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 supplements these guidelines with recently updated information on the sizing of rocks used in the simulation of natural bed roughness within waterway culverts.

One of the commonly used methods of benefiting fish passage conditions within a culvert is to recess one or more cells into the channel bed (forming 'wet' cells) and to mimic natural bed conditions within these cells (Photos 1 & 2).

The appropriate application of artificial bed roughness depends on the type of waterway in which the culvert is constructed. There are basically four types of waterways, clay-based, sand-based, gravel-based and rocky spilling waterways. In their natural condition, clay-based creeks normally have a stable bed (i.e. a fixed bed system) with minimal sediment load. On the other hand, clay-based rivers can have a significant natural sediment load. In both cases the sediment consists of relatively fine-grained matter that does not contribute significantly to the overall channel roughness or flow conditions. In these types of waterways, channel roughness is mostly achieved through vegetation and channel irregularities.

Both sand-based and gravel-based waterways are mobile bed systems where, under natural conditions, the bed material slowly migrates downstream, predominantly during flood events. In sand-based waterways the movement of the sandy bed material can significantly contribute to the development of a layer of slow-velocity water (the boundary layer) adjacent the bed. In gravel-based waterways the actual roughness of the bed material helps to develop fish-friendly boundary layer conditions adjacent to the bed.

When rock roughness is incorporated into culverts on clay-based waterways, the rocks usually needs to be grouted to the culvert bed to prevent movement during high flows. Grouting the rocks in place also assists in culvert maintained after flood events. The use of rock mattresses is not recommended due to possible breakage or displacement of the baskets.

In sand-based and gravel-based waterways, however, natural bed material is normally allowed too freely enter and pass through the culvert.

2. Sizing of rock placed on culvert beds

Ideally, the rocks and/or gravels placed on the bed of waterway culverts should mimic the size and roughness of natural bed material found within the waterway. However, the placement of loose, natural bed material may not be practical for various reasons, including:

- The watercourse is a clay-based system that has natural bed material of insufficient size to provide the desired bed roughness conditions for allowance of fish passage.
- The natural movement of bed material down the waterway has been interrupted by past modifications to the waterway. Consequently, if natural bed material were to be placed within the culvert, it would not be replenished by the natural movement of bed sediments.
- The culvert regularly requires the removal of sediments deposited by flood events. The removal of this sediment may mean that any introduced rock roughness would also be removed.

If the introduced rocks need to be stable during a specified design discharge, then the rocks need to be either grouted to the culvert bed, or of sufficient size to minimise the risk of their displacement. In the latter case, rock sizing should be based on Equation 1.

Low gradient (S < 5%) flow conditions:

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

For rock of high density, the above equation reduces to the commonly used Equation 2.

Angular rock with specific gravity (s_r) of 2.6:

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

where:

- d_{50} = nominal rock size (diameter) of which 50% of the rocks are smaller [m]
- g = acceleration due to gravity [m/s^2]
- K = equation constant based on flow conditions
  = 1.10 for typical low-turbulent, subcritical culvert flow conditions; or 0.86 for high-turbulent flow conditions
- K_1 = correction factor for rock shape
  = 1.0 for angular (fractured) rock, 1.36 for rounded rock (i.e. smooth, spherical rock)
- s_r = specific gravity of rock (e.g. sandstone 2.1–2.4; granite 2.5–3.1, limestone 2.6; basalt 2.7–3.2)
- S = bed slope = tan (θ) [m/m]
- V = actual depth-average flow velocity at location of rock [m/s]

3. Manning's roughness of rock-lined surfaces

The hydraulic analysis of culverts depends on an assessment of the culvert's bed and wall roughness. Equation 3 may be used to estimate the Manning's roughness (n) of rock-lined surfaces.

$$n = \frac{(d_{90})^{1/6}}{26\left(1 - 0.3593^{(X)^{0.7}}\right)} \qquad (3)$$

where:

- n = Manning's roughness
- X = $(R/d_{90})(d_{50}/d_{90})$
- R = hydraulic radius of flow over the rocks [m]
- d_{90} = rock size for which 90% of rocks are smaller [m]

For 'natural' river gravels have a typical relative roughness (d_{50}/d_{90}) in the range 0.2 to 0.5. For quarried rock the ratio is more likely to be in the range 0.5 to 0.8.

4. 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 1 to 4 provide the hydraulic parameters for various pipe culvert conditions (as per Figure 1). These tables are based on an assumed smooth wall Manning's roughness (n) of 0.013.

Table 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

Table 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 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 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

5. Hydraulic properties of box culverts containing artificial bed roughness

Tables 5 and 6 provide the hydraulic parameters for various box culvert conditions (as per Figure 2). These tables are based on an assumed smooth wall Manning's roughness, n = 0.013.

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 is usually required to avoid loss of the rocks during flood events.

If grouted rocks are used, then their installation cost 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 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.

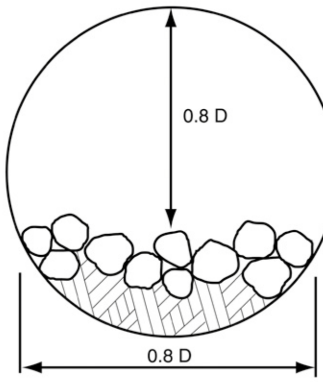

Diagram supplied by Catchments & Creeks Pty Ltd

Figure 1 – Fish-friendly pipe culvert with roughened bed conditions

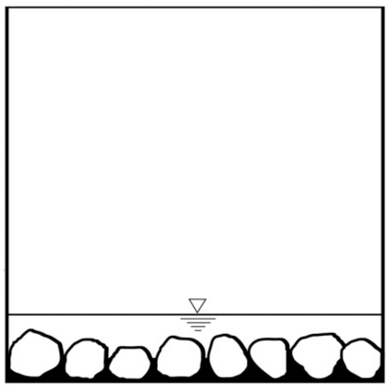

Diagram supplied by Catchments & Creeks Pty Ltd

Figure 2 – Fish-friendly box culvert with roughened bed conditions

Table 5 – Manning's roughness for rock lined channels 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 6 – Manning's roughness for rock lined channels 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

This fact sheet is presented for educational purposes as part of a series developed and published by:

Catchments & Creeks Pty Ltd (www.catchmentsandcreeks.com.au)
PO Box 314
Ferny Hills, Qld 4055
Australia