therefore can never provide a perfect seal over dispersive soils, which means covering these soils with a stable soil filter is always necessary.

Manning’s roughness of rock-lined surfaces



Channel geometry and flow conditions


Photo supplied by Catchments & Creeks Pty Ltd

Gravel-based alluvial waterway (Tas)


Photo supplied by Catchments & Creeks Pty Ltd

Deep water flow conditions (Qld)


Photo supplied by Catchments & Creeks Pty Ltd

Shallow water flow conditions (Qld)

Manning’s equation

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

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

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 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, usually 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°	42°
Slightly angular rock	40°	41°
Moderately rounded rock	39°	40°

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 sizes for waterway chutes. 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. Witter & Abt (1990) reported 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 for fish friendly structures (guide only)

Rock size ratio	Assumed distribution value
d_{100}/d_{50}	2.0
d_{90}/d_{50}	1.8
d_{75}/d_{50}	1.5
d_{65}/d_{50}	1.3
d_{40}/d_{50}	0.65
d_{33}/d_{50}	0.50
d_{10}/d_{50}	0.20

Thickness and height of rock layer

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.

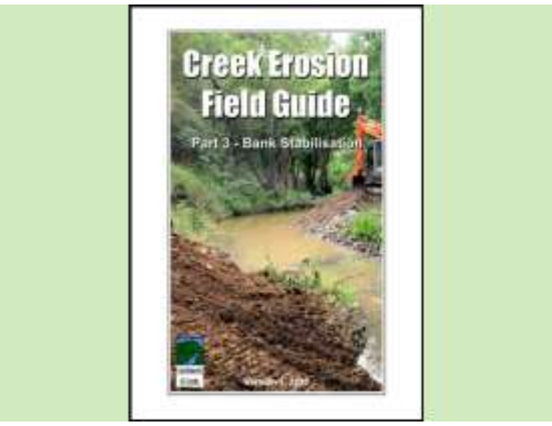
In order to allow at least two layers of rock, the minimum thickness of rock protection (T) can be approximated by the values presented in Table 6.

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.

Rock placed in bags and baskets



Creek Erosion Field Guide

Part 3 - Bank Stabilisation

Creek Erosion, Part 3

Introduction

- Rocks have been placed in wire baskets for many years.
- Rocks can also be placed in flexible mesh bags.
- The advantages and disadvantages of these scour protection systems is partially discussed in the field guides:
  - *Creek Erosion Field Guide Part 2 – Bed Stabilisation* (Section 13.2)
  - *Creek Erosion Field Guide Part 3 – Bank Stabilisation* (Section 15.2).

Photo supplied by Catchments & Creeks Pty Ltd

Lifting of rock mattress (Qld)

Allowable flow velocity

- When rocks are placed in a bag or cage, it is not appropriate to base the allowable flow velocity on the collective mass of the rocks placed in the bag or cage.
- Two issues can arise:
  - the cage can be broken by flood debris, which can allow the rocks to be washed away one at a time
  - part of the cage can be lifted into the flow stream, which increases the drag force on the cage, which can cause the cage to lift or role away from the bank.

Platypus

Environmental impacts

- Potential environmental impacts include:
  - preventing aquatic mammals and reptiles from burrowing dens into the banks of the waterway (some animals enter the bank below water level)
  - if the bag is made from elastic material, then animals have been caught trying to squeeze through the mesh
  - the cages can form a hydraulically-smooth bank that prevents aquatic life from sheltering from high-velocity flows.

Photo supplied by Catchments & Creeks Pty Ltd

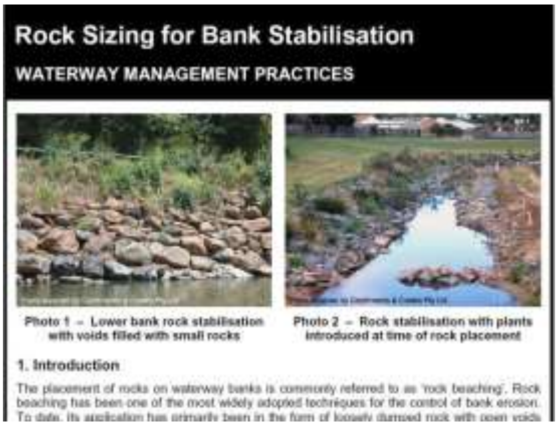
Gabion-lined waterway bank (NSW)

Aesthetics

- Rock-filled baskets and bags can be difficult to cover with suitable vegetation.
- These scour protection measures often assist weed growth.
- Exposed baskets and cages can give the waterway the appearance of a constructed channel instead of mimicking a desired natural appearance.
- The high cost of these treatment measures can limit the funds available for site revegetation.

1. Bank Stabilisation

Introduction


Rock Sizing for Bank Stabilisation

WATERWAY MANAGEMENT PRACTICES

Photo 1 – Lower bank rock stabilisation with voids filled with small rocks

Photo 2 – Rock stabilisation with plants introduced at time of rock placement

1. Introduction

The placement of rocks on waterway banks is commonly referred to as 'rock beaching'. Rock beaching has been one of the most widely adopted techniques for the control of bank erosion. To date, its application has primarily been in the form of loosely dumped rock with open voids

Waterway bank stabilisation fact sheet

Introduction

- Rock stabilisation has been one of the most widely adopted techniques for the control of waterway bank erosion.
- In the past its application has primarily been in the form of loosely dumped rock with open voids; however, the practice of filling the voids with soil and pocket planting is becoming more common.
- Various fact sheets on the placement of rock in waterways are available within the *Catchments and Creeks* website.


Photo supplied by Catchments & Creeks Pty Ltd

Bankfull flow conditions (Qld)

Factors affecting rock size

- The critical factors affecting rock size and rock selection include:
  - flow velocity
  - degree of flow turbulence
  - bank slope
  - rock shape (round or angular)
  - rock density
  - void condition (open or filled)
  - degree and type of vegetation cover.


Photo supplied by Catchments & Creeks Pty Ltd

Bank erosion d/s of rock-stabilised bank

Short-term stability of rock-lined banks

- Compared to most vegetated solutions, rock stabilisation provides the benefit of instantaneous scour protection.
- If however, the rock-lined channel has been designed to be fully vegetated, then in the short-term the non-vegetated bank will have a low hydraulic roughness, which will result in higher flow velocities.
- Because of the hydraulically-smooth nature of non-vegetated rock-lined surfaces, bank erosion often occurs downstream of newly placed rock.


Photo supplied by Catchments & Creeks Pty Ltd

Vegetated rock work (Qld)

Long-term stability of rock-lined banks

- Rock-protected waterway banks generally exhibit good long-term stability, especially if suitable deep-rooted vegetation is established over the rocks.
- In dynamic waterways (i.e. waterways subject to active channel expansion or migration) rock-lined banks can fail over the long-term.
- Large toe rock may be required if long-term bed lowering (bed erosion) is expected, especially on the outside of channel bends.

Attributes of rock stabilised waterway banks


Photo supplied by Catchments & Creeks Pty Ltd

Poor aesthetics without vegetation cover

Aesthetics

- Exposed rock can be unsightly.
- Weed invasion of rock-protected surfaces can also appear unsightly.
- Better long-term aesthetics can be achieved if the rock-lined surface is fully vegetated with native plants.
- The use of broken concrete and building rubble for bank protection can be extremely unsightly, and is generally not recommended, especially in publicly accessible areas.


Photo supplied by Catchments & Creeks Pty Ltd

Open voids below permanent waterline

In-stream ecology

- The battering of eroded banks for the purpose of rock placement may result in the formation of an open-canopy, which may adversely affect water temperatures.
- The establishment of leafy vegetation along the water's edge can reduce water temperatures and benefit aquatic habitat.
- Cavities around rocks placed **<u>below</u>** the permanent water level can provide desirable aquatic habitat and shelter, especially if rocks smaller than 200 mm are removed from the rock mix.


Photo supplied by Catchments & Creeks Pty Ltd

Bank stabilisation without revegetation

Riparian habitats

- Non-vegetated rock protection creates poor riparian values.
- Rock-lined waterway banks can cause significant problems to burrowing fauna, such as platypus—expert advice should be sought on such matters.
- Above the permanent water line, voids should be filled with soil and planted, but some exposed rock surfaces can be beneficial.
- Open voids **<u>above</u>** the water line can encourage vermin.


Photo supplied by Catchments & Creeks Pty Ltd

Lizard basking on an exposed rock

Terrestrial habitats

- Non-vegetated rock exposes migrating terrestrial wildlife to predators.
- Rock-lined surfaces can incorporate the occasional feature rock, or rock outcrop, that provides habitat diversity and habitat attributes such as:
  - areas for basking/roosting
  - protection from predators
  - protection from floods and bushfire.
- The occasional exposed rock surface can also benefit overall habitat diversity.

Attributes of rock stabilised waterway banks

Vegetated rock stabilisation works

Establishment of vegetation over rocks

- The establishment of vegetation over the rocks provides many benefits including:
  - increased stabilisation of the rocks
  - improved terrestrial habitat
  - improved aquatic habitat
  - improved fish passage conditions during periods of high flow
  - improved aesthetics.
- Vegetated rock-lined banks can be viewed as a form of 'soft engineering'.

Rock-lined channel in a golf course

Impact on waterway hydraulics

- Non-vegetated rock stabilisation can significantly reduce the hydraulic resistance of the watercourse, potentially resulting in increased channel velocities and bed scour, but with the possible benefit of reduced flood levels.
- The hydraulic roughness of rock-lined waterways very much depends on the degree of vegetation cover.
- In the long-term, some form of vegetation cover will usually occur unless controlled by regular maintenance.

Waterway maintenance (Qld)

Waterway maintenance

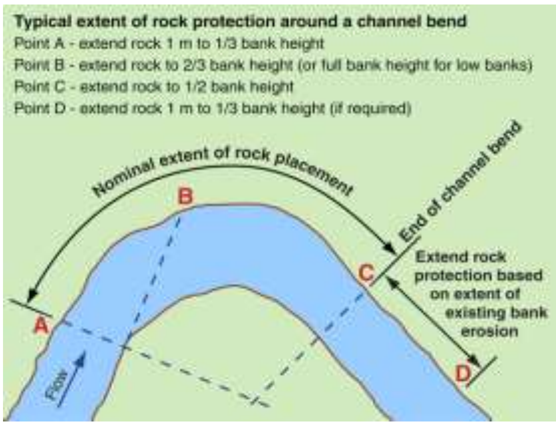
- Maintenance costs are usually related to the desired long-term aesthetics of the waterway.
- The control of weed growth can be an expensive, labour-intensive exercise.
- Long-term maintenance is best controlled through the development of a canopy cover over the waterway to reduce weeds.
- Appropriate plant selection is the key to reducing maintenance costs, which requires the guidance of experts.

Rock placement (Qld)

Construction issues

- Most structural bank failures result from inappropriate placement of the rock, normally as a result of inadequate design detailing, inappropriate rock selection, or poor construction supervision.
- Rock-lined waterway structures are usually most susceptible to failure during the first two years of their operation—that is before sediment and vegetation have begun to stabilise the rocks.

Critical design issues



Placement of rock on channel bends

Design velocity (V_{design}) adjacent banks

- In grass-lined channels with a uniform cross-section, adopt a design velocity equal to the calculated average flow velocity ($V_{design} = V_{average}$).
- In irregular, natural, woody/scrubby waterways, adopt a design velocity of two-thirds (67%) the average flow velocity.
- In all cases, on the outside of significant channel bends, adopt a design velocity adjacent to the outer bank of 133% of the average flow velocity ($1.33\ V_{average}$).

Rock stabilisation on channel bend (Qld)

Elevation of rock placement on banks

- Rock placement often does not need to extend to the top of the bank—refer to diagram above.
- A simple guide to rock placement:
  - straight reaches: 1/3 to 1/2 bank height
  - channel bends: 2/3 lowest bank height on the outside of bends; and 1/3 the lowest bank height on inside of bends.
- In most cases, the upper bank area only needs to be stabilised with suitable vegetation.

Partial vegetated bank stabilisation (NSW)

Rock type and grading

- Crushed rock is generally more stable than natural rounded stone.
- A 36% increase (i.e. $K_1 = 1.36$) in rock size is recommended for rounded rock.
- All rock should be durable and resistant to weathering.
- Neither the breadth nor the thickness of a given rock should be less than one-third its length.
- In most situations the nominal rock size is usually between 200 mm to 600 mm.

Vegetated bank with toe rock (Qld)

Low-level toe rock supporting a vegetated bank

- If flow velocities are low enough to allow the use of vegetated banks, then the rock stabilisation of the toe usually only needs to extend about 0.5 to 1.0 m above the bed within ephemeral streams.
- The toe rock should integrate well into the bank soil and toe vegetation.
- The rock should not sit on the bank, but within the bank.

Critical design issues

Larger rocks forming toe protection (NSW)

Thickness of rock protection

- The thickness of the armour layer should be sufficient to allow at least two overlapping layers of the nominal rock size (refer to Table 6).
- The thickness of rock protection must also be sufficient to accommodate the largest rock size.
- It is noted that additional thickness will **not** compensate for the use of undersized rock.

Rock placement over filter cloth (Qld)

Backing material or filter layer

- Non-vegetated armour rock must be placed over a layer of suitably graded filter rock, or geotextile filter cloth.
- The geotextile filter cloth must have sufficient strength, and must be suitably overlapped, to withstand the placement of the rock (which normally results in movement of the fabric).
- Armour rock that is intended to be vegetated by appropriately filling all voids with soil and pocket planting will generally not require an underlying filter layer.

Stacked boulder wall (Qld)

Maximum bank slope

- Maximum batter slope is typically 1:2 (V:H) for non-vegetated, and 1:2.5 (V:H) if vegetated—the flatter slopes being desirable (but not essential) to provide safe conditions for planting operations.
- Steeper banks can be achieved with the use of stacked boulders, but the rocks must sit on a stable bed.
- Steep, high banks can present a safety hazard to revegetation teams—seek advice from revegetation contractors.

Vegetated rock stabilisation of bank (Qld)

Establishment of vegetation

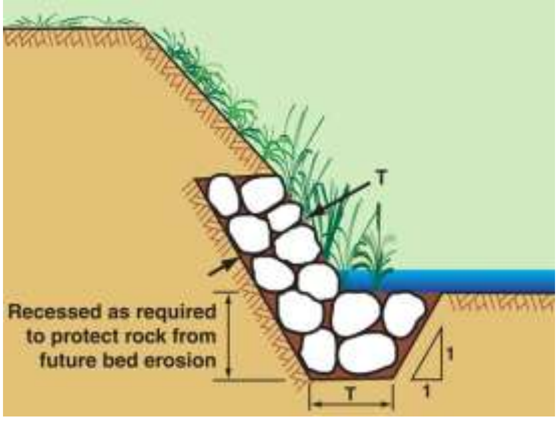
- The establishment of vegetation over rock-lined surfaces is generally encouraged.
- Common revegetation problems that may need to be addressed during the design phase include:
  - poor aesthetics due to poor plant selection or weed invasion
  - steep banks that can be difficult to maintain and weed
  - reduced hydraulic capacity of the waterway if woody species establish within critical hydraulic areas.

Toe stabilisation of waterway banks

Erosion along toe of bank

Toe erosion on channel banks

- Toe erosion is common on constructed channel banks if high flows occur during the plant establishment phase.
- Rock protection along the toe of newly formed or disturbed channel banks is usually necessary to provide short-term bank stabilisation during plant establishment.
- Without such rock protection, elevated stream flows can cause bank erosion before the plants are established.



Typical rock placement at toe of bank

Recessing rock below the toe of bank

- Extra rock may need to be placed **<u>below</u>** bed level to:
  - prevent slippage of the upper rock
  - increase toe stability during floods when short-term bed movement or bed lowering occurs during the flood peak
  - allow the bank to adjust to long-term variations in bed level.
- If the above conditions do not exist, then the rock can rest of the channel bed.

Large toe rock (NSW)

Toe stabilisation using large rock

- As an alternative to recessed mass rock (above), large toe rock can be placed along the toe of modified banks.
- Individual toe rock should be recessed 2/3 of its diameter into the earth.
- Toe rock provides the following benefits:
  - protects the bank from undercutting in the event of minor bed erosion
  - provides a visible control 'edge' during maintenance weeding or de-silting of the channel bed.

Coir 'geo-log' temporary toe protection

Alternative toe stabilisation measures

- Coir or jute 'geo logs' can be used as an alternative to rock stabilisation of the toe.
- These geo logs typically provide only temporary (less than 2-years) protection of the toe.
- These temporary protection measures are only successful if suitable vegetation is incorporated into, or around, the logs.
- It is important to ensure that bank erosion does not occur behind the logs during overtopping stream flows.

Vegetated bank stabilisation works

Planted rock-stabilised creek bank (Qld)

Introduction

- Wherever practical, rock protected areas should be lightly covered with soil (to fill all voids) and pocket planted to encourage the preferred plant growth across the bank and along the water's edge.
- In areas where revegetation is not desired (i.e. critical flood control areas), the establishment or retention of an effective canopy cover (i.e. shade trees) is generally the preferred means of controlling weed growth.

Voids filled with soil ready for planting

Infill soil

- Experience has shown that minimal soil is lost from the rock voids during flood events.
- The image presented left shows a recently planted bank that experienced a bankfull flow just weeks after planting—all plants were lost from the bank, but most of the soil remained.
- **Important:** In order to allow proper plant growth, the infill soil needs to be placed progressively as the layers of rock are added to the bank.

Planting along the water's edge (Qld)

Planting along the water's edge

- Wherever practical, vegetation should extend to the water's edge to increase the value and linkage of aquatic and terrestrial habitats.
- Plants that branch over the water's edge can provide essential shading of the water to provide pockets of cool water for aquatic life.
- Edge plants also assist aquatic life to shelter from predators.

Planted rock covered with jute mesh

Use of erosion control mats

- During plant establishment it may be necessary to mulch around newly placed plants to control soil moisture loss.
- Covering such areas with a jute or coir mesh can help to reduce the loss of mulch by wind and minor flows.
- However, it is noted that the complete loss of the matting during high flows can cause damage to, or the total loss of, any recently established plants.

Sizing of rock placement within low-gradient waterways

Equation 1.1 can be used to size rock placed on the bed of waterway channels. The same equation can be used for rock placed on waterway banks with 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.

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

Application of Equation 1.1	**Equation 1.1**
• Simplified velocity-based equation suitable for uniform and non-uniform flow conditions [1] • Low channel gradients, $S_o < 5\%$	$d_{50} = \frac{K_1 . V^2}{2.g.K^2 (s_r - 1)}$ (1.1) 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 1.1)

Note: Equation 1.1 represents a modification of the equation originally presented by Isbash (1936).

The 'K' variable takes into account the degree of flow turbulence. Table 1.1 provides the recommended K-values for various uniform channel gradients (i.e. straight, uniform cross-sectional channels where a constant flow velocity is achieved). In non-uniform flow a K-value of 1.1 should be used for low-turbulent deep water flow, 1.0 for low-turbulent shallow water flow, and 0.86 for highly turbulent and/or supercritical flow.

Table 1.1 – Suggested values of 'K' for 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 results 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 1.1)

K_1 = correction factor for rock shape

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

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

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 = depth-averaged flow velocity at location of rock [m/s]

Equation 1.1 reduces to the commonly used design equation (Equation 1.2) for angular rock based on a rock specific gravity, $s_r = 2.6$

$$d_{50} = 0.04\, V^2 \qquad (1.2)$$

Rock placement on banks

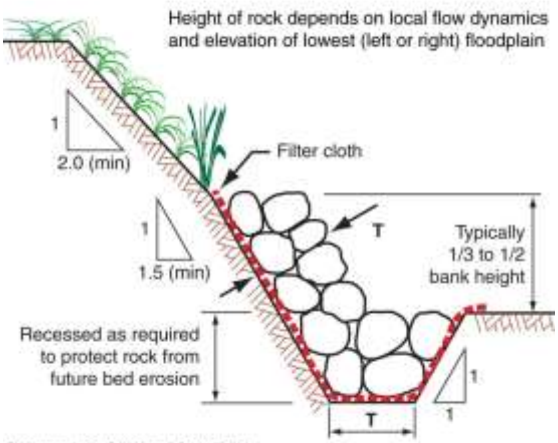


Diagram supplied by Catchments & Creeks Pty Ltd

Rock placement with open voids

Advantages:

- Reduced quantity of rock.

Disadvantages:

- Problems can occur with lateral inflows (i.e. local stormwater runoff) entering into, or passing under, the rock.
- Can result in reduced aquatic habitat values given the absence of vegetation.

Use:

- Ideally, this method of rock placement should have limited usage in new works.
- Typically used on the inside face of fully shaded, high velocity channel bends.

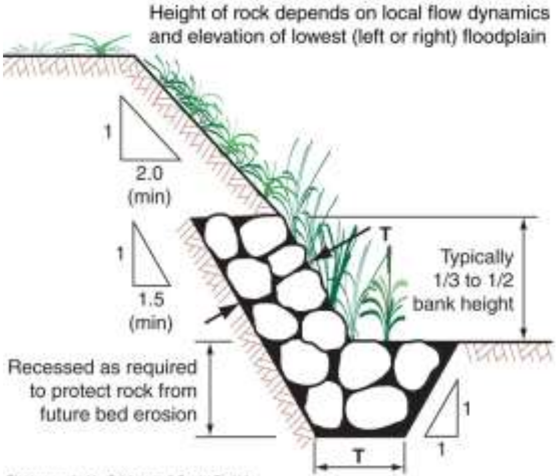


Diagram supplied by Catchments & Creeks Pty Ltd

Rock placement with soil-filled voids

Advantages:

- Improved aquatic habitat values.
- Retention of riparian values.

Disadvantages:

- Care must be taken to ensure all voids are filled with soil to prevent the seepage of the upper bank soil into the lower rock layer.

Use:

- Used for the toe protection of channel banks in regions of high flow velocity, or areas where the channel bed may experience scour.
- This is generally the preferred method of rock placement within waterways.

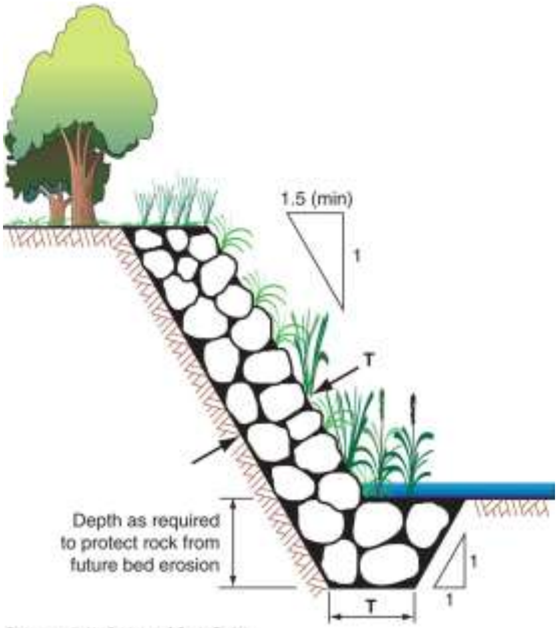


Diagram supplied by Catchments & Creeks Pty Ltd

Full-height rock placement

Advantages:

- Very high scour protection once vegetation is established.
- Retention of aquatic habitat values.
- Retention of riparian values.
- Banks can be steeper than vegetated banks that do not contain rock protection.

Disadvantages:

- High installation cost.

Use:

- Used on the outside face of high velocity or sharp channel bends.
- Also, used in areas where both the channel velocity and overbank flow velocities are likely to be very high and thus erosive.

Rock placement on banks

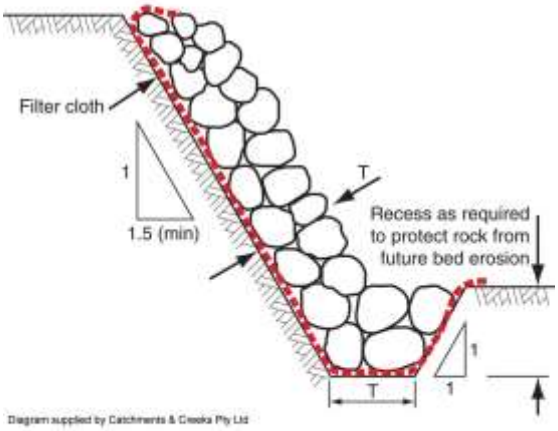


Diagram supplied by Catchments & Creeks Pty Ltd

Full-height with open voids

Advantages:

- Cheaper installation cost compared to vegetated rock protection.

Disadvantages:

- Poor aesthetics.
- Poor aquatic habitat and fish passage.
- High risk of weed invasion unless fully shaded.

Use:

- Heavily shaded, high velocity areas.
- Outside face of fully shaded channel bends.
- Very high velocity regions where vegetation is not expected to survive.

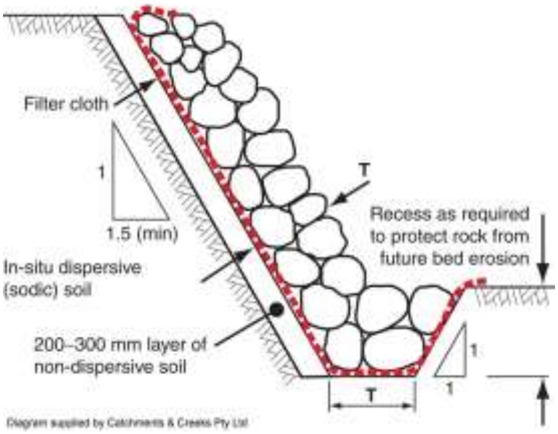


Diagram supplied by Catchments & Creeks Pty Ltd

Rock placement over dispersive soils

Advantages:

- Long-term protection of highly erodible soils.

Disadvantages:

- Poor aesthetics.
- Poor aquatic habitat and fish passage.
- High risk of weed invasion unless fully shaded.

Use:

- Heavily shaded areas containing dispersive soils.
- Outside face of fully shaded channel bends.
- Very high velocity regions where vegetation is not expected to survive.

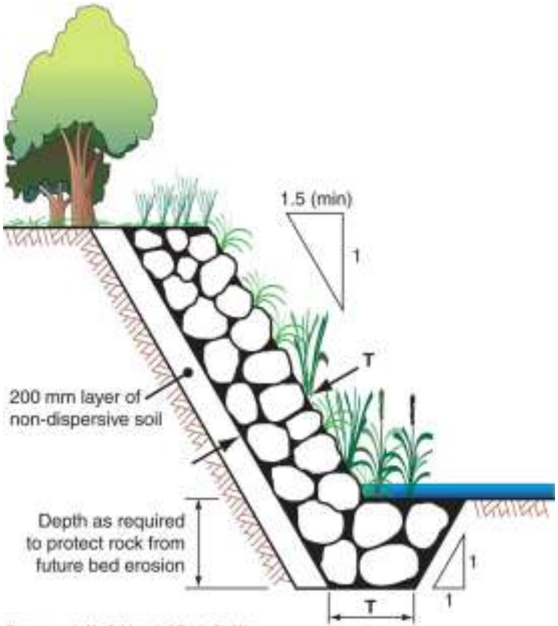


Diagram supplied by Catchments & Creeks Pty Ltd

Vegetated rock placement over poor soils

Advantages:

- Retention of aquatic habitat values.
- Long-term protection of highly erodible soils.
- Reduced maintenance costs.

Disadvantages:

- Higher installation cost compared to non-vegetated rock protection.

Use:

- Outside face of high velocity or sharp channel bends in dispersive soil regions.
- Dispersive soil areas where both the channel velocity and over-bank flow velocities are likely to be very high and therefore erosive.

Stacked boulder walls

Stacked boulder wall (Qld)

Stacked boulders

- As the slope of a boulder wall increases, an increasing proportion of the boulder weight rests on the lower boulders, and ultimately the channel bed, rather than on the channel bank.
- This means that if there is a significant flood and the creek bed erodes or weakens, then there is the risk that the entire boulder wall will slide down the face of the bank into the waterway.

Stacked boulder wall adjacent a footbridge

Use of boulder walls

- Stacked boulder walls can be used to:
  - form steep banks that can allow the construction of, or protection of structural assets such as roads and pathways
  - increase the stability of rock of a given size by increasing the vertical force placed on the rock as a result of the weight of the upper rock bearing down on the lower rocks.

Stacked boulder wall (Qld)

Problems commonly associated with stacked boulder walls

- In the absence of vegetation, ‘hydraulically’ smooth boulder walls can induce high flow velocities to occur adjacent the surface of the boulders.
- These same high velocities will also exist adjacent the creek bed, possibly causing bed scour.
- Toe erosion at the base of the boulder wall can caused the rocks to slide down the face of the bank into the waterway.

Failed boulder wall

Importance of stable subsoil conditions

- Unstable and/or dispersive subsoils can cause the failure of stacked boulder walls.
- The stability of boulder walls can be increased by incorporating earth reinforcing mesh into the wall and extending this mesh into the backfill.

Common problems associated with rock stabilisation of waterways

Rock placement without planting

Failure to introduce suitable vegetation cover

- The placement of loose rock on waterway banks may initially appear to be 'cheap' scour control option, but weed infestation can lead to ongoing maintenance costs.
- Wherever practical, rock-lined surfaces should be lightly covered with soil and appropriately planted.

Rock placement without planting

Same location (left) after weed infestation

Weak sandy bed structure after a flood

Placement of rock on sandy bed waterways

- Sand-based waterways often contain a deep bed of sand, which can liquefy during floods and migrate down the waterway like a viscous fluid.
- If heavy rocks are placed on the bed of a sand-based waterway, then these rocks may simply sink into the sand during flood events.
- The risk of the rocks displacing during floods depends on the depth of sand and how the sand moves (flows) during floods.

Rocks displaced down filter cloth

Rocks slipping down smooth filter cloth

- In certain conditions, filter cloth effectively acts as a low-friction surface, which can cause rocks to slowly slide down the face of a slope.
- If rocks need to be placed on steep slopes, then the rocks should be 'keyed' into the bank.
- Keying can be done by 'stair-stepping' the bank prior to placing the filter cloth, or providing suitable toe rock.

Common problems associated with rock stabilisation of waterways

Bank erosion at d/s end of rock work

Bank erosion at downstream end of rock-lined banks

- In the absence of a vegetative cover, rock-lined surfaces can act as hydraulically-smooth surfaces that can induce high flow velocities to exist adjacent the bank.
- These same high velocities can then pass over the unprotected bank immediately downstream of the rock-lined surface causing soil erosion.
- Erosion along the toe of the rock is also a common occurrence.

Tunnel erosion under rocks

Rock placed on dispersive or slaking soils

- Rocks should **not** be placed directly onto a dispersive, sodic, or slaking soil.
- Tunnel erosion is a common occurrence when rocks are placed directly over a dispersive soil.

Collapsed dispersive soil bank

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, but preferably 300 mm.
- 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.

Poorly placed rocks on creek bank

Rock not integrated into the bank

- Rocks should not be placed on a creek bank in a manner that detracts from the natural aesthetics of the waterway.
- Wherever possible, the rocks should be recessed into the soil, and appropriate native vegetation should be established over the rocks.
- The exception being when the establishment of vegetation would adversely affect local flood levels.

2. Culvert Bed Roughness

Introduction

Rock Sizing for Artificial Culvert Roughness

WATERWAY MANAGEMENT PRACTICES

Photo 1 – Fish-friendly box culvert with roughened bed conditions

Photo 2 – Enhanced bed roughness along the base of a box culvert

1. Introduction

Cross many countries there is a growing interest in the protection of fish habitats and fish passage corridors along waterways. Various guidelines exist on the design of fish friendly waterway structures, including the design of fish friendly culvert crossings. This fact sheet

Artificial culvert roughness fact sheet

Photo supplied by Catchments & Creeks Pty Ltd

Natural bed gravels on culvert bed (NSW)

Photo supplied by Peter Armstrong

Post-flood sedimentation within a culvert

Photo supplied by Catchments & Creeks Pty Ltd

Gravel bed within a culvert (NSW)

Introduction

- There is a growing acknowledgment that instream structures need to be designed in a manner that encourages fish passage.
- One method used to enhance fish passage conditions within culverts is to recess one or more cells into the channel bed (forming ‘wet’ cells) and to mimic natural bed conditions within these cells.
- Relevant fact sheet: https://www.catchmentsandcreeks.com.au/fact-sheets/esc_rock_sizing.html

Alluvial waterways

- There are basically four types of waterways: clay-based, sand-based, gravel-based and rock-based systems.
- Both sand-based and gravel-based waterways are mobile (alluvial) bed systems where the bed material slowly migrates downstream as a result of floods.
- In sand and gravel-based waterways, natural bed material is normally allowed to freely enter and pass through the culvert, thus forming natural bed roughness.

Clay-based waterways

- Some urban clay-based waterways can experience significant sediment flow during floods.
- The post-flood removal of sediment can be difficult if a gravel or rock bed has been formed on the base of the culvert.
- If rock roughness needs to be incorporated into culverts within clay-based waterways, then the rocks usually need to be grouted to the culvert floor to prevent movement during floods.

Sizing rock

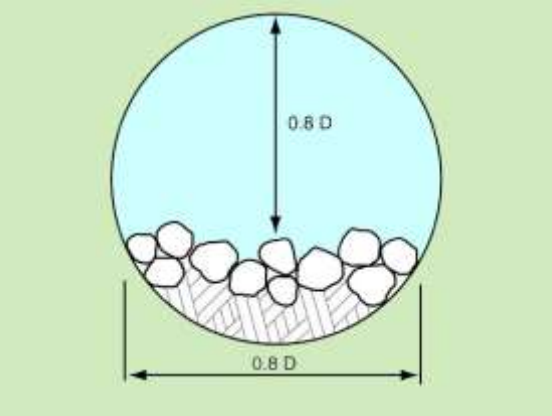
- If the rock is placed loose and is expected to resist movement, then the minimum size rock is given by:
  - to minimise the risk of movement, the minimum size of loose **angular** rock placed on the bed of culverts should be:

    $$d_{50} = 0.04\ V^2 \qquad (2.1)$$

  - alternatively, the minimum size of loose **rounded** rock placed on the bed of culverts should be:

    $$d_{50} = 0.05\ V^2 \qquad (2.2)$$

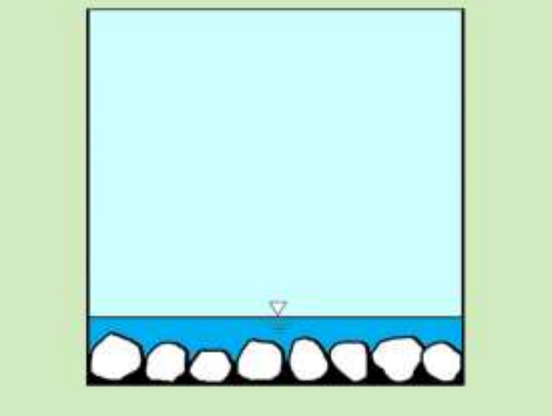
Rock placement



Natural bed material in a pipe culvert

Pipe culverts

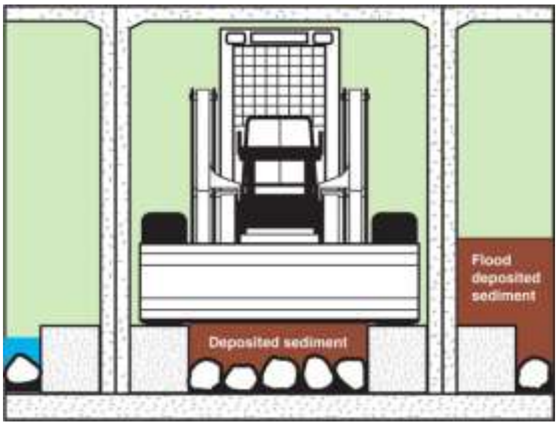
- Wet cell pipe culverts are typically recessed 20% of their diameter.
- Recessing the culvert cells will reduce the effective flow area (A), wetted perimeter (P), hydraulic radius (R) and alter the pipe roughness (n).
- Hydraulic parameters for pipe culverts flowing full and recessed 20% into the channel bed are provided in tables 2.1 to 2.4 for various rock size distributions (d_{50}/d_{90}).



Rocks grouted to bed of box culvert

Box culverts

- Wet cell box culverts are typically recessed 20% of the cell height or at least 300 mm.
- Hydraulic parameters for box culverts flowing full and recessed 20% into the channel bed are provided in tables 2.5 and 2.6 for various rock size distributions.
- If grouted rocks are used, then the installation costs may be reduced by grouting the rock onto the base slab prior to placement of the box units.



Post-flood sediment removal from culvert

Post flood de-silting of culverts

- Some culverts regularly require the removal of sediments deposited during flood events.
- The removal of sediment from culverts can cause the disturbance, or total removal of, the introduced rock roughness.
- If the culvert and the raised benching is appropriately sized, then ‘bobcats’ can be used to facilitate the removal of excessive sediment deposits, and in the general maintenance of the culvert.

Photo supplied by Catchments & Creeks Pty Ltd

Rock mattress placed on culvert bed

Use of rock mattresses

- The use of ‘rock mattresses’ as a form of bed roughness is <u>**not**</u> recommended due to possible breakage or displacement of the baskets.
- These mattresses have been known to move and block culverts during flood events.

Hydraulic properties of pipe culverts containing artificial bed roughness

The placement of rocks and gravels on the bed of pipe culverts will alter the overall hydraulic roughness of the conduit. Tables 2.1 to 2.4 provide the hydraulic parameters for various pipe culvert conditions. These tables are based on an assumed smooth wall Manning's roughness (n) of 0.013.

Hydraulic properties of box culverts containing artificial bed roughness

Tables 2.5 and 2.6 provide the Manning's roughness for the rock-lined bed of an artificially roughened box culvert. This bed roughness will need to be incorporated with the soffit and sidewall roughness to determine a composite Manning's roughness for a box culvert flowing full.

The placement of **loose** rock is most appropriate in gravel-based waterways that experience a regular movement of similar sized rocks down the stream. Loose rock can also be used in clay-based streams (if sediment flow down the stream is negligible) however, grouted rock may be required to avoid loss of the rocks during flood events.

If grouted rocks are used, then the cost of their installation may be reduced by grouting the rocks onto the base slab prior to installation of the pre-cast units. Grouted rocks are likely to have a slightly lower Manning's roughness to that of loosely placed rocks.

If loosely placed rocks are used, then consideration should be given to the placement of a raised sill at the downstream end of the culvert to help retain the rocks during high flows.

Benching is normally only used in single cell box culverts when it is necessary to provide both wet (aquatic) passage and dry (terrestrial) passage. If it is desirable for natural bed material to form across the bed of the culvert, then the height of the benching must be sufficient to allow a dry path to exist during normal base flow conditions.

If the culvert and the raised benching is appropriately sized, then 'bobcats' can travel along the raised benching to facilitate the removal of excessive sediment deposits, and the general maintenance of the culvert.

Table 2.1 – Pipe full hydraulic parameters for a pipe culvert recessed 20% into the channel bed with a loose or grouted rock bed and d_{50}/d_{90} = 0.2

			Mean bed rock size d_{50} =	**50 mm**	**100 mm**	**200 mm**	**300 mm**	**400 mm**
D (mm)	**A (m^2)**	**P (m)**	**R (m)**	**Pipe full Manning's roughness (n)**				
450	0.136	1.356	0.101	0.06				
525	0.192	1.610	0.119	0.05	0.09			
600	0.251	1.839	0.136	0.05	0.08			
750	0.391	2.297	0.170	0.05	0.07			
825	0.473	2.526	0.187	0.04	0.07			
900	0.564	2.758	0.204	0.04	0.07			
1050	0.765	3.213	0.238	0.04	0.06	0.10		
1200	1.001	3.674	0.272	0.04	0.06	0.09		
1350	1.268	4.136	0.307	0.04	0.05	0.09		
1500	1.564	4.594	0.341	0.034	0.05	0.08	0.11	
1650	1.892	5.052	0.375	0.032	0.05	0.08	0.10	
1800	2.251	5.510	0.408	0.031	0.05	0.07	0.10	
2100	3.143	6.511	0.483	0.029	0.04	0.07	0.09	0.11

Notes:

D = Nominal internal pipe diameter (mm)
A = Potential flow area within the pipe excluding the area taken up by the grouted rocks (m^2)
P = Potential wetted perimeter of a pipe with grouted bed rock (m)
R = Potential hydraulic radius of a pipe with grouted bed rock (m)

Table 2.2 – Pipe full hydraulic parameters for a pipe culvert recessed 20% into the channel bed with a loose or grouted rock bed and $d_{50}/d_{90} = 0.3$

Mean bed rock size d_{50} =				50 mm	100 mm	200 mm	300 mm	400 mm
D (mm)	**A (m^2)**	**P (m)**	**R (m)**	**Pipe full Manning's roughness (n)**				
450	0.136	1.356	0.101	0.038				
525	0.192	1.610	0.119	0.035	0.05			
600	0.251	1.839	0.136	0.033	0.05			
750	0.391	2.297	0.170	0.031	0.04			
825	0.473	2.526	0.187	0.029	0.04			
900	0.564	2.758	0.204	0.029	0.04			
1050	0.765	3.213	0.238	0.027	0.04	0.06		
1200	1.001	3.674	0.272	0.026	0.04	0.06		
1350	1.268	4.136	0.307	0.025	0.035	0.05		
1500	1.564	4.594	0.341	0.024	0.033	0.05	0.06	
1650	1.892	5.052	0.375	0.024	0.032	0.05	0.06	
1800	2.251	5.510	0.408	0.023	0.031	0.05	0.06	
2100	3.143	6.511	0.483	0.022	0.029	0.04	0.05	0.06

Table 2.3 – Pipe full hydraulic parameters for a pipe culvert recessed 20% into the channel bed with a loose or grouted rock bed and $d_{50}/d_{90} = 0.5$

Mean bed rock size d_{50} =				50 mm	100 mm	200 mm	300 mm	400 mm
D (mm)	**A (m^2)**	**P (m)**	**R (m)**	**Pipe full Manning's roughness (n)**				
450	0.136	1.356	0.101	0.024				
525	0.192	1.610	0.119	0.023	0.032			
600	0.251	1.839	0.136	0.022	0.030			
750	0.391	2.297	0.170	0.021	0.028			
825	0.473	2.526	0.187	0.021	0.027			
900	0.564	2.758	0.204	0.020	0.026			
1050	0.765	3.213	0.238	0.020	0.025	0.034		
1200	1.001	3.674	0.272	0.019	0.024	0.032		
1350	1.268	4.136	0.307	0.019	0.023	0.031		
1500	1.564	4.594	0.341	0.019	0.023	0.030	0.037	
1650	1.892	5.052	0.375	0.018	0.022	0.029	0.035	
1800	2.251	5.510	0.408	0.018	0.022	0.028	0.034	
2100	3.143	6.511	0.483	0.018	0.021	0.027	0.032	0.037

Table 2.4 – Pipe full hydraulic parameters for a pipe culvert recessed 20% into the channel bed with a loose or grouted rock bed and $d_{50}/d_{90} = 0.8$

Mean bed rock size d_{50} =				50 mm	100 mm	200 mm	300 mm	400 mm
D (mm)	**A (m^2)**	**P (m)**	**R (m)**	**Pipe full Manning's roughness (n)**				
450	0.136	1.356	0.101	0.019				
525	0.192	1.610	0.119	0.018	0.022			
600	0.251	1.839	0.136	0.018	0.021			
750	0.391	2.297	0.170	0.017	0.020			
825	0.473	2.526	0.187	0.017	0.020			
900	0.564	2.758	0.204	0.017	0.020			
1050	0.765	3.213	0.238	0.017	0.019	0.024		
1200	1.001	3.674	0.272	0.017	0.019	0.023		
1350	1.268	4.136	0.307	0.016	0.019	0.022		
1500	1.564	4.594	0.341	0.016	0.018	0.022	0.025	
1650	1.892	5.052	0.375	0.016	0.018	0.021	0.024	
1800	2.251	5.510	0.408	0.016	0.018	0.021	0.024	
2100	3.143	6.511	0.483	0.016	0.018	0.020	0.023	0.025

Table 2.5 – Manning’s roughness for rock-lined surfaces in shallow water

d_{50}/d_{90}	$d_{50}/d_{90} = 0.2$					$d_{50}/d_{90} = 0.3$				
d_{50} (mm)	50	100	200	300	400	50	100	200	300	400
R (mm)	Channel bed Manning’s roughness (n)					Channel bed Manning’s roughness (n)				
200	0.12	0.21	0.38	0.53	0.67	0.07	0.12	0.21	0.37	0.37
300	0.10	0.17	0.30	0.40	0.51	0.06	0.10	0.16	0.28	0.28
400	0.08	0.14	0.24	0.33	0.42	0.05	0.08	0.14	0.23	0.23
500	0.07	0.12	0.21	0.29	0.37	0.05	0.07	0.12	0.20	0.20
600	0.07	0.11	0.19	0.26	0.32	0.04	0.07	0.11	0.18	0.18
700	0.06	0.10	0.17	0.23	0.29	0.04	0.06	0.10	0.17	0.17
800	0.06	0.09	0.16	0.21	0.27	0.04	0.06	0.09	0.15	0.15
900	0.06	0.09	0.15	0.20	0.25	0.04	0.06	0.09	0.14	0.14
1000	0.05	0.08	0.14	0.19	0.23	0.04	0.05	0.08	0.13	0.13
1200	0.05	0.08	0.12	0.17	0.21	0.03	0.05	0.07	0.12	0.12
1400	0.05	0.07	0.11	0.15	0.19	0.03	0.05	0.07	0.11	0.11
1600	0.04	0.07	0.10	0.14	0.18	0.03	0.04	0.06	0.10	0.10
1800	0.04	0.06	0.10	0.13	0.16	0.03	0.04	0.06	0.10	0.10
2000	0.04	0.06	0.09	0.12	0.15	0.03	0.04	0.06	0.09	0.09

Table 2.6 – Manning’s roughness for rock-lined surfaces in shallow water

d_{50}/d_{90}	$d_{50}/d_{90} = 0.5$					$d_{50}/d_{90} = 0.8$				
d_{50} (mm)	50	100	200	300	400	50	100	200	300	400
R (mm)	Channel bed Manning’s roughness (n)					Channel bed Manning’s roughness (n)				
200	0.04	0.06	0.10	0.14	0.17	0.03	0.04	0.06	0.08	0.09
300	0.04	0.05	0.08	0.11	0.14	0.03	0.03	0.05	0.06	0.08
400	0.03	0.05	0.07	0.09	0.12	0.03	0.03	0.04	0.05	0.07
500	0.03	0.04	0.06	0.08	0.10	0.03	0.03	0.04	0.05	0.06
600	0.03	0.04	0.06	0.08	0.09	0.03	0.03	0.04	0.05	0.05
700	0.03	0.04	0.05	0.07	0.09	0.03	0.03	0.04	0.04	0.05
800	0.03	0.04	0.05	0.07	0.08	0.03	0.03	0.04	0.04	0.05
900	0.03	0.04	0.05	0.06	0.08	0.03	0.03	0.04	0.04	0.05
1000	0.03	0.03	0.05	0.06	0.07	0.03	0.03	0.03	0.04	0.05
1200	0.03	0.03	0.04	0.06	0.07	0.03	0.03	0.03	0.04	0.04
1400	0.03	0.03	0.04	0.05	0.06	0.03	0.03	0.03	0.04	0.04
1600	0.03	0.03	0.04	0.05	0.06	0.03	0.03	0.03	0.04	0.04
1800	0.03	0.03	0.04	0.05	0.06	0.03	0.03	0.03	0.04	0.04
2000	0.03	0.03	0.04	0.05	0.05	0.03	0.03	0.03	0.04	0.04

3. Culvert Outlet Structures

Introduction

Rock Sizing for Multi-Pipe & Culvert Outlets

STORMWATER AND WATERWAY MANAGEMENT PRACTICES

Photo 1 – Rock pad outlet structure at end of a duel stormwater pipe outlet

Photo 2 – Rock pad outlet structure at end of a multi-cell box culvert

1. Introduction

The hydraulic forces generated by multiple pipe/cell outlets are higher than those expected at single pipe/cell outlets. Consequently the rock sizes required within outlet structures can be significantly different from those used on single pipe outlets.

Multi-pipe and culvert outlet fact sheet

Introduction

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

Photo supplied by Catchments & Creeks Pty Ltd

Culvert outlet scour protection (Qld)

Critical design parameters

- The critical design parameters for multi-cell 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 the outlet that could potentially undermine the culvert.

Photo supplied by Catchments & Creeks Pty Ltd

Multi-cell box culvert 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, or when the culvert is operating under ‘outlet control’ conditions, bed and bank erosion can occur well downstream of the outlet.
- When the outlet is fully or partially drowned (i.e. high tailwater) then ‘jetting’ from the outlet can transfer energy well downstream of the rock pad.

Photo supplied by Catchments & Creeks Pty Ltd

Movement of rocks within rock pad

Ongoing movement of rock

- The rock sizing design 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 periods of high flow.

Hydraulics of culvert outlets


Photo supplied by Catchments & Creeks Pty Ltd

Culvert discharge with very low tailwater

Outlet flow conditions

- The hydraulics of culvert 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.


Photo supplied by Catchments & Creeks Pty Ltd

Culvert discharge with low tailwater (NSW)

Low tailwater flow conditions

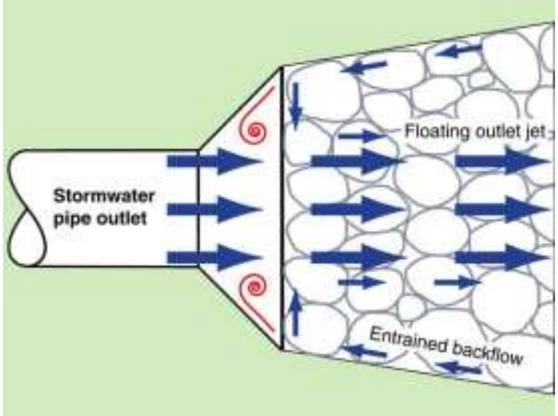
- During low tailwater conditions, discharges tend to ‘spill’ from the culvert cells spreading the flow energy over a wider pathway than during high tailwater.
- Energy dissipation is much more efficient and the required length of the rock pad is smaller than is required during high tailwater conditions.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


Photo supplied by Catchments & Creeks Pty Ltd

Outlet jetting during high tailwater (NSW)

High tailwater flow conditions

- During high tailwater conditions, discharges from the cells 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 culvert 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.

Sizing rock downstream of culvert outlets

Recommended mean (d_{50}) rock sizes are presented in tables 3.2 and 3.3. 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 3.1. Some minor variations should be expected between Figure 3.1 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 3.4 and 3.5. A typical layout of the rock pad is shown in Figure 3.2. 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 3.2) 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 circumstances 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.

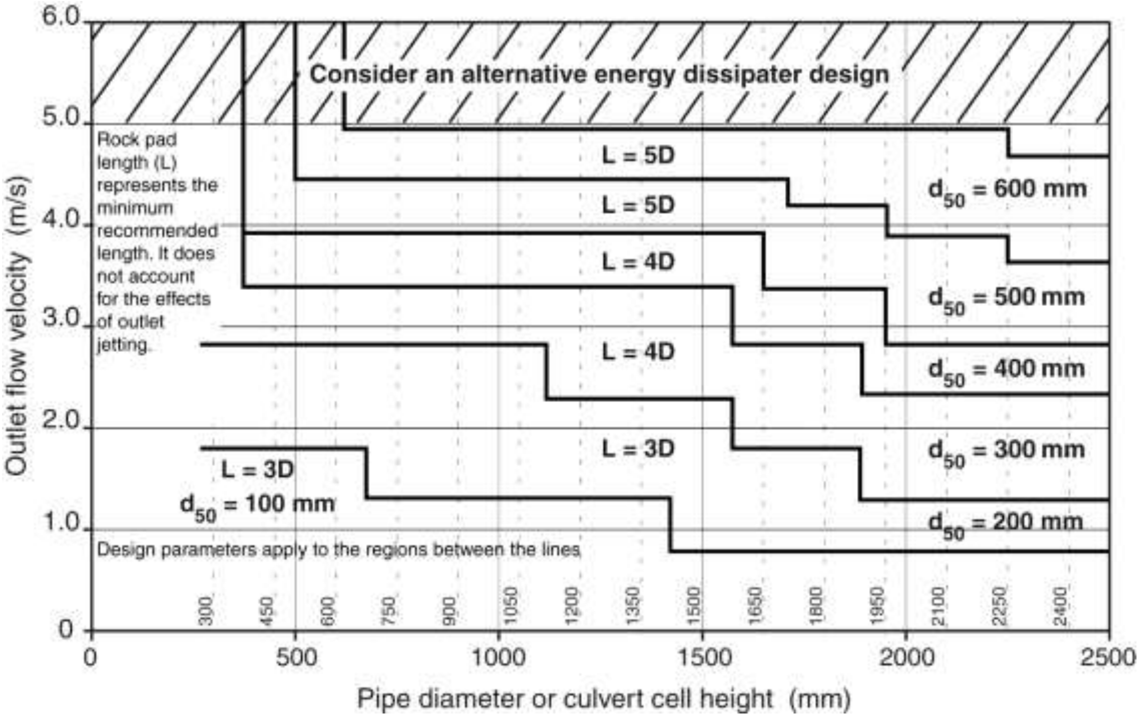


Figure 3.1 – Sizing of rock pad outlet structures for multi-pipe and box culvert outlets

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 3.1.

Table 3.1 – 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.

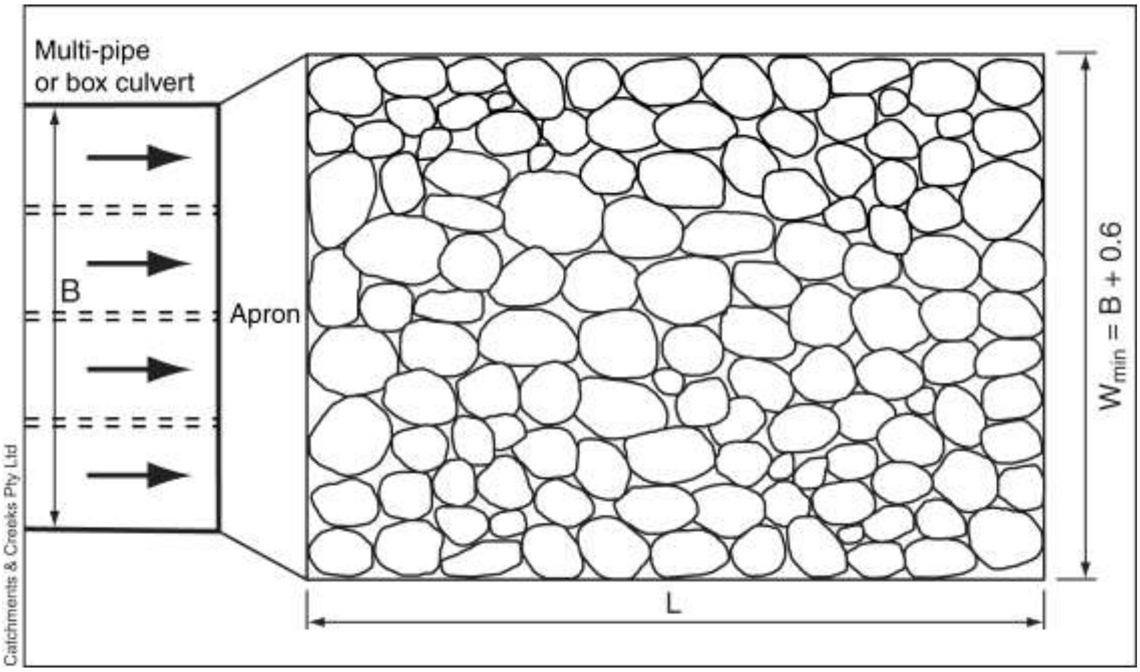


Figure 3.2 – Typical layout of a rock pad for multiple pipe and box culverts (plan view)

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 3.3) 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.

Selecting the appropriate length of rock protection

In circumstances where it is essential to minimise the risk of bed scour downstream of the culvert, then the length of the rock pad should be **twice** that presented in tables 3.4 and 3.5; 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 culvert, 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 or cell depth away from the multi-cell outlet.

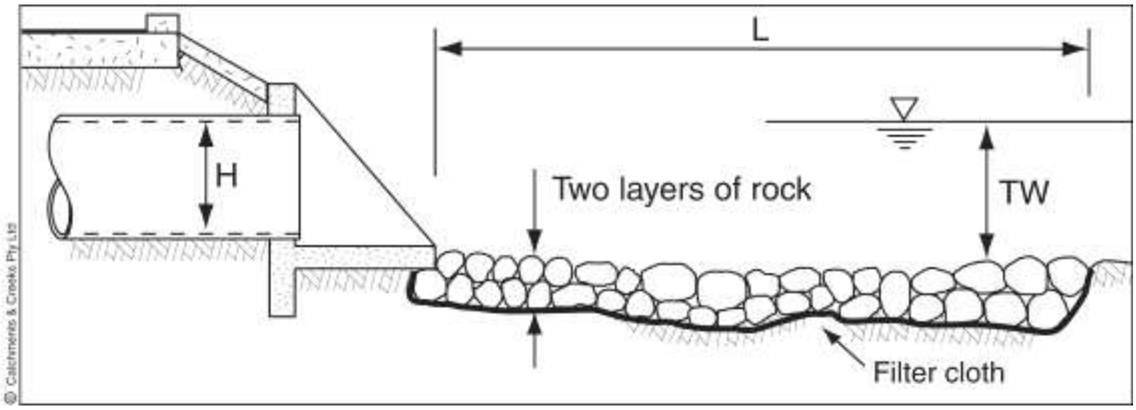


Figure 3.3 – Rock pad recessed into the receiving channel

Table 3.2 – Mean rock size, d_{50} (mm) for culvert 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	871
6.00	300	400	500	600	600	800	900

Table 3.3 – Mean rock size, d_{50} (mm) for culvert 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 3.4 – Minimum length (L) of rock pad relative to cell height (H) for culvert 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 3.5 – Minimum length (L) of rock pad relative to cell height (H) for culvert 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.

Common construction problems


Photo supplied by Catchments & Creeks Pty Ltd

Displacement of rock pad

Inadequate rock size

- Rock of inadequate size can readily be displaced downstream of the culvert potentially causing a scour hole.

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 a dispersive soil.


Photo supplied by Catchments & Creeks Pty Ltd

Undermining of culvert


Photo supplied by Catchments & Creeks Pty Ltd

Same culvert outlet eight years later


Photo supplied by Catchments & Creeks Pty Ltd

Inappropriate rock placement

Poor placement of rock

- If the rock sits above the invert of the culvert, then:
  - sediment is likely to collect within the culvert, and
  - the outlet 'jet' can 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.


Photo supplied by Catchments & Creeks Pty Ltd

Bank erosion well downstream of culvert

Outlet jetting

- During periods of high tailwater, or when the culvert is operating under 'outlet control' conditions, the outlet jet can float along the water surface with minimal energy dissipation.
- Floating outlet jets can travel a distance of around 10 to 15 times their diameter (pipe culverts), or effective flow depth (box culverts), depending on the exit velocity of the jets and the spacing between the jets (two outlet jets in close proximity to each other can join into a single, larger jet).

4. Waterway and Gully Chutes

Introduction

Rock Sizing for Waterway & Gully Chutes

WATERWAY MANAGEMENT PRACTICES

Photo 1 – Rock-lined waterway chute

Photo 2 – Rock-lined gully chute

1. Introduction

A 'waterway chute' is a stabilised section of channel bed used to control bed erosion while maintaining desirable fish passage conditions in a manner similar to a natural riffle (Photo 1). These structures may also be referred to as 'Grade Control Structures' or 'Rock Ramps'.

Waterway and gully chute fact sheet

Reference document

- In waterways, the terms 'chutes' and 'ramps' are generally interchangeable.
- The term *chute* is more commonly used by hydraulic engineers (because flow goes down a chute), while the term *ramp* is more commonly used by fishery officers (because fish swim up a ramp).
- Relevant fact sheet: https://www.catchmentsandcreeks.com.au/fact-sheets/esc_rock_sizing.html

Waterway chute (NSW)

Waterway chutes

- A waterway chute is a stabilised section of waterway used to control bed erosion while maintaining desirable fish passage conditions in a manner similar to a natural riffle.
- These structures may also be referred to as *Grade Control Structures* or *Rock Ramps*.
- A ridge rock fishway is similar to a rock ramp; however, the sizing and placement of the rock is different.

Gully chute (Qld)

Gully chutes

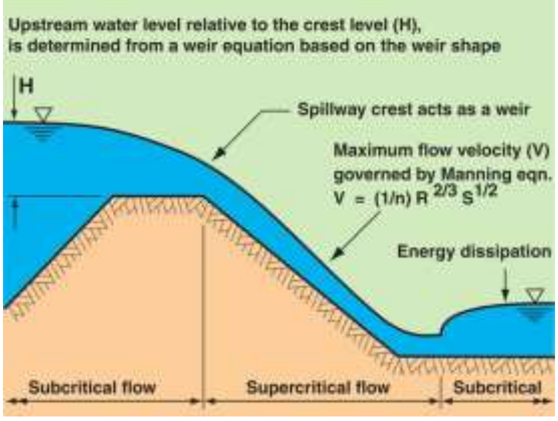
- A gully chute is a steep drainage channel, typically of uniform cross-section, used to stabilise the head of a gully, or to control flow into, or out of, a gully.
- The main design difference between waterway chutes and gully chutes is that gully chutes rarely need to be fish-friendly (because these dry gullies are rarely recognised as viable fish habitats).
- In effect, gully chutes are just large versions of a drainage batter chute.

Failed gully chute (NSW)

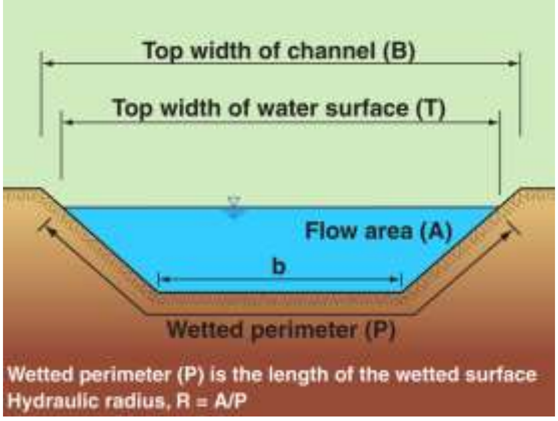
High failure risk

- Rock-lined chutes are considered high-risk waterway structures because they have a relatively high structural failure rate, especially within the first few years after construction.
- Structural failure can occur either through the direct displacement of the rocks by water flow, or the undermining of the structure as a result of downstream erosion, or flows bypassing either under or around the rocks.

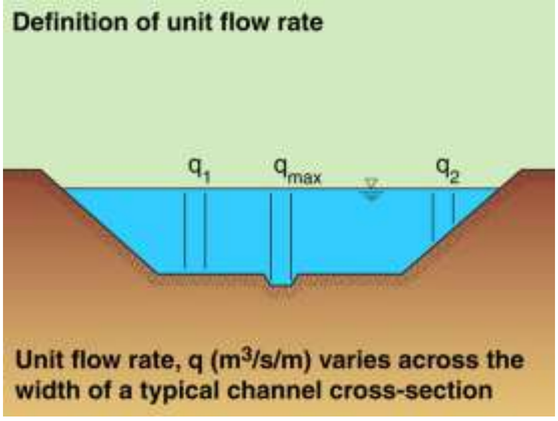
Key design considerations



Waterway/gully chute hydraulics



Trapezoidal weir geometry



Defining the unit flow rate (q)

Energy dissipation basin for a chute

Critical design issues

- Critical design components of a chute are:
  - flow entry into the chute
  - the maximum allowable flow velocity down the face of the chute
  - energy dissipation at base of chute.
- Most chutes fail as a result of rock displacement; therefore, it is critical to size the rocks using rock properties (e.g. rock density, size distribution and shape) that are representative of the rocks that will actually be used in the structure.

Design of chute inlet

- Flow conditions upstream of the chute may be determined using an appropriate weir equation.
- It is important to ensure that the water level upstream of the chute does not cause undesirable flooding (of adjacent land) or flow bypassing around the edges of the chute.

Design of the face of the chute

- Determination of the mean rock size for use on the face of the chute can be based on either the unit flow rate (equations 4.1 & 4.2) or the estimated flow velocity (equations 4.3 & 4.4) down the chute.
- To the maximum degree practicable, the crest and face of the chute should be designed to achieve near-uniform flow conditions across the width of the chute, thus minimising 3-dimensional flow patterns.

Design of the chute outlet and energy dissipation

- Suitable energy dissipation is required at the base of the chute.
- The design of energy dissipaters **must** be assessed on a case-by-case basis.
- The type and extent of scour control within the energy dissipater depends on:
  - the fall height of the chute
  - the expected tailwater conditions, and
  - whether or not the energy dissipation basin can be recessed into the bed.

Design features

Looking 'down' a rock ramp fishway (NSW)

Constructed waterway riffle (Qld)

Low-flow channel set in grouted rock

Low-flow channel set in grouted rock

Fish passage

- Studies of natural riffles indicate that the maximum desirable fall of a fish-friendly chute or rock ramp is around 500 mm.
- It is noted that constructing fish-friendly chutes from large rocks (> 500 mm) can be problematic.
- The maximum recommended rock size (d_{50}) is 600 mm due to the difficulties of both obtaining larger rock, and the difficulties of placing such rock within natural waterways.

Chute fall and gradient

- Chute gradients flatter than 1 in 6 are inherently much more stable, safer and fish friendly in comparison to steeper bed slopes.
- If the chute is required to be fish friendly, then a gradient of between 1 in 20 and 1 in 30 is normally specified.
- For reasons of stability, the fall height should be limited to 1200 mm; however, fish passage requirements generally limit the fall of individual chutes to 500 mm.

Use of low-flow channels

- The placement of a low-flow channel through a rock chute should be avoided.
- In most cases, trickle flows simply pass between the voids of the larger rocks, thus negating the need for a formal low-flow channel.
- The problem caused by the existence of a low-flow channel is that it can significantly increase the required rock size due to increased shear stress, often requiring the rocks to be grouted in place.

Formation of a low-flow channel through the weir crest

- If a low-flow channel must pass through the structure, then the depth of this channel should be minimised, especially at the crest of the chute.
- Typically the rocks around a low-flow channel need to be grouted in place to obtain the necessary stability and desirable flow conditions.
- The use of grouted rock within natural waterways should be avoided wherever possible.

Sizing rock for the face of waterway and gully chutes

Application of Equation 4.1 - Preferred design equation - Applicable for uniform flow conditions only, $S_e = S_o$ - Batter slopes (S_o) less than 50% (1 in 2)	**Equation 4.1:** $d_{50} = \frac{127.SF.K_1.K_2.S_o^{0.5}.q^{0.5}.y^{0.25}}{(s_r - 1)}$
Application of Equation 4.2 - A simplified equation independent of flow depth - Applicable for uniform flow conditions only, $S_e = S_o$ - Batter slopes (S_o) less than 50% (1 in 2)	**Equation 4.2:** $d_{50} = \frac{SF.K_1.K_2.S_o^{0.47}.q^{0.64}}{(s_r - 1)}$
Application of Equation 4.3 - A simplified, velocity-based equation - Applicable for uniform flow conditions only, $S_e = S_o$ - Batter slopes (S_o) less than 33% (1 in 3)	**Equation 4.3:** $d_{50} = \frac{SF.K_1.K_2.V^2}{(A - B.\ln(S_o)).(s_r - 1)}$ For SF = 1.2: A = 3.95, B = 4.97 For SF = 1.5: A = 2.44, B = 4.60
Application of Equation 4.4 - Suitable for use in the design of partially drowned waterway chutes - Applicable for steep gradient, non-uniform flow conditions, $S_e \neq S_o$ - Batter slopes (S_o) less than 50% (1 in 2)	**Equation 4.4:** $d_{50} = \frac{127.SF.K_1.K_2.S_o^{0.5}.V^{2.5}.y^{0.75}}{V_o^{2.0}(s_r - 1)}$

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’
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 4.1 provides suggested safety factor values. Tables 4.5 to 4.8 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 4.1, 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 4.9 and 4.10 provide mean rock size for angular rock and a safety factor of 1.2 and 1.5, based on Equation 4.1, but with flow velocity presented as the primary variable. These tables are best used in the design of waterway chutes where uniform flow conditions are unlikely to be achieved down the face of the chute.

Table 4.1 – 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.	• Waterway chutes where failure of the structure is likely to result in easily repairable soil erosion. • Waterway chutes that are likely to experience significant sedimentation and vegetation growth before experiencing high flows. • Temporary (< 2 yrs) gully chutes 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).	• Gully chutes where failure of the structure may cause severe gully erosion. • Waterway chutes where failure of the structure may cause severe gully erosion or damage to important infrastructure.

Thickness and height of rock layer

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 additional thickness will **not** compensate for the use of undersized rock.

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

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 4.2.

Table 4.2 – 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.

Rock type and grading

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 for rounded rock (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.

Broken concrete and building rubble should not be used.

Typical rock densities (s_r) are presented in Table 4.3.

Table 4.3 – 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

In most situations the nominal rock size is usually between 300 mm to 600 mm.

Maximum rock size generally should not exceed twice the nominal (d_{50}) rock size. On very steep grades, the maximum rock size should not exceed 1.25(d_{50}).

Table 4.4 provides a suggested distribution of rock sizes for waterway chutes. 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 2.70, but typically around 2.1. Witter & Abt (1990) reported that poorly graded rock ($C_u = 1.1$) has a critical discharge 8% greater than well-graded rock ($C_u = 2.2$).

Table 4.4 – Typical distribution of rock size for 'fish friendly' structures (guide only)

Rock size ratio	Assumed distribution value
d_{100}/d_{50}	2.0
d_{90}/d_{50}	1.8
d_{75}/d_{50}	1.5
d_{65}/d_{50}	1.3
d_{40}/d_{50}	0.65
d_{33}/d_{50}	0.50
d_{10}/d_{50}	0.20

Backing material or filter layer

Rock placed in gully chutes must be placed over a layer of suitably graded filter rock, or geotextile filter cloth (minimum 'bidim A24' or the equivalent). The geotextile filter cloth must have sufficient strength and must be suitably overlapped to withstand the placement of the rock.

Use of a geotextile filter is unlikely to be required in the construction of waterway chutes.

If the rock is placed on a dispersive (e.g. sodic) soil (a condition **not** recommended), then prior to placement of filter cloth, the exposed bank **must** first be covered with a layer of non-dispersive soil, typically minimum 200 mm thickness, but preferably 300 mm.

Placement of vegetation over the rock

Vegetating rock-lined gully chutes 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 on waterway structures.

Table 4.5 – 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 4.6 – 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 4.7 – 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 = 1:2**		**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	0.10	**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 4.8 – 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 4.9 – 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 4.10 – 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.

Grouted boulder waterway structures

Grouted rock drop structure (USA)

Use of grouted boulder structures

- Grouted rock has been used for centuries in the form of stone pitching, which has often been used to stabilise bridge abutments.
- Grouted boulder construction is used as an alternative to loose rock placement in circumstances where the rock size required for loose rock placement is larger than that which is commercially available within a given area.

Grouted rock gully chute (Qld)

The need for stable foundations and subsoil conditions

- Grouted boulder structures require very stable foundations (i.e. good subsoil) otherwise excessive cracking of the grout can occur, leading to movement of the boulders, or total failure of the structure.
- The grouted boulder drop structure shown left continues to experience the loss of rocks as head-cut erosion slowly migrates up the chute initiated from a downstream disturbance.

Grouted rock gully chute (Qld)

Incorporation of vegetation

- The incorporation of vegetation into grouted boulder structures is a bit of a ‘hit or miss’ exercise.
- The long-term success of vegetation greatly depends on the care and experience of the revegetation contractor.

Grouted rock wetland outflow weir (Qld)

Retention of natural appearance

- It is essential for the grout to be placed with great care, otherwise the rock surface can appear as just another form of stone pitching.
- The grout should not extend above 70% of the rock size so that minimal grout is visible on the finished surface.

Common construction problems

Gully chute formed from small rocks

Insufficient rock size

- The stability of waterway and gully chutes is highly dependent on the size of the rock.
- In circumstances where only small rock can be obtained, then the rocks need to be covered with grassy-type plants as soon as possible to increase the effective scour resistant of the rock.
- However, the preferred option should always be to obtain the specified rock size.

Gully chute formed on a dispersive soil

Inappropriate placement of rocks on dispersive or slaking soils

- Waterway and gully chutes can experience catastrophic failure if the rocks are placed directly on a dispersive soil.
- The successful placement of rocks on dispersive soils requires special care and attention to small details, especially the sealing of these highly erodible soils with a layer of non-dispersive soil prior to placement of the rock.
- A soil scientist can supply expert advice.

Non fish friendly rock chute

Insufficient fine rock to control seepage flows through the voids

- In most cases, waterway chutes, riffles and rock weirs are required to be fish friendly.
- In order for fish to migrate over the rocks during periods of low flow it is essential for these flows to pass **over** the rocks and **not** through the open voids.
- Fish friendly structures require sufficient fines (smaller rocks) to fill the voids between the larger rocks (see Table 5).

Gully chute formed from round rocks

Use of unstable round rock

- The rock sizing equations presented within this document are based on the use of fractured, angular, quarry rock.
- Rounded river stone is less stable than angular rock, and therefore is generally not suitable for most gully chutes, which typically have a steeper gradient.
- Rounded river stone is however, often preferred in the formation of low-gradient, fish-friendly, waterway chutes and riffles.

5. Waterway Riffles

Introduction

Rock Sizing for Waterway Riffles

WATERWAY MANAGEMENT PRACTICES

Photo 1 – Constructed riffle

Photo 2 – Constructed fishway ramp

1. Introduction

A riffle is an isolated section of channel bed where the steepness of the bed allows for the exposure of the bed rocks and gravels during periods of low flow, often resulting in the formation of whitewater conditions (Photo 1). In pure hydraulic terms, riffles are the same as rock chutes; however, their small size and low gradient means the design procedures used for sizing the

Rock sizing fact sheet for waterway riffles

Reference document

- The following section summarises the design data provided in the fact sheet: *'Rock sizing for waterway riffles'*.
- Relevant fact sheet: https://www.catchmentsandcreeks.com.au/fact-sheets/esc_rock_sizing.html

Accelerated flow over a natural riffle

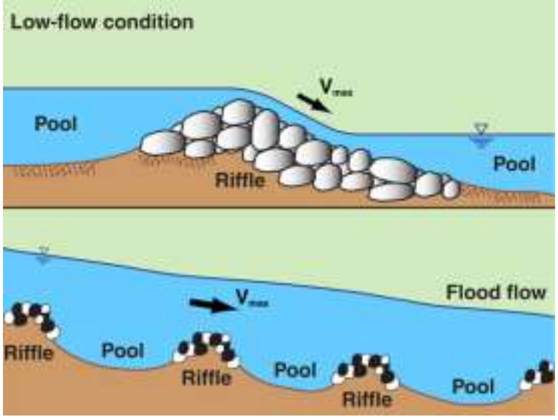
Waterway riffles

- A riffle is an isolated section of channel bed where the steepness of the bed allows for a local acceleration of flows and the possible exposure of the bed rocks during periods of low flow.
- In pure hydraulic terms, riffles are the same as rock chutes and ramps; however, their small size and low gradient means the design procedures used for sizing the rock are different from those used in the design of drainage structures, such as batter chutes and dam spillways.

Rock sitting high with exposed edges

Critical design issues

- The size of the rock is generally governed by the following hydraulic factors:
  - the maximum flow velocity during which the rock is required to be stable
  - the degree of exposure of the rock to direct river flow (i.e. does the rock sit flush with the adjacent rock, or does part of the rock extend into the flow)
  - the degree of turbulence within the water flow—this usually varies with water depth and flow velocity.



Design flow conditions

Design flow conditions

- The stability of the rocks used in constructed riffles usually needs to be checked for both low-flow (shallow water) and high-flow (deep water) conditions.
- During low-flow conditions the flow down the riffle is normally supercritical, and flow velocity is governed by the riffle slope.
- During high-flows, the flow conditions over the riffle may be governed by the overall channel slope (i.e. the riffles become part of the overall bed roughness, and riffle slope is not a critical hydraulic factor).

Constructed riffles – Use of riffles in different types of waterways


Photo supplied by Catchments & Creeks Pty Ltd

Constructed riffle in a clay-based creek


Photo supplied by Catchments & Creeks Pty Ltd

Sand becomes 'unstable' after a flood


Photo supplied by Catchments & Creeks Pty Ltd

Unstable riffle in a gravel-based creek


Photo supplied by Catchments & Creeks Pty Ltd

Exposed bedrock (Qld)

Clay-based waterways

- In an ideal world, pool-riffle systems would not be constructed within waterways where such features do not naturally exist.
- However, our waterways do not exist in an ideal world, and there are circumstances where a constructed pool-riffle sequence could benefit a clay-based waterway.
- In clay-based waterways there is no natural migration of bed rock; therefore, the rock used in a constructed riffle must be sized to be stable (i.e. not move).

Sand-based waterways

- Constructing a rock riffle on the bed of a sand-based creek can be problematic.
- If the depth of the sand exceeds the foundation depth of the rock structure, then the rocks could simply 'sink' into the sand during a major flood.
- If the depth of the bed sand does not exceed the depth of the rock structure, then the structure could interfere with the natural migration of sand, or could simply become buried by the sand.

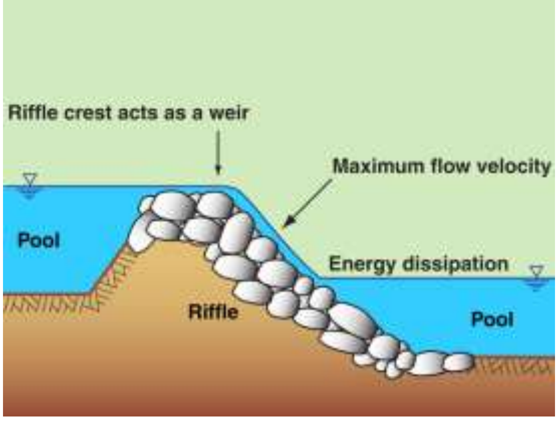
Gravel-based waterways

- If a new riffle needs to be constructed within a gravel-based waterway, then natural bed rock should be used in circumstances where the natural migration of bed rock and gravel can be maintained.
- However, if a riffle needs to be constructed downstream of a water feature that is likely to prevent the natural migration of bed rock (e.g. downstream of a constructed lake), then larger rock may be required (such as that recommended for constructed riffles).

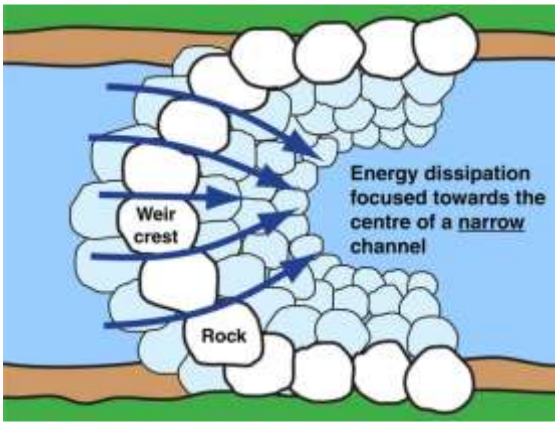
Rock-based waterways

- It would be rare for constructed riffles to be required near sections of exposed bedrock.
- If constructed riffles are needed, then they are more likely to be associated with the sections of clay, sand or gravel-based channels found between the sections of exposed bedrock.
- If bed erosion results in the formation of an unnatural waterfall, then a riffle may be used to raise the downstream bed in order to maintain natural fish passage.

Constructed riffles – Hydraulics of the riffle

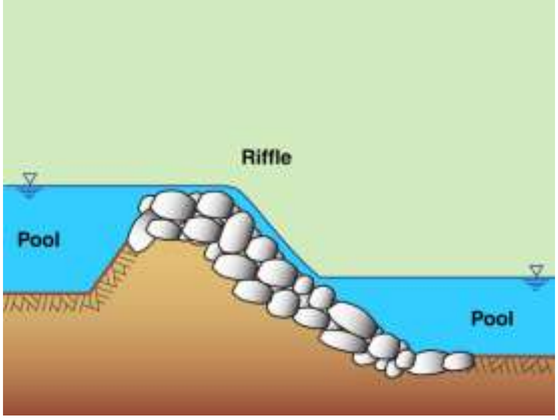


Riffle hydraulics



A curved riffle crest in a narrow channel

Constructed riffle (Qld)



Rock riffle profile

Riffle gradient

- There are three aspects to the hydraulics of a riffle:
  - crest hydraulics
  - chute hydraulics
  - downstream energy dissipation.
- A survey of natural riffles found in South-East Queensland creeks found that riffles had a typical gradient of 1 in 30.
- In order to be considered fish friendly, it is recommended that constructed riffles have a maximum gradient of 1 in 20.

Weir crest in narrow channels

- A 'pool' must exist downstream of a riffle in order to facilitate energy dissipation.
- In narrow channels, the width of this pool can be a critical factor in some designs.
- The existence of a curved (concave) riffle crest helps to focus the flow energy towards the centre of the pool, thus reducing the risk of bank erosion.
- Hydraulically, the significance of the weir crest profile reduces as the length of the riffle increases.

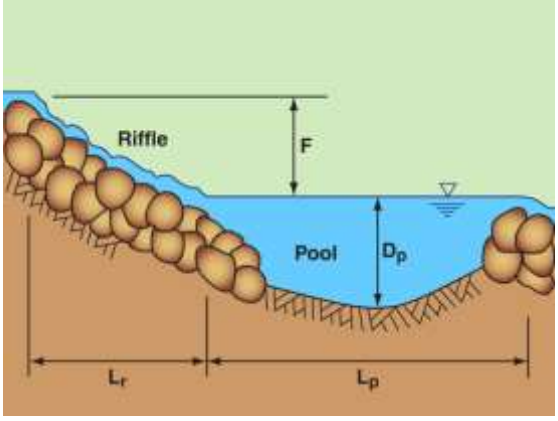
Weir crest in wide channels

- In wide channels it is normal for the crest of the riffle to be relatively straight and flat, and aligned at 90-degrees to the riffle chute.
- If the pool-riffle sequence meanders across the bed of a wide channel, then 'changes of direction' can either occur:
  - within a long pool, or
  - at the crest of a riffle, but
  - the riffle chute must remain straight.

Elevated weir crests

- Unlike some rock chutes, the crest of a riffle is normally elevated above the upstream channel in order to facilitate the existence of an upstream pool.
- Elevating the weir crest also helps to reduce flow velocities immediately upstream of the riffle, which helps to provide a rest area for migrating fish.

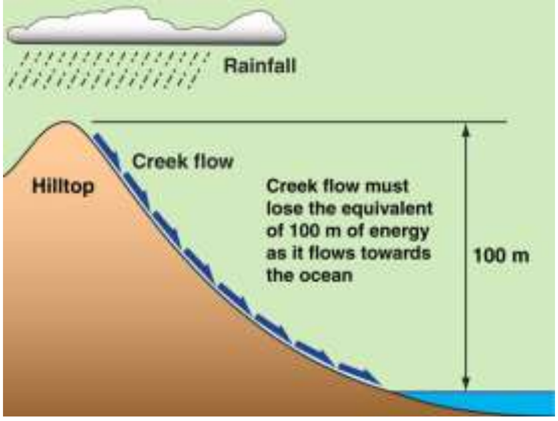
Constructed riffles – Hydraulics of the downstream pool



Profile of a pool-riffle system

Introduction

- The existence of both pools and riffles increases the habitat diversity and resulting biodiversity of the waterway.
- There is also an important hydraulic relationship that develops between a riffle and the downstream pool.
- This hydraulic relationship means that there are some attributes (dimensions) of a pool that can be linked back to the riffle.



Energy loss

Energy dissipation along creeks

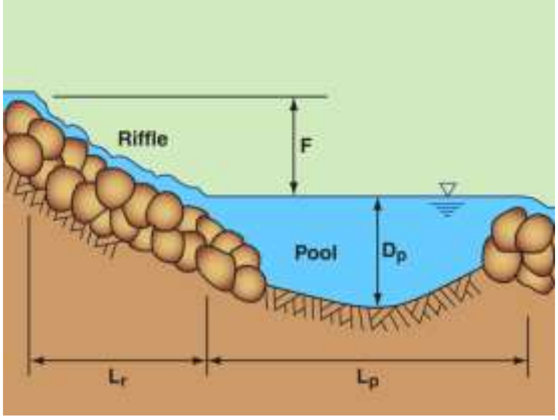
- If a creek starts on a hilltop 100 m above sea level, then as the water travels the full length of the creek, it must lose the equivalent of 100 m of energy by the time the water enters the sea.
- Similarly, if the water descends a riffle that falls 500 mm, then the equivalent of 500 mm of energy must be consumed while the water passes down the riffle and into the downstream pool.

Photo supplied by Catchments & Creeks Pty Ltd

A pool-riffle type water slide (NSW)

Types of energy dissipation

- In pool-riffle systems, energy loss can occur in two ways:
  - friction (down the chute)
  - turbulence (within the pool)
- As the flow enters the downstream pool, the jetting effects of the inflow cause turbulence within the pool, which contributes to energy loss.
- These same hydraulic principles exist within a wide range of hydraulic structures, including water slides.



Profile of a pool-riffle system

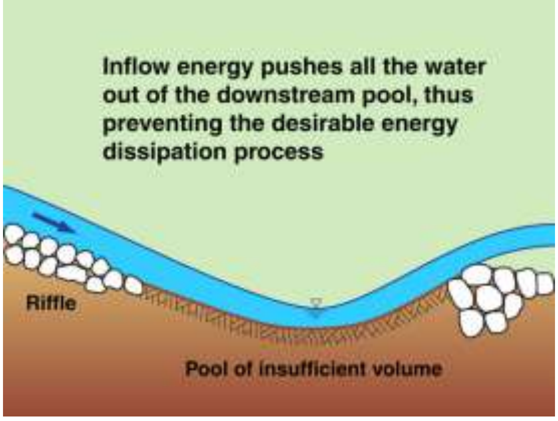
Factors affecting the depth of a pool (D_p)

- A study of natural pool-riffle systems in South-East Queensland revealed that the depth of the downstream pool (D_p) was usually equal to, or greater than, the fall (F) of the upstream riffle.

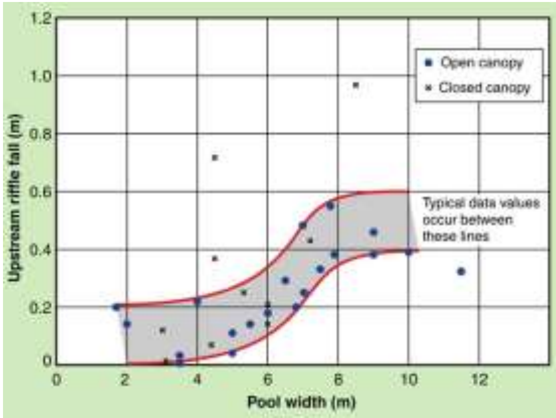
$$D_{p\ (min)} = F \text{ (typical)} \qquad (5.1)$$

- Waterfalls are different, however, the depth of the pool below a waterfall also increases with the height of the waterfall, but only to the point where the falling water reaches terminal velocity.

Constructed riffles – Pool dimensions in narrow channels



Outcome of insufficient pool volume



Relationship between the fall & pool width

Pool downstream of a rock ramp (NSW)

Pool-riffle in a narrow channel (Qld)

Factors affecting the volume of a pool

- The volume of water contained within the downstream pool is important in order to maintain the correct operation of the pool.
- If the downstream pool has insufficient volume, then as the flow rate increases, the water energy passing down the riffle will eventually push the water out of the downstream pool causing the pool to act as a ‘ski jump’.
- The volume of a pool is governed by its depth, width and length.

Factors affecting the width of a pool (W_p)

- Hydraulic factors mean that:
  - pool depth is linked to riffle fall, and
  - the minimum pool volume is linked to the riffle’s fall and width.
- For relatively narrow channels (i.e. creeks) the pool width (W_p) should be taken as the greater of:

$$W_{p\,(min)} = 1.3 + 4.5\,D_p \qquad (5.2)$$

$$W_{p\,(min)} = W_r + 4.5\,D_p \qquad (5.3)$$

Factors affecting the length of a pool (L_p)

- The minimum length of a pool is in-part governed by the minimum required volume of a pool in order to achieve efficient energy dissipation.
- A survey of pool-riffle systems in SE Qld creeks showed that the minimum pool length is around twice the pool width.

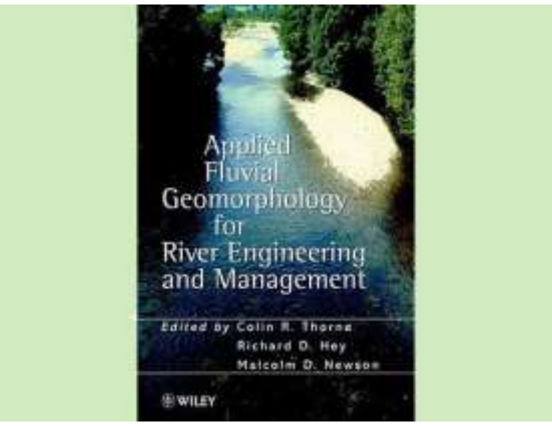
$$L_{p\,(min)} = 2 \text{ to } 4 \text{ times } W_p \qquad (5.4)$$

- However, the actual length of the pool is usually governed by the gradient of the creek, and the spacing of the riffles.

Use of rock to stabilise narrow pools

- In constructed channels, limits on the overall width of the channel may not allow the construction of the ideal pool width.
- In such cases, a narrower (but longer) pool can be constructed, but the sides of the pool will need to be stabilised with rock and hardy plants (e.g. Lomandra) in order to control potential bank erosion.
- The length of the pool should exceed the minimum length determined for the pond width based on equations 5.2 and 5.3.

Constructed riffles – Pool and riffle dimensions in wide channels



Thorne, Hey & Newson, 1997


Photo supplied by Catchments & Creeks Pty Ltd

Riffle on the Gwydir River, NSW


Photo supplied by Catchments & Creeks Pty Ltd

Gwydir River, Moree, NSW


Photo supplied by Catchments & Creeks Pty Ltd

Pool-riffle system, Queanbeyan River, NSW

Introduction

- The previous discussion referred to the sizing of pool-riffle systems in narrow creeks based on a survey of creeks in South-East Queensland.
- It is not the intent of this field guide to provide sufficient information to allow the reader to design pool-riffle systems for larger waterways (i.e. rivers).
- Designing works in rivers requires the guidance of experts (river morphologists) and survey data from local river systems.

Width of riffles in wide channels

- In rivers, riffles are:
  - located at inflection points, midway between bends (but not always)
  - usually exposed across the full width of the channel bed, even though dry weather flows may only spill over a portion of the riffle.

$$W_r = 1.03\ b \qquad (5.5)$$

where:

- W_r = crest width of riffle (m)
- b = average width of channel bed (m)

Depth and width of pools in wide channels

- In rivers, pools:
  - have a dry weather water surface width approximately equal to the channel width, and
  - typically extend from riffle to riffle, with the deepest part of the pool located at channel bends.
- The depth of pools at channel bends depends on the bed width (b) and the bend radius (refer to text books for typical relationships).

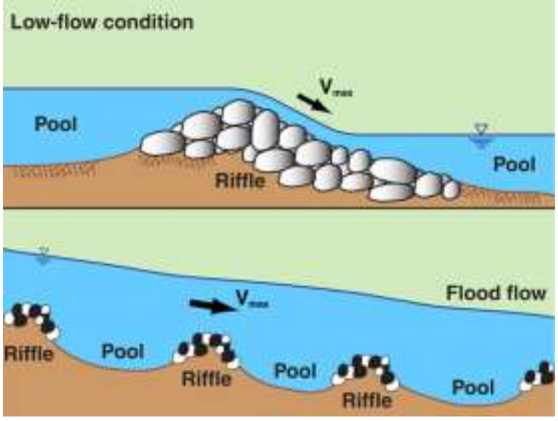
Length and volume of pools in wide channels

- The length of the pool is likely to relate solely to the spacing of the riffles.
- A pool of some type must exist at the base of the riffle in order to dissipate energy.
- The depth of the pool immediately downstream of the riffle will likely relate to the riffle fall.
- The suggested minimum length of a pool is twice the pool width, but it would be better to survey existing pools in the river.

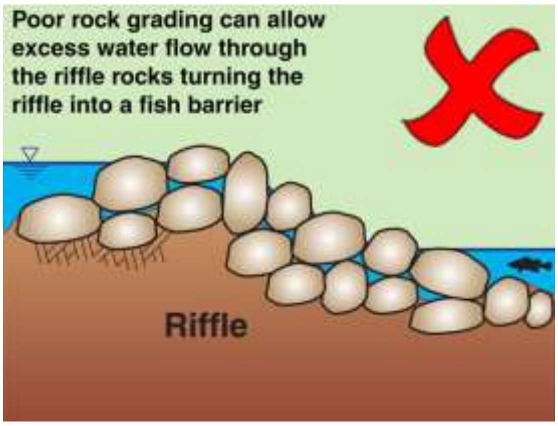
Constructed riffles – Rock sizing for riffles


Photo supplied by Catchments & Creeks Pty Ltd

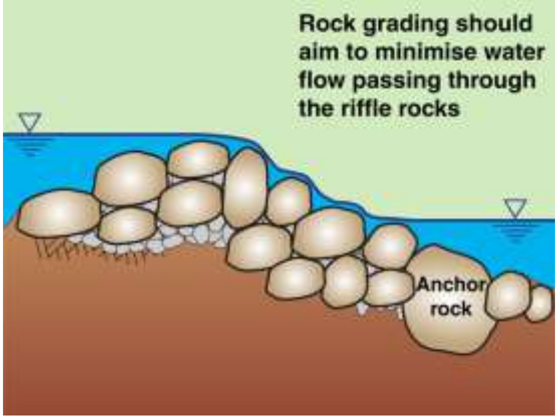
Rock sitting high with exposed edges



Design flow conditions



Consequence of poor rock grading



Optional use of anchor rocks

Critical design issues

- The size of the rock is generally governed by the following factors:
  - the maximum flow velocity during which the rock is required to be stable
  - the degree of exposure of the rock to direct river flow (i.e. does the rock sit flush with the adjacent rock, or does part of the rock extend into the flow)
  - the degree of turbulence within the water flow—this usually varies with water depth and flow velocity.

Design flow conditions

- Rock size usually needs to be checked for both low-flow (shallow water) and high-flow (deep water) conditions.
- During low-flow conditions the water velocity is usually governed by the riffle slope.
- During high-flow conditions the water velocity is likely to be governed by the overall channel slope (i.e. the pools and riffles simply become part of the overall bed roughness).

Distribution of rock sizes

- There are many circumstances where a near-uniform rock size is desirable, but in constructed riffles this can result in fish passage problems.
- The rocks used in constructed riffles are usually larger than those found in natural riffles because it is usually necessary for these rocks to be stable (i.e. not migrate downstream during flood events).
- The use of large rock can result in excess water passing through the rock during dry weather (low flow) conditions, which can block fish passage.
- To avoid such problems, there needs to be a certain percentage of smaller rocks in order to minimise the void spacing.
- The recommended distribution of rock sizes for constructed riffles is provided in Table 5.2 over the page.
- An option also exists for the placement of large anchor rock at the base of the riffle (i.e. below the normal pool water level) in order to increase the stability of the riffle rock during flood events.

Constructed riffles – Sizing rock for low-flow conditions

Low-flow condition (Qld)

Sizing rock for low-flow conditions

- In most cases, the required rock size will **not** be governed by the low-flow conditions.
- The low-flow hydraulic check requires the determination of the maximum flow velocity that occurs on the riffle prior to the riffle being drowned-out by backwater.
- This analysis usually involves numerical modelling of the stream for a range of flow conditions.

Flow approaching drowned conditions

Rock sizing equation for low-flow condition

$$d_{50} = \frac{SF.K_1.K_2.V^2}{(A - B.\ln(S_o)).(s_r - 1)} \qquad (5.6)$$

For SF = 1.2: A = 3.95, B = 4.97 (default)

For SF = 1.5: A = 2.44, B = 4.60

Tabulated rock sizes are given in tables 4.6, 4.8, 4.9 & 4.10.

(Note: ‘ln’ means Natural logarithm to base-e)

A & B = equation constants; typically adopt A = 3.95 and B = 4.97 based on SF = 1.2

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

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

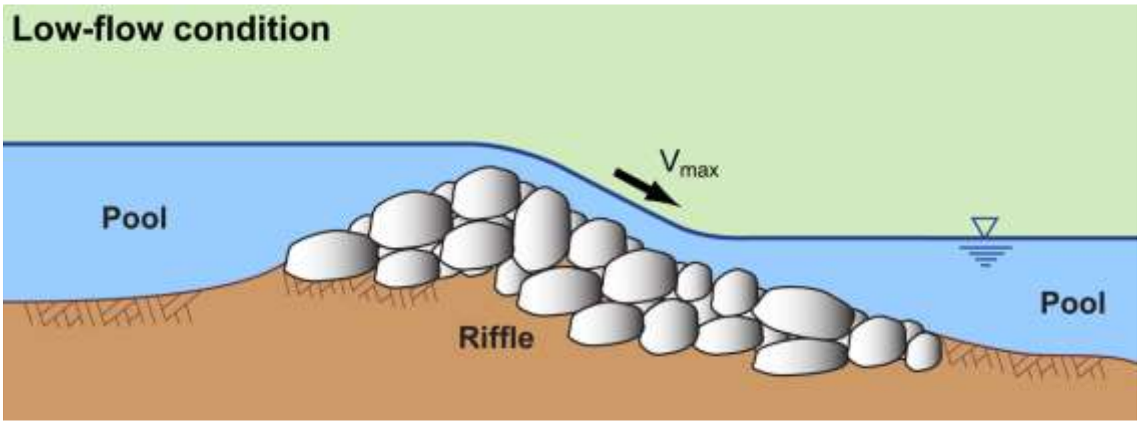
= 0.95 for poorly graded rock ($C_u = d_{60}/d_{10} < 1.5$), 1.05 for well-graded rock ($C_u > 2.5$), otherwise $K_2 = 1.0$ ($1.5 < C_u < 2.5$)

SF = safety factor = 1.2 (recommended)

S_o = gradient of the riffle face [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 = maximum depth-average flow velocity over the rocks during low flow [m/s]



Shallow water, low-flow design conditions

Constructed riffles – Sizing rock for <u>high-flow</u> conditions

The high-flow hydraulic check requires the nomination of the maximum flood event during which the riffle rock is required to be stable, e.g. the 1 in 10 year (10% AEP) or 1 in 50 year (2% AEP) discharge. This flow condition is then modelled to determine the maximum depth-average flow velocity passing over the riffle.

It is important that the calculated depth-average velocity is representative of the **actual** flow velocities above the riffle, **<u>not</u>** the flow velocity averaged across the full cross-section.

Minimum mean rock size for these high-flow conditions may be determined from Equation 5.7.

$$d_{50} = \frac{K_1 . V^2}{2.g.K^2 (s_r - 1)} \qquad (5.7)$$

where:

K = equation constant based on flow conditions

= 1.1 for low-turbulence deep water flow, or 0.86 for highly turbulent flow; otherwise, refer to Table 5.1 for suggested vales of ‘K’ based on the flood gradient

V = nominated design flow velocity over the rocks [m/s]

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

Table 5.1 – Suggested values of ‘K’ for various <u>flood</u> gradients

Flood gradient (%)	**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)							

Specification of rock for constructed riffles

In circumstances where the constructed riffle is required to simulate ‘natural’ bed conditions, and the riffle is located in a waterway that contains natural pool–riffle systems, then the rocks used in construction of the riffle should match the size distribution of the natural riffle systems. However, for constructed riffles that are required to be stable during major flood flows, then the following rock specifications should be considered.

Crushed rock is generally more stable than natural rounded rock; however, rounded rock has a more ‘natural’ appearance and is considered more fish friendly. A 36% increase in rock size is recommended for rounded rock (i.e. $K_1 = 1.36$).

Broken concrete and building rubble should <u>not</u> be used.

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 should be less than one-third its length.

The maximum rock size generally should not exceed twice the mean (d_{50}) rock size.

Table 5.2 provides a recommended distribution of rock sizes for constructed riffles.

Table 5.2 – Recommended distribution of rock sizes for constructed riffles

Rock size ratio	**Assumed distribution value**
d_{100}/d_{50}	2.0
d_{90}/d_{50}	1.8
d_{75}/d_{50}	1.5
d_{65}/d_{50}	1.3
d_{40}/d_{50}	0.65
d_{33}/d_{50}	0.50
d_{25}/d_{50}	0.45
d_{10}/d_{50}	0.20

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