Scour Protection Design Criteria for Mine Site Infrastructure

Krey Price[1], David Westwater[2]

[1]*Surface Water Solutions, 57 Bromfield Drive, Kelmscott, WA 6111, Australia, krey.price@surfacewater.biz*

[2]*Superintendent Hydrology, Rio Tinto, Central Park, Perth, WA 6000, Australia, dave.westwater@riotinto.com*

Abstract

This paper challenges velocity-based rock sizing methodologies traditionally applied for mine site infrastructure drainage management and proposes alternative shear-based methods. Standard velocity-based rock-sizing methodologies are considered to have potential to lead to overdesign of rock armour requirements, resulting in higher costs. The relevance of alternative rock sizing methods for a range of scales is presented in this paper in light of the limitations on total energy resulting from depth and velocity thresholds under typical design conditions. A literature review was undertaken to identify the sources that serve as a basis for standard rock sizing approaches. In past practice, shear-based methods for rock sizing have typically been dismissed due to requirements for iterative solutions. Recent advances in computational analyses mean that shear-based analyses can now be readily adopted for previously impractical applications. Published shear-based rock sizing approaches were reviewed for this study; these methods generally show a linear relationship between the critical tractive force and the effective diameter of the particle. In order to assess the typical distribution of shear stress and velocities a range of channel and culvert configurations were assessed by application of the USACE HEC-RAS program. Maximum velocity and shear stress profiles were extracted from the model results and applied in rock sizing criteria. A 1:1 ratio between shear stress in pascals and median rock size (D50) in millimetres was developed based on a range of reviewed data sources and a safety factor of 2.0 was achieved against incipient motion through a 25% increase in diameter. Recommended armour rock gradations were developed using the shear-based method and compared to results from the standard velocity-based approach. The comparison shows that the shear-based method generally results in a smaller rock size than the velocity-based approaches, indicating that there is a fair degree of conservatism in the application of the velocity-based criteria for the simulated scenarios.

Keywords: Drainage, Flood Management, Erosion, Scour, Hydraulics

Introduction

Standard velocity-based rock-sizing methodologies are generally intended for the protection of bridge abutments/piers and other applications with relevant flow depths. Much of the published rock sizing guidance is based on assumed depth-to-stone size ratios that may differ from design conditions at typical mine-site drains and culvert inlets and outlets. Figure 1 presents a graphical representation of one example of velocity-based rock sizing in common use in Australia. The velocity thresholds are compiled from the Austroads Guide to Road Design (2013), which, in turn, is derived from the Main Roads Western Australia Floodway Design Guide (2006). This paper provides a literature review of the sources that serve as a basis for this Australian rock sizing approach and compares velocity-based methods with alternatives that use shear stress.

Background Theory

Velocity vs. shear: Many published sources for rock sizing methodologies include both empirical and derived relationships between hydraulic conditions and the recommended gradation and sizing of armour rock. Empirical relationships typically include safety factors for design, while some derived

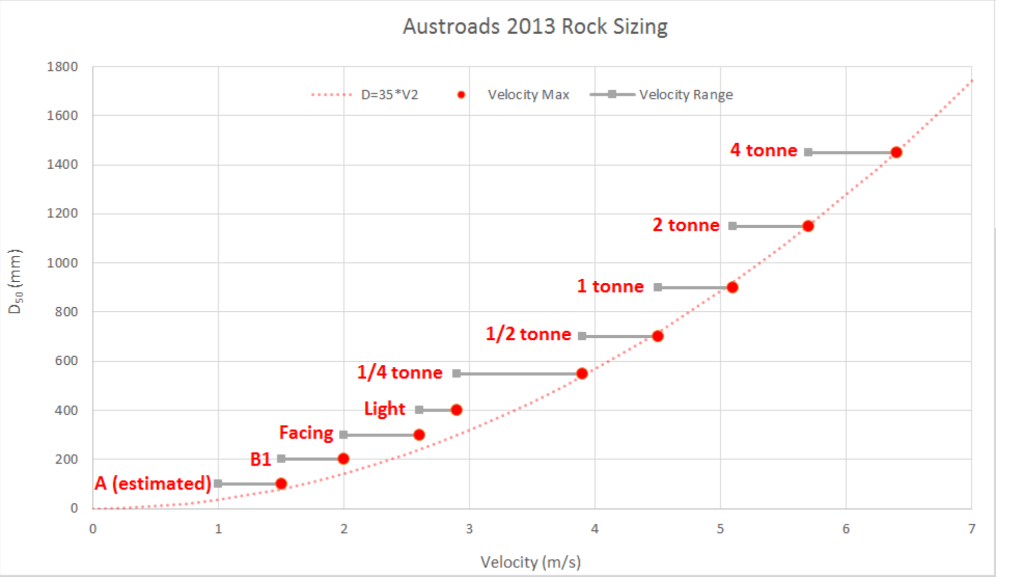

Figure 1 *Rock sizing data compiled from the Austroads Guide to Road Design (2013) and the MRWA Floodway Design Guide (2006).*

relationships predict critical thresholds for incipient motion. Additional considerations are required where characteristics deviate from assumed values and could reduce factors of safety.

Published rock sizing methodologies can typically be separated into two categories:

1. Velocity-based methods which are simplified relationships that recommend an armour rock gradation based on velocity only.
2. Force-based approach methods which may also include the fluid velocity in some form along with the addition of other parameters such as the depth, hydraulic radius, shear stress, or other flow characteristics to account for the tractive forces acting on the stones.

A commonly applied alternative to velocity-based rock sizing is the use of shear stress as the primary indicator of rock size requirements. In simplified form for uniform flow conditions, shear stress is equal to the product of the unit weight of water (γ), the hydraulic radius (R), and the unit-less energy gradient (S):

$$\tau = \gamma R S \qquad \text{(Equation 1)}$$

Figure 2 and Table 1 illustrate an example of two different uniform flow conditions in which the velocities are identical, but the shear stress differs. The scenarios in Figure 2 represent substantially different open channel flow conditions with identical velocities. The smaller channel requires a steeper energy gradient to represent the same velocity; this results in a higher shear than in the larger channel. The results presented are based on a simplified equation for uniform, normal-depth flow; in reality, flow conditions in the vicinity of a bridge or culvert inlet and outlet can be much more complex, and the calculation of shear stress can be highly iterative. In the past, these iterative solutions were difficult to calculate. The U.S. National Cooperative Highway Research Program (NCHRP 2006) compiled previously applied rock sizing methodologies. Referring to computation efforts in the 1970s and 1980s, the NCHRP report states that shear-based methods are preferable to the velocity-based methods, but that velocity-based methods have generally been applied because "most designers prefer velocity-based methods, and shear is difficult to measure and little information regarding shear stress on riprap was available." With the increasing capacity of

Table 1 Comparison of velocity and shear stress for armour rock sizing.

Case	Discharge	Side Slope	Base Width	Top Width	Velocity	Shear from R
	m^3/s	H:V	m	m	m/s	Pa
1	300	2	10	26	4	125
2	35	2	2	9	4	180

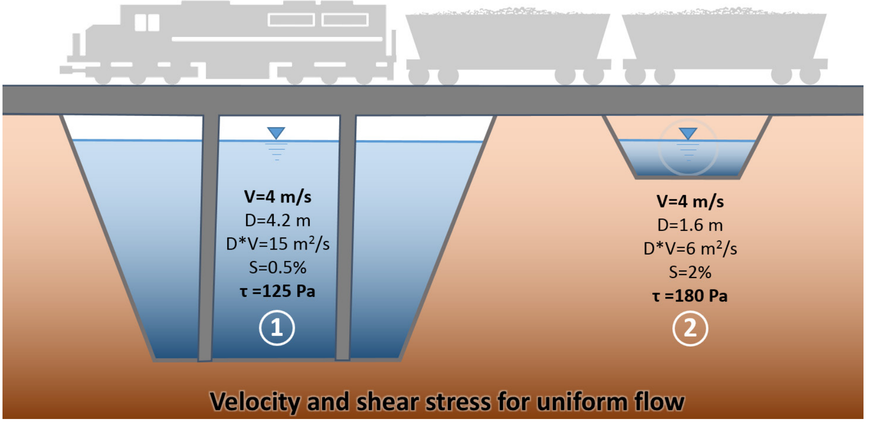

***Figure 2** Comparison of velocity and shear stress for armour rock sizing (Indicative scale for reference only).*

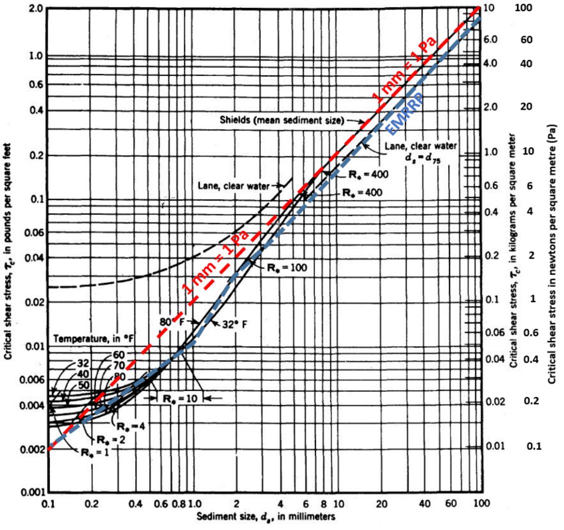

***Figure 3** Relationship between shear stress and rock diameter (Annotated from USDA SCS 1983).*

two-dimensional (2D) hydraulic modelling applications, previous limitations based on the complexity of iterative solutions may no longer be applicable, and shear-based rock sizing approaches are now viable alternatives to velocity-based approaches.

Incipient motion of a particle occurs when the forces acting on the particle exceed the forces resisting motion. The critical conditions required to produce incipient motion are often represented by equations that make use of the Shields parameter, which is a unit-less number that relates the fluid force on a particle to the weight of the particle. Figure 3 shows the relationship between rock size and critical shear stress based on a study by Shields (1936), Meyer-Peter and Mueller (1948), and Lane (1955). The added dashed line shows a 1:1 relationship between shear stress in pascals and an equivalent median rock size in millimetres, which corresponds to a typical Shields Number of approximately 0.063. When safety factors are applied to linear dimensions such as the median diameter of the rock, the actual safety factor against motion increases in cubic relationship. A 25% increase in diameter, for instance, increases the particle weight by almost 100%, providing an effective safety factor of 2.0. Based on the studies cited above, for the purpose of this paper, a 1:1 ratio between shear stress and rock size is assumed for incipient motion, with a 25% increase in D_{50} (corresponding to a 100% increase in W50) applied as a safety factor against mobilisation.

Rock Sizing Methods – Literature Review

The following summarises selected rock sizing methodologies and the evolution of the original source data that served as a basis for the criteria currently adopted in Australia. The current Austroads Guide to Road Design Part 5 (Austroads 2013) incorporates velocity thresholds from several previous publications, including the 1994 Austroads Waterway Design guide (Austroads 1994). Some of the limitations cited in the 1994 guidance have not been carried forward into the 2013 version. Specifically, the 1994 guide cites a 1960 California Highways manual (CDPW 1960) as the source for the rock sizing methodologies. A 1.5H:1V batter slope and specific gravity of 2.65 are assumed, along with bank velocities of two-thirds of the average channel velocity in straight reaches and four-thirds of the average channel velocity along bends. The recommended rock size is increased to convert from a numerical count of individual rocks to a recommended median diameter (D_{50}) by total weight in the Austroads manual. The Austroads guidance generally appears to be intended for adoption in large channel designs; as such, the recommendations should be interpreted with caution when applied to smaller-scale applications. Main Roads Western Australia (MRWA) generally follows Austroads guidance for selecting rock class based on velocity, with the addition of several supplemental rock classes, including two sub-facing-class rock specifications.

The Austroads Guide makes frequent reference to the United States Federal Highway Administration (FHWA) series of Hydraulic Engineering Circulars (HEC) and Hydraulic Design Series (HDS) documents that relate to highway design. The documents with the most relevance to scour protection for culvert inlet and outlets are HEC 11, HEC 15, HEC 23, HEC 26, and HDS 5. Some of the shear-based methods presented in HEC 15, HEC 23, and HEC 26 are acknowledged to be iterative in nature. The 1960 CABS method (CDPW 1960) that was originally used as a basis for the Austroads and MRWA velocity-based approaches was superseded by a 1970 edition and the 2000 CABS method (CDT 2000). A 2006 NCHRP report re-examined the CABS methods along with several others rock sizing approaches, and recommended falling back on the 1994 U.S. Army Corps of Engineers EM 1110-2-1601 method (USACE 1994) for riprap sizing, essentially superseding the methods that serve as a basis for Austroads and MRWA. The 1994 U.S Army Corps of Engineers riprap sizing method (USACE 1994) traces back to equations presented in Stephen Maynord's 1988 Stable Rip Rap Sizing for Open Channel Flows (Maynord 1988) and subsequent validation tests performed on very large physical models. The USACE method is presented in the form of an equation that shows riprap size being inversely proportional to the depth for the same velocity.

In general, the application of the rip-rap equation is intended for large channels; for smaller channels, the 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 in the publication Stability Thresholds for Stream Restoration Materials (Fischenich, 2001). The rock sizes presented in the EMRRP publication tables are based on a nearly linear relationship between shear stress and particle size for particles above 10mm in diameter. Nearly identical values have also been adopted by the U.S. Forest Service (USDA 2008), the U.S. Geological Survey (1986), and the U.S. Federal Highway Administration (2010), which trace their sources to U.S. canal studies conducted in the 1920s. Figure 3 presents the SI unit conversion of the tabulated values along with a comparison to values derived from the use of a typical Shields Number of 0.063 with a 1:1 relationship between critical shear stress in pascals and rock size in millimetres. The 1:1 relationship provides a slightly less conservative rock size than the published values. For the cases shown in Figure 2, application of the 1:1 relationship would result in a recommended median rock size of 200 mm for the large channel and 320 mm for the smaller channel. Applying a 25% safety factor yields a recommended D_{50} of 250 mm for the large channel and 400 mm for the small channel. A comparison to velocity-based rock sizing according to Austroads, the velocities of 4.0 m/s in both channels would yield ¼-tonne class rock with a recommended median rock size of 550 mm. In this case, the shear-based method provides a potential reduction of 30% to 55% in the D_{50} size.

Computational Approach

An assessment of typical shear stress and velocity distributions along drains and at culvert inlets and outlets was performed utilising the USACE HEC-RAS software program for a range open channel and culvert configurations. Recommended rock classes were compiled for each channel and culvert size. Velocity-based criteria were applied using Austroads guidelines in the selection of a recommended D_{50} for armour rock. As a comparison to shear-based methods, a 1:1 ratio between shear stress in pascals and median rock size (D_{50}) in millimetres was applied based on a range of reviewed data sources and field tests. In order to provide a recommended safety factor of 2.0 against incipient motion, a 25% increase in diameter was applied to the critical value of D_{50}. A uniform Manning's roughness coefficient of 0.035 was applied to all channels for consistent comparison of results. Figure 4 summarises the results for the configurations assessed using peak velocities and shear stresses. The velocity-based criteria result in a recommended rock size that exceeds the shear-based recommendations by a factor of approximately 2.6. A comparison of peak results to the average channel velocity and shear stress results is shown in Figure 5. Using the peak values as opposed to the average values results in an average increase of 1.5 times the recommended diameter.

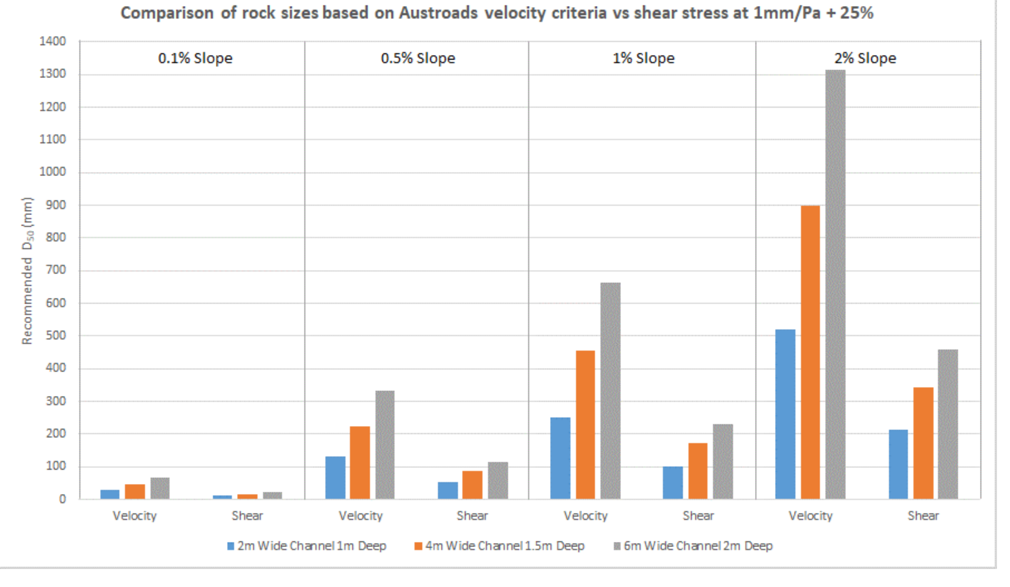

Figure 4 Comparison of channel rock sizes based on velocity criteria vs shear stress.

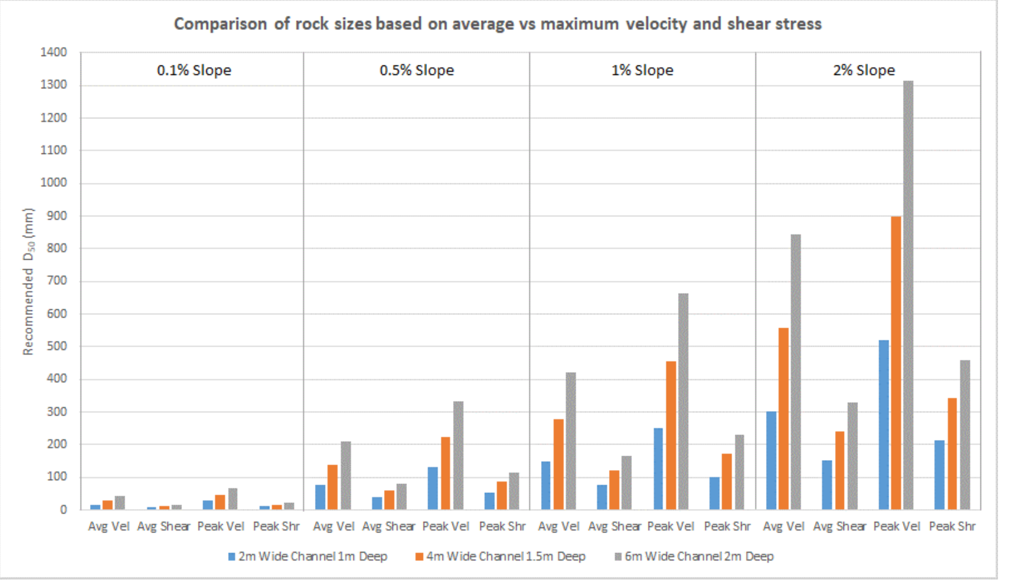

***Figure 5** Comparison of channel rock sizes based on average vs maximum velocity and shear stress.*

Conclusions

Erosion control measures for drain embankments and roadway and rail culverts in the mining sector are typically designed using velocity-based criteria. In Australia, these criteria are published in Austroads and MRWA guidelines. Shear-based criteria have historically been avoided due to computational limitations. Advances in hardware and software allow the application of standardised 2D models to a range of channel and culvert configurations. Velocity-based approaches generally account for the lateral distribution of velocities, and average channel velocities should be applied for riprap sizing under this methodology. The application of localised velocities may cause results to differ from the laboratory or field assessments on which the empirical methods are based. If shear-based criteria are applied, using the maximum channel shear stress is recommended as a conservative approach.

Using the maximum design depths and velocities associated with individual culvert sizes, calculation of maximum shear for application in shear-based rock sizing methodologies generally results in smaller rock size recommendations than the standard velocity-based (Austroads and MRWA) criteria. In order to assess the typical distribution of shear stress and velocities along drains and at culvert inlets and outlets, a range of drain and culvert sizes, configurations, and slopes was entered into the U.S. Army Corps of Engineers (USACE) HEC-RAS program. Average and maximum velocity and shear stress profiles were extracted from the model results and applied in rock sizing criteria. A 1:1 ratio between shear stress in pascals and median rock size (D_{50}) in millimetres was assumed based on a range of reviewed data sources and field tests. In order to provide a recommended safety factor of 2.0 against incipient motion, a 25% increase in diameter was applied to the critical value of D_{50}. A relationship using 1 mm of rock diameter for each pascal of shear stress was applied with a safety factor of 25% on the diameter (resulting in a safety factor of 2.0 by weight or resistance to motion). The proposed shear-based methodology generally results in a reduction of recommended rock sizes in comparison to velocity-based methods. For the range of channel sizes covered in this study (1-2m depth, 2-6m bottom width) the shear-based method resulted in a reduction in the median diameter of approximately 50%. If velocity-based methods are applied for design, shear-based calculations can be presented as a comparison to demonstrate the level of conservatism or additional safety factors inherent in the velocity-based design parameters.

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