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Advancing Australian Riprap Sizing Approaches

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ABSTRACT

The placement of riprap is the most commonly implemented scour countermeasure in Australia. Nationwide guidance for riprap sizing is provided in Austroads and Australian Rainfall and Runoff (ARR) documents. ARR guidance generally defers to Queensland Department of Transport and Main Roads (QDTMR) publications that, in turn, defer to Austroads guidance for riprap sizing. Austroads riprap sizing procedures fall back on methods developed by the United States Bureau of Reclamation (USBR), the U.S. Army Corps of Engineers (USACE), and the Federal Highways Administration (FHWA). The cited procedures generally relate the recommended riprap size to flow velocity because alternative parameters such as shear stress have historically been difficult to visualise, compute, and measure.

Austroads and ARR guidance manuals cite different methods for sizing riprap associated with bridges, culverts, floodways, energy dissipation structures, and channel lining applications; in some cases, the cited methods provide conflicting guidance. Some of the references that serve as a basis for Australian riprap sizing guidance have been superseded by more recent publications that should be incorporated into future editions of Australian guidance documents.

Both Austroads and ARR manuals recommend computing shear stress to determine the potential for mobilising material, but no guidance for applying shear-based rock sizing design criteria is presented. Recent advances in computational methods allow shear-based analyses to be more readily developed for previously impractical applications, leading to the potential introduction of standardised, shear-based, Australian riprap design approaches to supplement velocity-based procedures.

The increasing prevalence of 2D and 3D flood modelling relative to 1D modelling warrants a reappraisal of previously adopted riprap sizing criteria that have traditionally been based on 1D approaches. 2D and 3D results used for riprap sizing are subject to the proper selection of grid sizes, computational methods, turbulence coefficients, and other modelling parameters. A recommended interim approach for estimating stable design riprap size is presented using hydraulic modelling results for velocity, depth, and shear stress.

BACKGROUND

The Use of Riprap in Australia

Relative to other scour countermeasures, the installation of riprap in Australia is a primary scour protection option because it is "abundant, inexpensive, and requires no special equipment" (ARR 2019). Nationwide guidance for the application of hydraulic modelling results to scour protection designs is provided by Austroads and ARR. This paper provides a literature review of the sources that serve as a basis for Australian riprap sizing approaches and recommends selected adjustments to those approaches. Guidance provided by local jurisdictions is only included in this review where referenced in the national guidelines.

Velocity vs Shear

Both Austroads and ARR guidance documents cite velocity-based criteria for sizing riprap. In simplest terms, flow velocities are extracted from measurements or hydraulic models and converted directly into a recommended stone size. In general, the velocity refers to a depth-averaged channel velocity, and the stone size refers to the median diameter (D_{50}) of an individual riprap stone based on total weight of the rock classes. Figure 1 shows an example of a riprap sizing chart based on tabulated values in Austroads (2013a and 2013b).

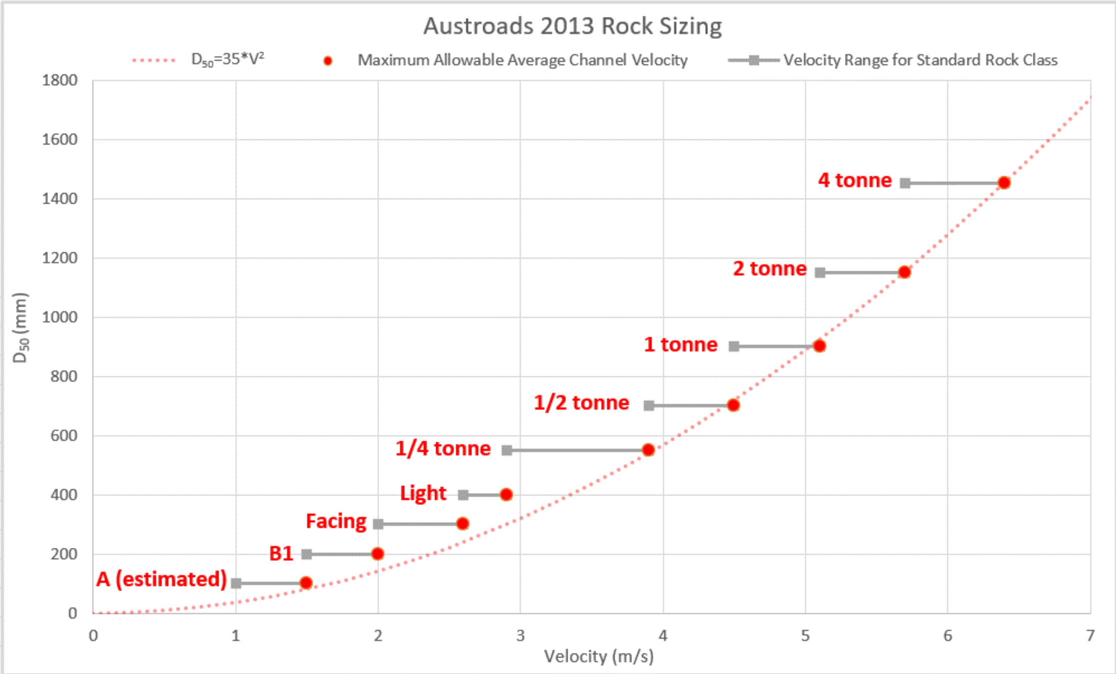

Figure 1. Riprap sizing chart (based on Austroads 2013a, 2013b).

Velocity-based riprap sizing methods can generally be summarised by stating the required rock diameter in terms of a coefficient "a" that is multiplied by the velocity raised to an exponent "b":

$$D_{50} = a*V^b \quad \text{(Equation 1)}$$

The coefficient "a" can vary with side slope, bend angle, density, angularity, safety factor, and other elements. The exponent "b" generally ranges between a value of 2 and 3 among the various available methods. The applicable velocity ranges associated with standard Australian rock classes are shown in Figure 1 against a relationship curve with a value of 35 for "a" and 2 for "b", where the median rock size (measured in milimetres) is 35 times the square of the velocity (measured in metres per second).

Figure 2 shows an alternative relationship where the velocity on the x axis is taken as the bottom velocity rather than a depth-averaged velocity (Austroads 2013b). The maximum allowable average channel velocities from Figure 1 are shown in red for comparison. The effective "a" values range from 20 to 35 for average channel velocities, and from 40 to 70 for bottom velocities, with the exponent "b" held constant at 2 for both curves.

Increasing the applied velocity has an exponential effect on the computed stone weight. Because the stone diameter in Figure 1 and Figure 2 increases with the square of the velocity, and the stone weight increases with the cube of the stone diameter, doubling the velocity results in a 64-fold increase in stone weight. Using the relationship shown in Figure 1, a 3 m/s flow velocity results in a recommended median stone diameter of 315 mm. Assuming a spherical shape with a specific gravity of 2.65, the equivalent mass of the stone is 43 kg. Doubling the flow velocity to 6 ms/, the diameter increases to 1260 mm with an equivalent mass of 2776 kg, 64 times higher.

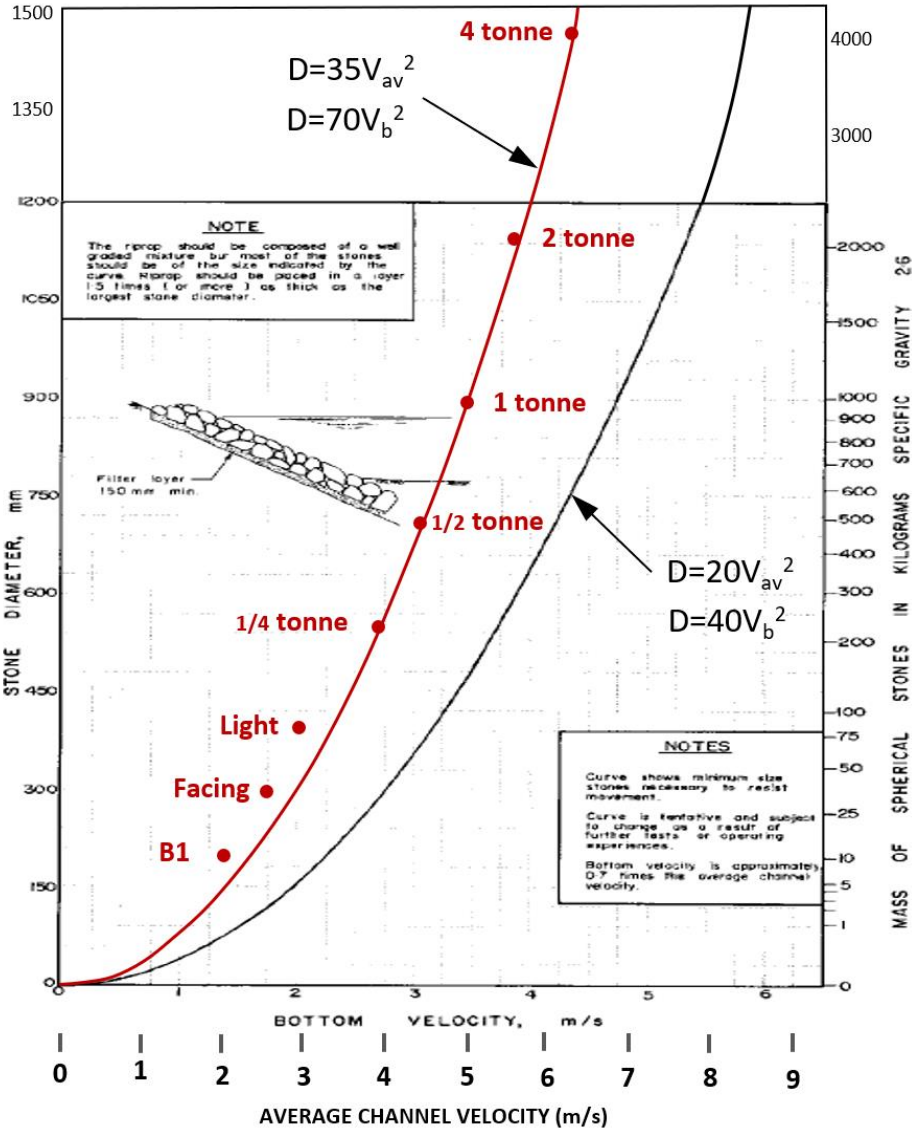

Figure 2. Comparison of riprap sizing in Austroads Part 5 (2013a) and Part 5B (2013b).

Shear-based riprap sizing can generally be summarised by stating the recommended rock diameter in terms of a coefficient or safety factor that is mulitplied by the tractive force, which accounts for the depth and energy gradient of the flow but does not explicitly include the velocity:

$$D_{50} = S_f * \tau \quad \text{(Equation 2)}$$

This approach can be iterative in that the applied S_f required for stability (preventing incipient motion of the particle) varies with Shield's parameter (Shields 1936), which varies with the relative roughness (particle size versus depth). Shear-based analyses are referenced in both Austroads and ARR guidance but without recommended methodologies for implementation.

Published, shear-based, permissible velocity thresholds can generally be traced back to low-gradient canal studies, so the applicability to floodways, bridge abutments, and other hydraulic structures is somewhat limited. In past practice, shear-based methods for rock sizing have sometimes been dismissed due to requirements for iterative solutions. Shear-based methods have generally been preferred in principle, but velocity could be more easily computed, visualised, and measured, leading to the more common adoption of velocity-based rock sizing methods (NCHRP 2006). Given recent advances in computational analyses, however, shear-based analyses can now be readily applied using standard flood modelling results.

ANCESTRY

Riprap sizing references cited in ARR and Austroads trace their source material through publications dating back to 1786. The riprap sizing applications cited in the Australian guidance documents are categorised in this review as follows:

1. Channel bed and bank lining (levees, armoured revetments, bank protection/stabilisation)
2. Bridge scour countermeasures (pier and abutment protection)
3. Culvert outlets (rock aprons)
4. Spillways (floodways, energy dissipation structures, overflow spillways, rock chutes)

Channel Bed and Bank Lining

Figure 3 shows ARR and Austroads riprap sizing references for channel bed and bank lining applications along with explanatory notes.

ARR

Australian Rainfall and Runoff: A Guide to Flood Estimation (ARR 2019) does not include specific guidance for channel bed and bank lining, with the exception of a statement that an assessment of bed shear stress is "important" for sediment motion in alluvial channels. No resources or recommendations are provided for the application of computed bed shear stress values in sizing rock protection for channels. The implementation of hardened channel banks is generally discouraged in favour of designs that avoid causing instabilities that would require riprap (ARR 2019).

Austroads

The Austroads Guide to Road Design Part 5B Drainage (Austroads 2013b) includes a riprap sizing chart for channel bed and bank lining applications that references the "bottom velocity." The accompanying text refers to "bed velocity" and states that it "can be taken as 0.7 times the average channel velocity." The chart is shown in Figure 2. The chart in Austroads (2013b) is taken from the Queensland Department of Transport and Main Roads Road Drainage Manual (QDTMR 2010). The 2010 manual has been superseded by 2015 and 2019 versions that do not include the figure. QDTMR 2019, in turn, refers back to Austroads (2013b) for channel riprap sizing applications.

The riprap sizing chart in QDTMR 2010 is taken directly from an earlier version of the Roadway Drainage Design Manual (QDTMR 2002) in which the figure is cited from Rouven et al (1984). The citation is incorrect and presumably refers to a vegetative lining paper produced by Kouwen et al (1984) that does not reference riprap sizing. The reference list in QDTMR 2002 includes the USBR Hydraulic Design of Stilling Basins and Energy Dissipators (USBR 1984) which includes a version of Figure 2 in US Customary units without the explanatory note about converting average velocity to bed velocity.

USBR (1984) cites an unpublished Masters Thesis manuscript by Nicholas Berry (1948), in which the graduate student compiled six previous velocity-based rock sizing equations and averaged them. The sources referenced by Berry include the results of flume tests, the earliest of which were conducted by Du Buat, who published his findings in 1786. The theoretical background equations for Du Buat's experiments are taken from Brahms (1753), who documented economic damages associated with the Great Christmas Flood of 1717, which caused dike breaches that resulted in an estimated 14,000 fatalities across Europe. Brahms found that the rock weight required to resist motion and prevent dike breaching varies with the "square cube" of the velocity, or the 6^{th} power, which resolves to a "b" exponent of 2 in Equation 1.

The use of Berry's adopted average "a" values was confirmed by a number of subsequent studies, including early iterations of USBR stilling basin design guidance (USBR 1956). USBR 1984 includes prototype testing that confirms the use of Berry's bottom velocity values, but bases the measured velocities on unconverted average velocities, stating that the results are tentative and require further analysis. It should be noted that while QDTMR (2002) includes a velocity-based riprap sizing chart, it recommends that rock sizes should "more accurately" be based on boundary shear stress. No guidance is provided on the application of boundary shear stress to riprap sizing.

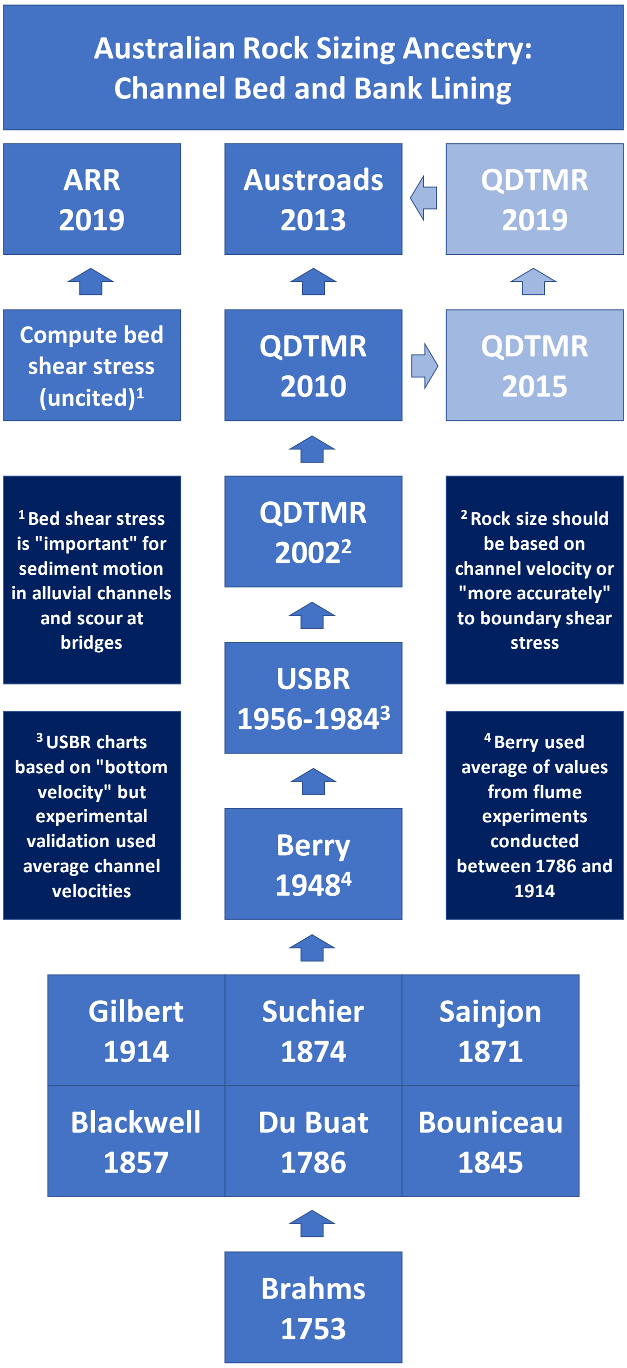

Figure 3. Riprap sizing references for channel bed and bank lining.

Bridge and Scour Countermeasures

Figure 4 shows ARR and Austroads riprap sizing references for bridge scour countermeasure applications along with explanatory notes.

ARR

ARR (2019) cites the QDTMR Bridge Scour Manual (2013) for riprap sizing related to bridge piers and abutments. ARR (2019) states that models should be used to identify bed shear stress increase locations for scour protection, but it does not cite sources for the listed shear equations or methodologies for applying bed shear stress to riprap sizing.

QDTMR 2013 has been superseded by a 2019 version that defers to Austroads (2019) for riprap sizing. The riprap methodologies presented in QDTMR 2013 rely on the FHWA manual Bridge Scour and Stream Instability Countermeasures (2009) which is published as Hydraulic Engineering Circular (HEC) 23. HEC 23 cites the 1936 paper Construction of Dams by Dumping Stones into Flowing Water by Sergey Isbash (1936) as the original source of the background equations. Isbash based his recommendations for "a" values (Equation 1) on experiments in Russian river channels conducted in 1930, with results originally published in Russian in 1932. Isbash used a "b" value of 2 based on Airy's review of Shelford's work on the Tiber River (Airy 1885).

Austroads

The Austroads Guide to Bridge Technology Part 8: Hydraulic Design of Waterway Structures (2019) recommends using HEC 23 for pier riprap sizing (for existing structures only) and Main Roads Western Australia (2006) for abutment riprap sizing. MRWA (2006), in turn, refers to Austroads Waterway Design: A Guide to the Hydraulic Design of Bridges (1994) for the adopted riprap sizing tables. Austroads 1994 derives the tabulated values from an equation provided in the 1960 California Department of Public Works Highways Manual (CPDW 1960). The CPDW equation does not include reference details but can be derived directly from the equation developed by Isbash (1936). CPDW (1960) was superseded by updates in 1970 and 2000 that included the revised Isbash equation and introduced alternative riprap sizing methods.

A 2006 National Cooperative Highway Research Program (NCHRP) report sponsored by the American Association of State Highway and Transportation Officials (AASHTO) and FHWA re-examined the CPDW method along with several others and recommended dismissing the Isbash equation in favour of a methodology developed by the US Army Corps of Engineers (USACE 1994). The USACE method is based on experimental results and background equations derived from Bogardi (1968), Neill (1967), and Straub (1953). Subsequent Caltrans design manuals have adopted the USACE method for channel riprap sizing as a replacement of the CPDW method (Caltrans 2020).

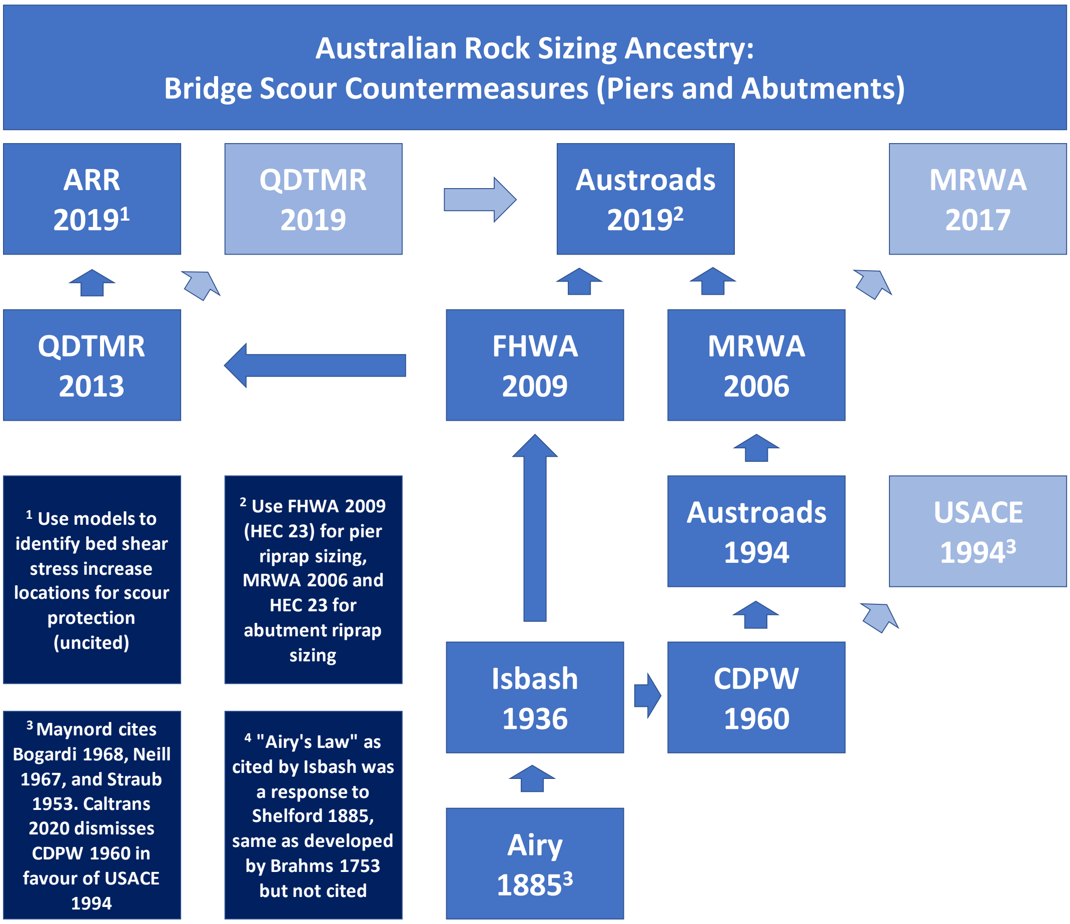

Figure 4. Riprap sizing references for bridge scour countermeasures.

The riprap sizing tables for bridge applications in Austroads (1994, 2013a) and MRWA (2006) are shown graphically in Figure 1. The chart includes supplemental classifications that were provided in MRWA's standard specifications (2009) but are not referenced in Austroads 2013 or included in subsequent printings of the MRWA specifications.

The "a" value of 35 reflected in Figure 1 is based on straight channels with assumed side slopes of 1.5H:1V and a specific gravity of 2.65. The original CPDW documentation recommends factoring the average channel velocity by 4/3 for the outside of bends and by 2/3 for "tangent (parallel)" velocities (CPDW 1960). There is no provision for applying the velocity without factoring, but the recommendations for factoring the velocities were not carried through into the MWRA or Austroads guidance. The equivalent "a" value (Equation 1) associated with the factored velocities results in a range from 15 to 60, representing a potential four-fold difference in stone diameter, with a corresponding 64-fold difference in stone weight.

The gradation recommendations have also been altered. CPDW (1960) states that the "two thirds of stone should be heavier" than the computed stone weight, reflecting the D_{33} value. Austroads (1994, 2013) and MRWA (2006) tables reference the median stone diameter (D_{50}), applying an assumed D_{50}:D_{33} ratio of 1.2 in accordance with NCHRP gradation recommendations (2006). In reference to the recommended gradation, Austroads (1994) states that "at least 2/3 of all rocks in the Class have a greater mass" than the computed value. The Austroads interpretation indicates that riprap gradations should be based on a numerical count of individual stones, which is incorrect.

There are apparent contradictions in NCHRP 2006 and other source materials in which similar statements referring to the "number of particles" seem to indicate a numerical count of the stones in determining the gradation. This misinterpretation can result in median stone weights that vary by an order of magnitude or more. Future editions of Austroads would benefit from clarification of the CPDW method, including gradation requirements; however, the USACE method, which results in a computed D_{30} value, has superseded the source material presented in both ARR (2019) and Austroads (2019). The method is not referenced in the Australian guidance documents and should be added to future editions with clear instructions for gradations and scaling the computed D_{30} value to the D_{50}.

Culvert Outlet Aprons

Figure 5 shows ARR and Austroads riprap sizing references for culvert outlet protection along with explanatory notes.

ARR

ARR (2019) cites a Portland Cement Association handbook (PCA 1964) for the determination of erosive velocities at culvert outlets; however, the reference is provided for natural soils only and not for the determination of design riprap sizing. ARR (2019) includes recommendations for concrete outlet aprons but no references to rock, referring to Austroads (2013) for determining the length and composition of culvert outlet aprons.

Austroads

Austroads (2013b) includes five methodologies for culvert outlet apron sizing. A method developed by Alderson (2006) is cited but is followed by a reference to MRWA 2006 as a "more accurate method." The QDTMR Road Drainage Manual (2010) and VicRoads design manual (2003) are also cited but are specifically limited to "unprotected stream beds" rather than design riprap sizing. The tabulated permissible velocities in Austroads include some discrepancies. Citing the same source material (Neill 1973), for example, Austroads Part 5 (2013a) reports a maximum allowable stream velocity of 5.0 m/s for 300-mm rock, while Part 5B (2013b) reports the original source value of 4.0 m/s. In this instance, a 5 m/s allowable velocity equates to an "a" value of 12 in Equation 1, which is outside of the range of any other cited sources. Other erroneous values are also included in other Austroads tables. 550-mm rock is reported to have a mass of 250 kg in Part 5, for example, while the correct mass of 500 kg is reported in Part 5B. Part 5B also erroneously assigns 1-tonne rock a diameter of 600 mm (a rock size that would have a mass of only 300 kg).

For determination of design riprap size and apron length, Austroads (2013b) reproduces two rock sizing figures for single and mulitple barrel culverts from field guides and fact sheets developed by Catchments and Creeks (2011). A superseded version of the Catchments and Creeks fact sheet for single pipe outlets (2015) states that the recommended values are based on averages of results published by the American Society of Civil Engineers (ASCE 1992), Orange County (OC 1989), and original experimental work in Bohan (1970). The fact sheet for multi-pipe culverts (Catchments and Creeks 2017) states that the rock sizing figure (as reproduced in Austroads 2013b) is based on "complex derivations" with supplemental details derived from Isbash (1936).

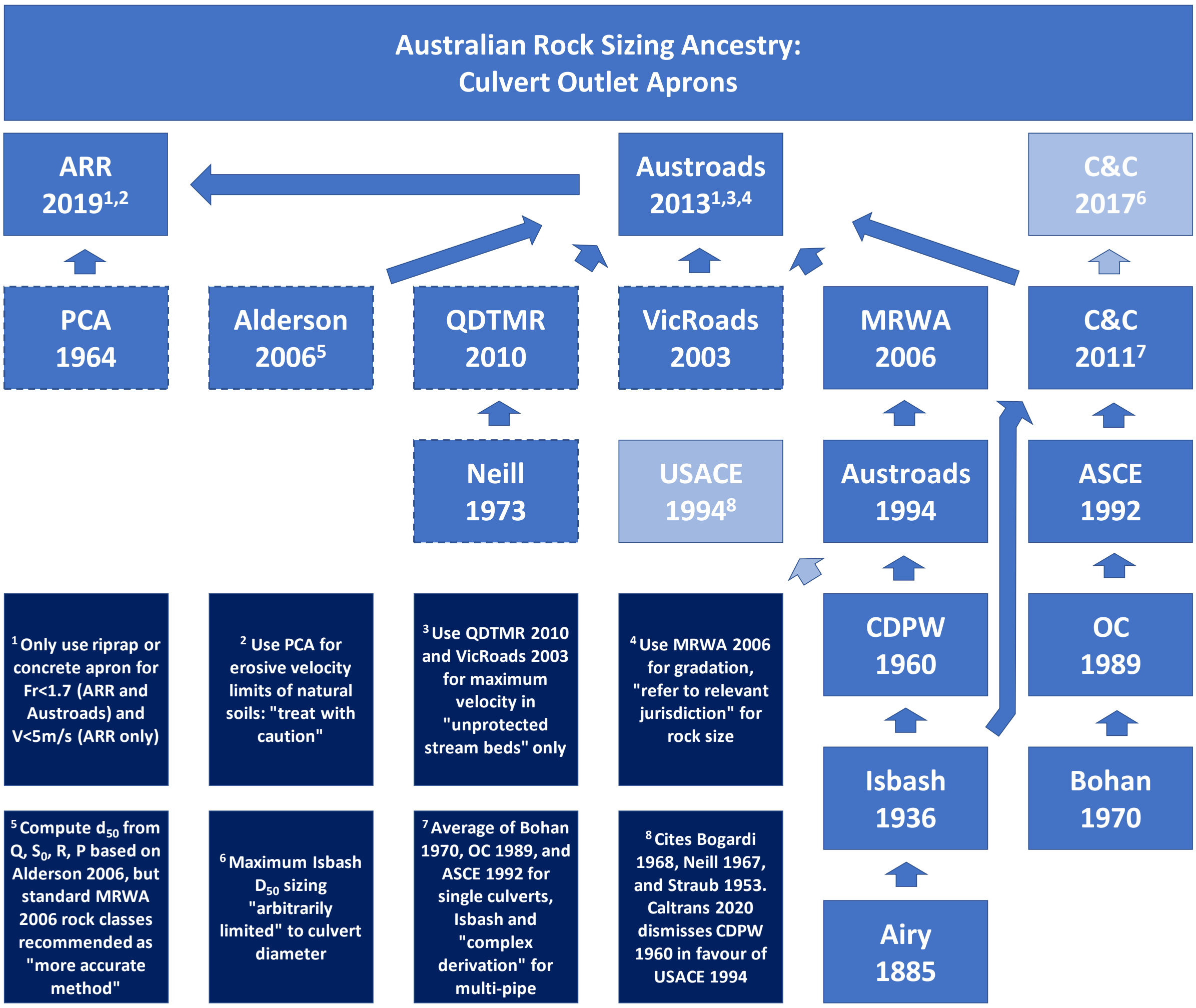

Figure 5. Riprap sizing references for culvert outlet aprons.

Floodways, Spillways, Rock Chutes, and Dissipation Structures

Figure 6 shows ARR and Austroads riprap sizing references for floodways, spillways, and dissipation structures.

ARR

ARR (2019) recommends computing bed shear stress for predicting sediment motion but does not provide guidance on the application of shear stress in designing floodways, spillways, or dissipation structures. ARR (2019) cites the New South Wales document Managing Urban Stormwater (2004), which includes maximum velocity limits for individual stone sizes in overflow spillways. NSW 2004 does not cite a specific sources for the recommended rock sizes but rather states that the limits are "compiled from various sources." The values presented in NSW 2004 are based on a linear relationship between rock size and velocity, effectively representing a "b" value of zero, which contradicts all other referenced rock sizing methodologies. In addition, turf reinforcement systems are recommended for velocities up to 7 m/s, with rock or concrete recommended for velocities exceeding 7 m/s. The 7 m/s threshold is far higher than the upper limits of any other reviewed sources, reflecing an 8-tonne rock based on the standard Austroads approach (Figure 1). This size is impractical for most applications, and any turf subjected to velocities approaching 7 m/s would not withstand the hydraulic forces. These references should be revised in future editions of ARR.

Austroads

Austroads (2013a) refers to MRWA (2006) for floodway riprap sizing and related structures. The derivation of the MRWA values is the same as listed in the previous section on bridge scour countermeasures.

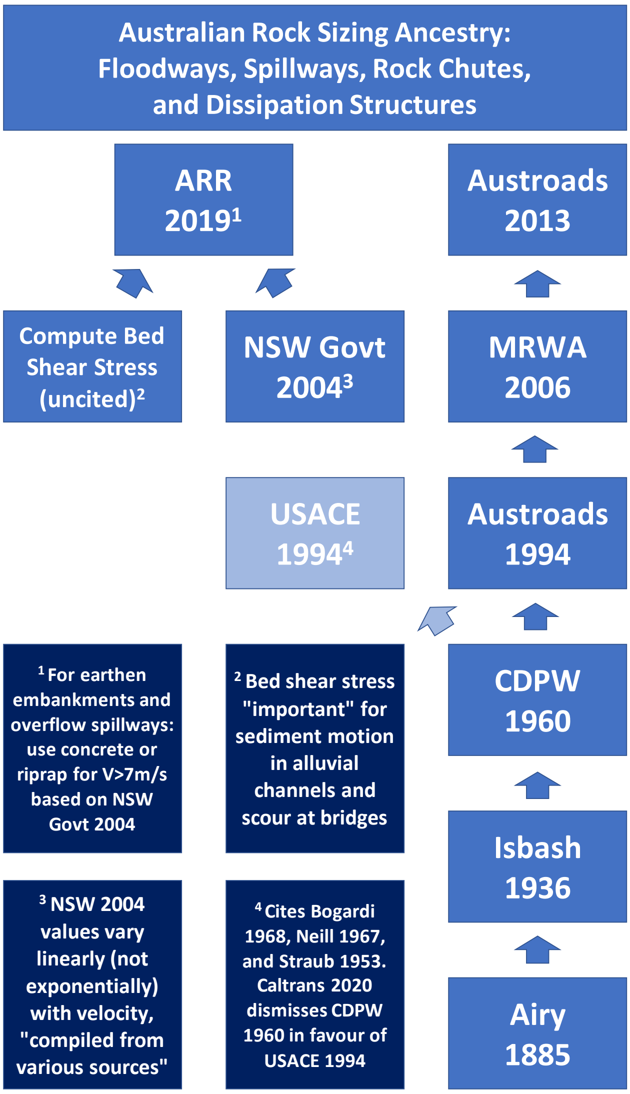

Figure 6. Riprap sizing references for floodways, spillways, and dissipation structures.

SIZING RIPRAP WITH VELOCITY-BASED RESULTS

Table 1 shows the tabulated velocity limits for rock classes as listed in Austroads (2013a and 2013b), which also presents tables for converting the rock class into the median diameter and other gradation parameters; these tables include minimum 0% larger values, which should be revised to provide more practical D_{85} or D_{90} values. The tabulated values apply to floodways and hydraulic structures and are shown graphically in Figure 1. For channel bed and bank lining applications, only a graphical chart is presented, and no tabulated values are provided (Austroads 2013b). Figure 2 shows the graphical chart for channel applications along with a comparison to the tabulated values for hydraulic structures.

The classes shown in red in Figure 2 apply to bridges, culverts, and floodways (Austroads 2013a and 2013b) whilst the black line applies to channel lining (Austroads 2013b). The comparison highlights the extreme difference in rock size that results from application of the two methods for applying velocities. A 6 m/s velocity, for example, requires half-tonne class riprap for channel lining applications; but the same velocity would require 4-tonne stone – eight times the weight – for floodways and bridges. The difference is even more pronounced when average channel velocities are increased for use in bridge pier applications in accordance with HEC 23 guidance.

Table 1. Design of rock slope protection (Austroads 2013).

Velocity (m/s)	Class of rock protection (tonne)	Section thickness, *T* (m)
< 2	None	–
2.0–2.6	Facing	0.50
2.6–2.9	Light	0.75
2.9–3.9	¼	1.00
3.9–4.5	½	1.25
4.5–5.1	1.0	1.60
5.1–5.7	2.0	2.00
5.7–6.4	4.0	2.50
> 6.4	Special	–

Additional methodologies are included in the reference material to convert average channel velocities to maximum velocities for a range of channel bend angles. The velocity-based criteria are typically derived for one-dimensional (1D) hydraulic modelling as most of the adopted methods were developed prior to the widespread use of two-dimensional (2D) and three-dimensional (3D) models.

With the increasing prevalence of 2D flood models and 3D hydraulic structures models, local velocities can be extracted directly from modelling results rather than computed based on typical ratios. Raster calculator applications are available in many GIS and hydraulic programs, allowing an adopted "a" value to be multiplied by the velocity layer raised to a "b" exponent at each computational grid, providing a graphical representation of the resulting D_{50} values.

The FHWA document Two-Dimensional Hydraulic Modeling for Highways in the River Environment (2019) includes recommendations for applying 2D results to riprap sizing. Figure 7 shows an example from that report in which riprap size is plotted graphically. Instabilities and local effects can result in unrealistic spikes in the recommended output, however, as demonstrated by the nearly 5000-mm recommended median rock size highlighted as the maximum recommended size in the figure.

An iterative approach would generally be needed in modelling a riprap design, as the implemented solution would generally affect the underlying terrain as well as the effective roughness. Both 1D and 2D results are depth-averaged and must be scaled to account for vertical effects; whereas 3D results include the vertical variation and may be applied directly.

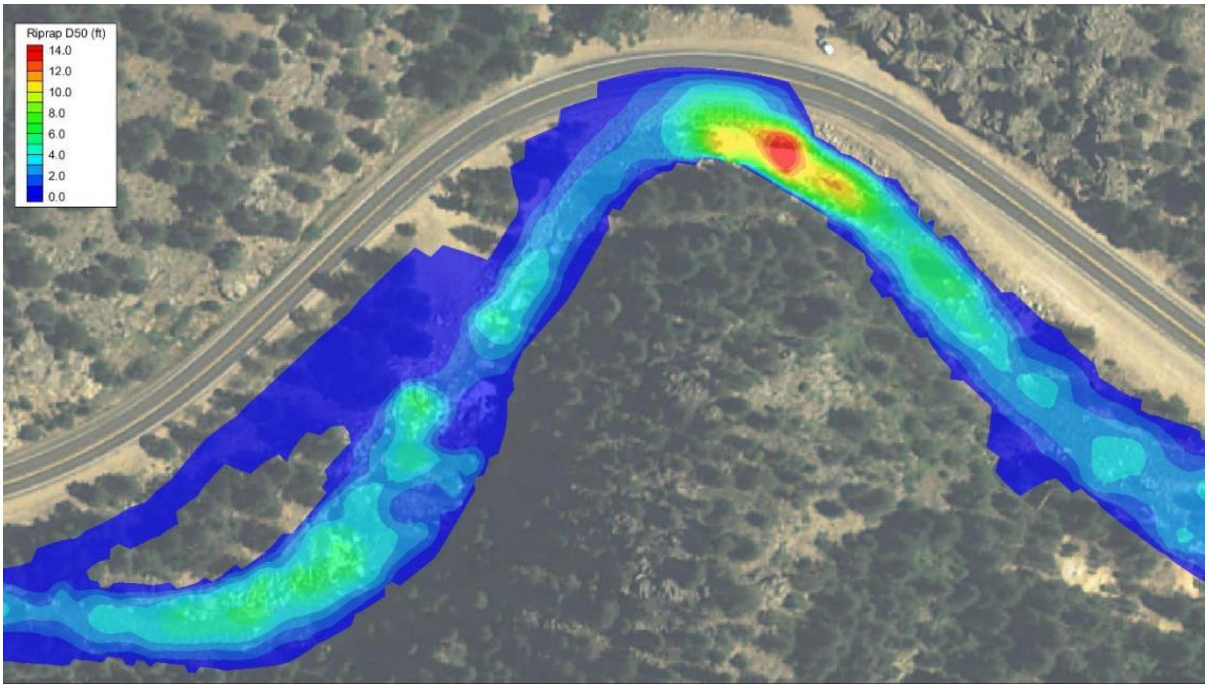

Figure 7. Example of recommended riprap sizing from 2D results (FHWA 2019)

SIZING RIPRAP WITH SHEAR-BASED RESULTS

The Australian guidance documents cited above do not reference shear-based riprap sizing methods despite recommending the computation of shear stress for design purposes.

As an example of a shear-based rock sizing method, the U.S. Army Corps of Engineers' Ecosystem Management and Restoration Research Program (EMRRP) has adopted shear-based stream stability thresholds that were compiled by the U.S. Soil Conservation Service (reorganised as the U.S. Natural Resources Conservation Service) in the publication Stability Thresholds for Stream Restoration Materials (Fischenich, 2001).

Table 2 shows one of the material tables in the EMRRP publication, correlating maximum permissible shear values and shear velocity values to individual rock classes. Metric conversions have been added as appropriate for clarity. The published values are nearly identical to similar tables developed by other entities (USDA 2008, USGS 1986, and FHWA 2010) and are based on relationships determined for canal studies beginning in the 1920s (Julien 1995, Chang 1988, Chow 1959, and Fortier and Scobey 1926). The source study results are typically limited to particle sizes of 100mm or less, and the larger rock size recommendations in Table 2 are based on extrapolations of the linear relationship with a constant Shields parameter.

Table 2. Limiting shear stress by particle size (Fischenich 2001).

Rock class	Particle diameter	Angle of repose	Critical shear stress	Critical shear velocity	Particle diameter	Critical shear stress	Critical shear velocity
Class name	d_s *(in)*	ϕ *(deg)*	τ_{cr} *(lb/sf)*	V_{*c} *(ft/s)*	(mm)	(Pa)	(m/s)
Boulder							
Very large	>80	42	37.4	4.36	2032	1791	1.33
Large	>40	42	18.7	3.08	1016	896	0.94
Medium	>20	42	9.3	2.20	508	445	0.67
Small	>10	42	4.7	1.54	254	225	0.47
Cobble							
Large	>5	42	2.3	1.08	127	110	0.33
Small	>2.5	41	1.1	0.75	64	53	0.23
Gravel							
Very coarse	>1.3	40	0.54	0.52	33	26	0.16
Coarse	>0.6	38	0.25	0.36	15	12	0.11
Medium	>0.3	36	0.12	0.24	8	6	0.07
Fine	>0.16	35	0.06	0.17	4	3	0.05
Very fine	>0.08	33	0.03	0.12	2	1	0.04
Sands							
Very coarse	>0.04	32	0.01	0.070	1.0	0.5	0.021
Coarse	>0.02	31	0.006	0.055	0.5	0.3	0.017
Medium	>0.01	30	0.004	0.045	0.3	0.2	0.014
Fine	>0.005	30	0.003	0.040	0.13	0.1	0.012
Very fine	>0.003	30	0.002	0.035	0.08	0.1	0.011
Silts							
Coarse	>0.002	30	0.001	0.030	0.05	0.05	0.009
Medium	>0.001	30	0.001	0.025	0.03	0.05	0.008

Compilations of over thirty difference sources by USBR (1952) and Catchments and Creeks (2021) have confirmed the linear relationship between the critical tractive force and the effective diameter of larger particles (typically gravels and cobbles exceeding 10mm in diameter), with representative S_f values (Equation 2) varying by +/- 50%.

Figure 8 compares the EMRRP values to a Shields diagram for critical tractive forces (1936) along with a reference to a 1:1 relationship between shear stress and rock size, representing a constant Shields parameter of 0.063. This relationship predicts incipient motion of particles when the shear stress measured in pascals (N/m^2) exceeds the particle size in mm. Incipient motion should be avoided in riprap designs, so additional factors of safety are needed to provide stable designs.

Becaused shear stress is recommended for analyses in ARR and Austroads documents, shear-based criteria for riprap sizing should be included as a design option in future iterations of Austroads and ARR guidance documents, including recommended safety factors.

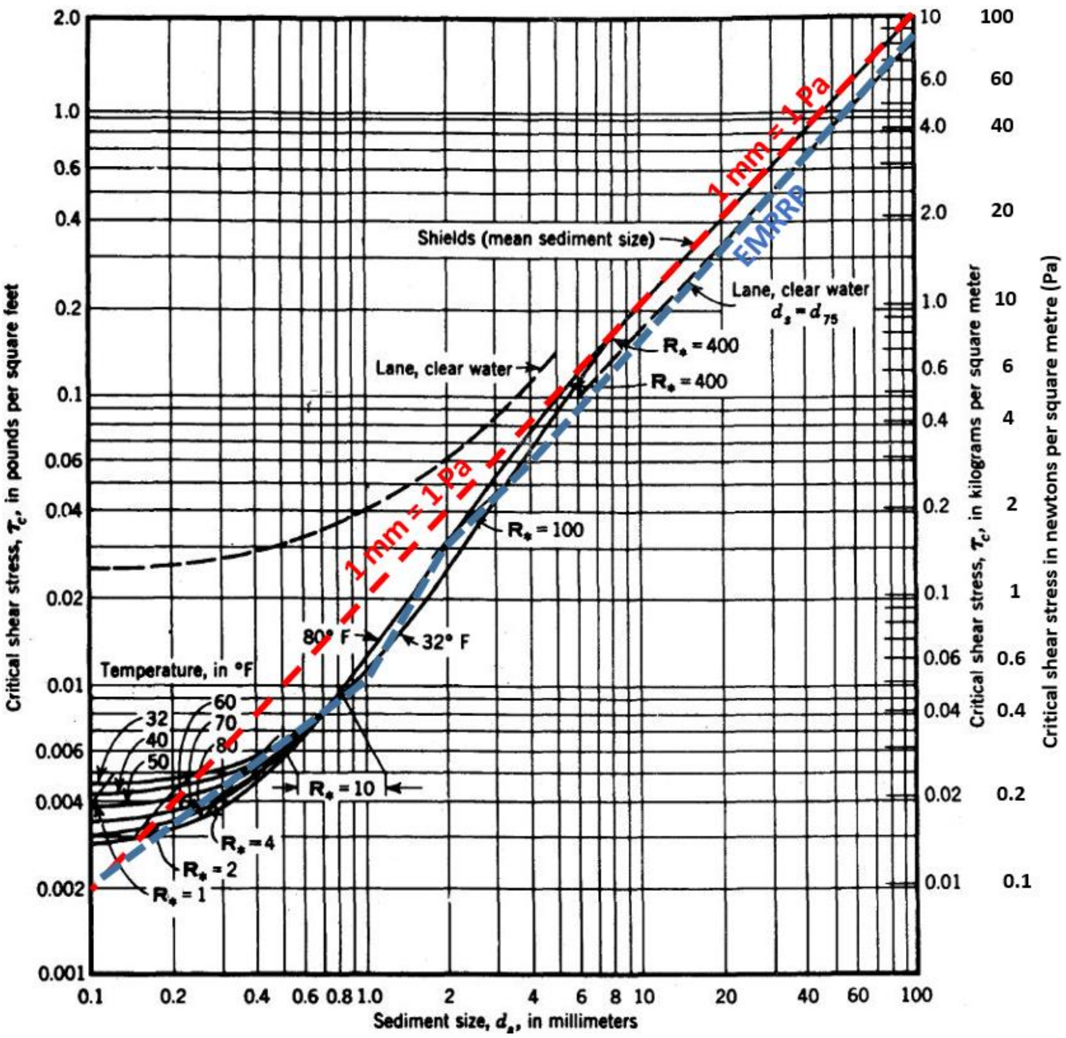

Figure 8. Shields diagram (1936) with EMRRP critical thresholds.

The Australian Cooperative Research Centre for Catchment Hydrology (CRCCH) developed a riprap sizing software program named RIPRAP, which was released as part of the eWater Toolkit in 2005 The spreadsheet-based RIPRAP program applies a critical shear stress rock sizing approach using a constant Shields coefficient of 0.047, with correction factors applied to account for bend angles, bank slopes, specific gravity, and safety factors.

The theoretical background to the RIPRAP spreadsheet aligns with the shear-based methods in the sources presented above. The documented maximum angle of repose (46°) is markedly different than the constant 70° degree assumption in the CPDW method (1960) that serves as a background for Austroads riprap sizing tables (2013a and 2013b). This CPDW assumption has been called into question, however, and the method has been dismissed in current guidance (NCHRP 2006).

RIPRAP computes the median stone size for a range of depths and bank angles for a given energy slope. The program does not incorporate velocity results directly, but the results show the required riprap size increasing with depth. The recommended method outlined in NCHRP (2006) shows the opposite effect, with the required riprap size decreasing with depth; however, this method assumes that a steeper energy gradient is required to maintain constant velocities in shallower flow.

RIPRAP and additional rock sizing guidance by Keller have been in frequent use in Victoria but are not referenced in the ARR or Austroads guidance (Keller 2005). The program and associated documentation have not been updated since 2005 and are intended for 1D hydraulics. Where energy gradients can be readily extracted from 1D models for use in the spreadsheet, compiling results from 2D or 3D models with multi-directional flow can be more complex. The incorporation of the methodology into the national guidance is recommended, updated to accomodate modelling results for the computed shear stress and flow depth, with the side slope and specific gravity of the riprap incorporated into an S_f value (Equation 2) for display in 2D and 3D hydraulic modelling software.

COMPARISON OF VELOCITY AND SHEAR-BASED RIPRAP SIZING METHODS

In a research project conducted for Rio Tinto Iron Ore, Price and Westwater (2020) extracted gridded depth, velocity, and shear stress results from 1D and 2D hydraulic models of 400 channel and culvert configurations typical of mine site drainage infrastructure. Figure 9 shows selected riprap sizing results for straight, trapezoidal channels up to 6m wide and up to 2m deep.

Velocity-based results were computed using an "a" value of 35 and a "b" value of 2 in Equation 1. Shear-based results were computed using a safety factor of 1.25 in Equation 2 (resulting in an effective safety factor of 2.0 by mass). Both maximum localised results and average channel results were applied for comparison. As shown in the results, the shear-based recommendations resulted in substantially smaller recommended rock sizes for the simulated channels, indicating potential cost savings in implemented designs. The results in Figure 9 do not account for velocity reductions in average channel velocities recommended in the original source material (CDPW 1960) but not carried forward in Austroads (2013a, 2013b). Accounting for the velocity reduction would bring the velocity and shear-based results to more equivalent values.

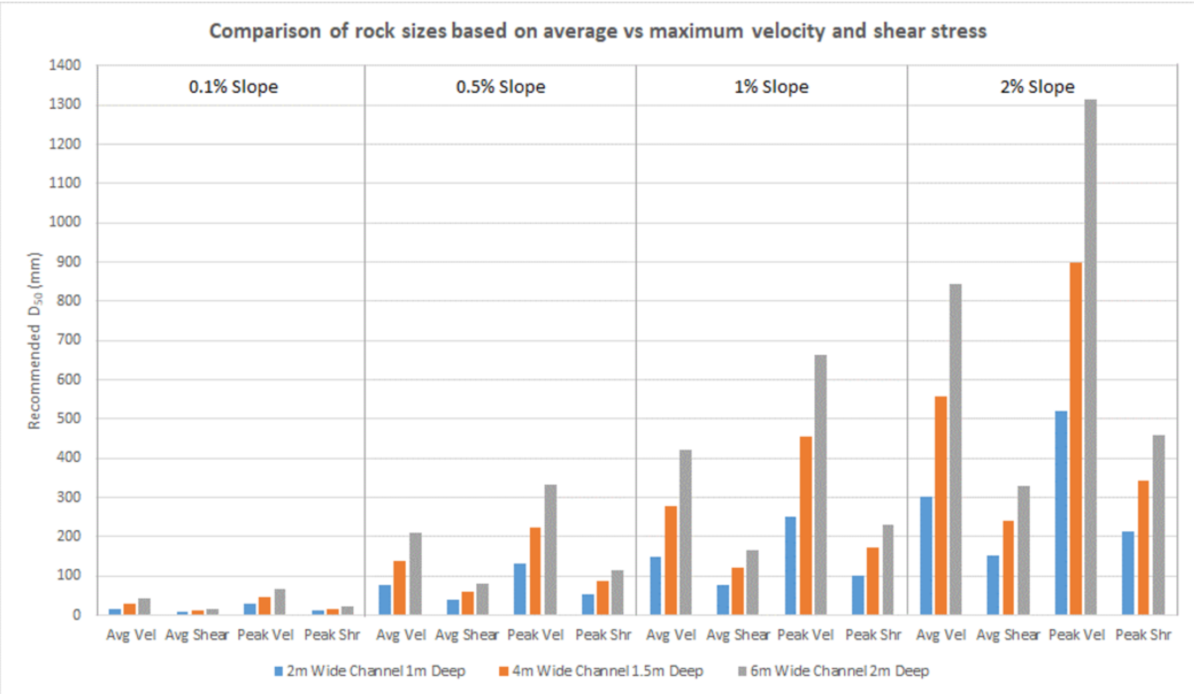

Figure 9. Comparison of channel rock sizes based on Austroads velocity criteria vs shear stress (based on Price and Westwater 2020).

SIZING RIPRAP WITH MAYNORD'S EQUATION

Some of the riprap sizing approaches in Austroads (2013a, 2013b) and ARR (2019) have been superseded by the 1994 Corps of Engineers riprap sizing method (USACE 1994). The basic equation for determining stone size can be derived from a modification of the shear stress equations, but it does not use shear stress explicitly, instead relying on depth-averaged velocity and local depth of flow:

$$D_{30} = S_f C_s C_V C_T d \left[\left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{1/2} \frac{V}{\sqrt{K_1 g d}} \right]^{2.5} \quad \text{(Equation 3)}$$

where:

D_{30} = riprap size of which 30 percent is finer by weight

S_f = safety factor

C_S, C_V, and C_T are coefficents for angularity, channel bends, and thickness d = local depth of flow at a point 20% upward along the embankment

γ_w = unit weight of water

γ_s = unit weight of stone

V = local depth-averaged velocity at a point 20% upward along the embankment

K = side slope correction

g = gravity

This equation was presented in Stephen Maynord's Stable Rip Rap Sizing for Open Channel Flows (Maynord 1988), supported by a range of validation tests performed on very large ("near-prototype") physical models. Velocities are assumed to be derived from 1D methodologies; applying depth-averaged 2D velocities to the equation should thus be approached with caution as the coefficients account for both horizontal and vertical variations that are present in channel bends.

Maynord's equation shows riprap size being inversely proportional to the depth (by the power of 0.25) for the same velocity. This concept is somewhat counterintuitive from a flood hazard perspective: If the flood hazard is defined as the product of depth and velocity, the flood hazard increases linearly with increasing depth for a constant velocity. However, the inverse relationship between particle size and depth aligns with historical findings that smaller canals require larger particle sizes to resist erosion than large canals under the same velocity (NCHRP 2006), a notion that was also confirmed by Maynord's experimental tests.

Stone size in Maynord's equation is based on the D_{30} and must be converted to a median diameter if required for design gradation specifications. Figure 10 shows a graphical representation of Equation 3, with the Austroads 2013 rock classes plotted for comparison (converted from D_{50} to D_{30} using a ratio of 1.2). The stated range of applicability in Maynord's 1988 study is a depth-to-D_{30} ratio falling between 4 and 50. These bounds have been added to Figure 10, with the applicable area shown in green and the non-applicable area shown in red.

The plotted area shows that the Austroads sizing (based on Isbash 1936) co rresponds to a depth of approximately 1m, requiring a larger rock size than the deeper flows. This may be further explained by the limitation of Maynord's work, which assumes slopes of less than 2%, whereas the Austroads guidelines are intended to apply to floodway slopes and energy dissipation basins where flow may approach riprap at slopes steeper than 2%. Additional limitations for Equation 3 include low turbulence systems only, with Froude Numbers less than 0.8.

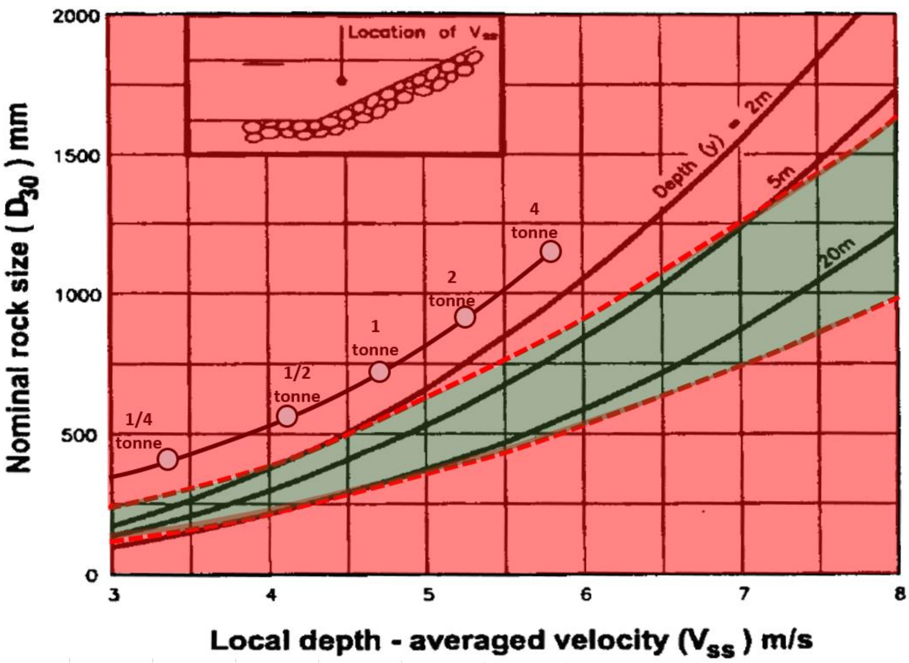

Figure 10. Applicability of Maynord's equation (from BCME 2000).

It should be noted that the C_v coefficient intended to reflect vertical variation of velocities at bends in Maynord's equation is applied outside of the velocity term. Adjustments applied directly to the velocity will be much more pronounced than adjustments applied to the outside coefficient. A C_v of 1.25 applies a 25% increase to the recommended rock diameter, for example, resulting in twice the recommended stone weight; however, this represents a velocity increase of only 10% if the adjustment were to be applied directly to the velocity. Regarding the power of 2.5 applied to the velocity in Equation 3:

> "The extreme values of the power are from 2 to 3. A power of 2 results in the Isbash equation (no dependence on depth) and is generally used when there is no boundary layer development. A power of 3 results from application of existing shear stress and the Manning-Strickler equations and represents the condition of completely developed boundary layer and a relative roughness low enough to yield a constant Shields coefficient. Because most bank and channel riprap proection prolblems fall somewhere between these two extremes, the 2.5 power was adopted for all bank and channel riprap proection problems." (TRB 1993)

USBR (2015) recommends using a minimum of three rock sizing approaches in riprap designs. Because the sources cited by ARR (2019) and Austroads (2013) have been superseded by the Maynord equation, in addition to standard velocity-based and shear-based approaches, Australian projects involving riprap designs should be checked against the currently adopted USACE standards where hydraulic parameters fall within the stated limitations.

Recommended rock sizes can be generated from 1D, 2D, and 3D hydraulic results; however, checking Maynord's equation against hydraulic results involves additional considerations. The extracted depths and velocities, for example, are intended to be taken from specific points measured along the embankment slope; final results should thus incorporate geometric changes in the modelling.

CONCLUSIONS AND RECOMMENDATIONS

Some of the methodologies referenced in Austroads (2013) and ARR (2019) guidance have been superseded by more recent publications. The guidance documents should be updated to reflect the latest iterations of the cited references where applicable and should incorporate recommendations for interpretation of 2D and 3D model results. In the interim, rock sizing should be checked with a minimum of three methods for sizing riprap due to uncertainties and limitations of each method:

1. Velocity-based: D_{50}=a*V^2 (adopted from CPDW 1960) using values of "a" ranging from 20 (channels) to 35 (structures) without vertical scaling, with D_{50} in mm and V in m/s.
2. Shear-based: $D_{50} = S_f * \boldsymbol{\tau}$ with a recommended minimum S_f of 1.25 (effective S_f by weight of 2.0), with D_{50} in mm and V in m/s.
3. Maynord's equation (Equation 3, USACE 1994) where channels are within the stated limitations, with D_{30} (converted to D_{50}) in mm, V in m/s, and d in m.

The adoption of standard approaches that take advantage of 2D flood modelling and 3D hydraulic structure modelling results is recommended, allowing localised velocities to be applied to riprap sizing. Where coefficients are intended to represent lateral flow distribution from average 1D channel results, the use of the coefficients in 2D results should be avoided to prevent double-counting the effect. While 2D models account for lateral variation, the results are depth-averaged, and adjustment of resulting velocities may be required to account for vertical effects.

Inherent safety factors are generally included in velocity-based equations but typically require project-specific adjustments. Where incipient motion is predicted for critical conditions using shear-based methods, additional safety factors should be applied. All methods require additional considerations for steep embankment slopes, sharp channel bends, rounded stones, low density, or other characteristics that deviate from assumed values and could reduce factors of safety.

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