MINE WATER SOLUTIONS

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Kia ora koutou – Greetings dear Delegate for the 14th IMWA Congress,

“Welcome to IMWA 2020 New Zealand!”, that’s how we intended to greet you in Christchurch, the largest city on the South Island of New Zealand. We’re sure many of you had planned an itinerary before or after IMWA 2020 to explore our islands and make the most of your time in our remote part of the globe. Sadly, we had to inform our delegates that IMWA 2020 in New Zealand has been postponed in response to disruption by the COVID-19 pandemic on global travel and economic conditions. This was a difficult decision several months ago as the trajectory of the COVID-19 pandemic was less clear than now, but the right decision was made. The New Zealand based Organizing Committee has agreed with the IMWA Executive Committee that another IMWA Conference in New Zealand at a similar time of year and with similar offerings of short courses, field trips and keynote speakers will happen. We hope that the delay, though frustrating, only builds your anticipation and desire to visit New Zealand and participate in IMWA 2022 in Christchurch.

We discussed holding IMWA 2020 online but withdrew from this type of format, because all of us had negative experience with online meetings, and IMWA is a truly international organisation with delegates in every time zone around the globe. We are almost a year into the Pandemic, and electronic ways to communicate and hold online meetings have substantially improved, but we still think that the IMWA family is only a family when we can see and chat with each other face to face. Presentations online are a useful tool, but simply don’t replace live speakers’ attentive audiences, insightful questions, or subsequent discussions over coffee, food or great beer and wine. So, we believe we made the correct decision.

All of us were looking forward to a fantastic IMWA Congress in New Zealand this year. 223 abstracts were accepted for presentation, and 40 of them are now published in these proceedings. They cover the full range of mine water related topics by experts from all around the world. Though you can’t listen to the presentations, we hope that you still can enjoy reading the related papers. Especially because of these unintended changes, the authors did a great job to compile and write their papers for these proceedings. It shows us that a Pandemic like that can interrupt face to face communication, but it can’t beat our enthusiasm for mine water and our international friendship.

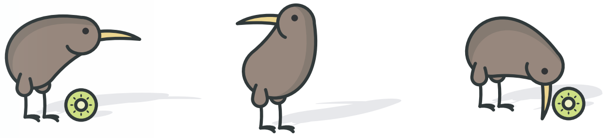
We want to thank all our reviewers from the International Scientific Committee (ISC), the people behind the scenes who partially organised IMWA 2020, and our collaborators and sponsors. It was fantastic to work together with you to share a vision and we look forward to working together again to deliver IMWA 2022.

Stay tuned, dear friends all around the world, and let’s work on IMWA 2021 in Wales and IMWA 2022 in New Zealand. Let’s keep in contact through e-mail and social media and online meetings. And let’s look positively into the future. There will be a time when the Pandemic is over, we will have a vaccine and we will be able to see each other again.

Keep healthy and with the German miner’s greeting “Glückauf” we are wishing you all the best!

Christian Wolkersdorfer – IMWA President

James Pope – IMWA 2020 Chair



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Rethinking Hydrologic Design Criteria for Mine Closure

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Abstract

Hydrologic design criteria for mine closure landforms in riverine environments commonly specify that landforms need to be stable under extreme, single hydrologic events such as the probable maximum precipitation or probable maximum flood. The cumulative geomorphic effects of multiple, more frequent, and lower magnitude hydrologic events may well exceed that of a single, extreme event. In addition, failure of a closure landform in the riverine environment may be dictated by non-fluvial factors such as settlement, cracking, piping or mass failure of emplaced fill or pit walls. Factors other than extreme hydrologic events need to be considered in mine closure planning.

Keywords: mine closure, design criteria, hydrology, geomorphology

Introduction

Rehabilitation of creek and river corridors remains, arguably, the most challenging aspect of mine closure in the Pilbara region of Western Australia. This is particularly the case where Channel Iron Deposits (CID) in Tertiary-age paleochannels are open pit-mined in spatially coincident modern drainages and the ratio of waste material to extracted ore is very low and thus pit backfill is an on-going challenge.

Closure in the riverine environment can encompass re-establishment of drainage features over fully backfilled pits, partial pit backfill with land bridges to convey sediment and flows, and total or partial hydrologic disconnection between partially-filled open pits and the channel system. Typical closure scenarios for non-backfilled pits are illustrated in Figure 1 (Price 2018).

In general, fluvial processes in the Pilbara tend to be driven by infrequent, high intensity and short duration hydrologic events that are related to the occurrence of Tropical Cyclones (Harvey et al. 2014, Rouillard et al. 2015, Rouillard et al. 2016). Climate change projections suggest that it is likely that intense rainfall in most locations in Australia, including the Pilbara, will become more extreme, driven by a warmer, wetter atmosphere (Department of Industry Innovation and Science 2016).

Regulatory Guidance for Design of Closure Landforms in Australian Riverine Environments

Mine closure guidelines in Western Australia include language requiring post-closure landforms to be physically safe, geotechnically stable, geochemically non-polluting and sustainable in the long term (Western Australian Department of Mines and Petroleum 2015) which is in accordance with the hierarchy of closure needs identified by the Asia-Pacific Economic Cooperation Mining Task Force (APEC Mining Task Force 2018).

The Australian National Council on Large Dams (ANCOLD) defines long term as 1,000 years (ANCOLD 2019) which significantly exceeds the limits of engineering practice, which is generally considered to be between 100 and 200 years, and also exceeds the duration of most human institutions that would monitor and regulate the post-closure landscape (APEC Mining Task Force 2018). Leading practice in Australia dictates that a post-closure design life of 1,000 years be adopted as being considered ‘in perpetuity’ (Department of Industry Innovation and Science 2016).

Guidance from Western Australian regulatory agencies on hydrologic design criteria for closure landforms in the riverine environment is either not clear (300 years or longer for landforms, voids and ecosystems to 500-1,000 years for pit lake modelling) or recommends that landforms are constructed to be stable under single extreme events such as the probable maximum precipitation (PMP) or the probable maximum flood (PMF). While extreme events such as the PMP, or the resulting PMF, may be attractive from a perceived regulatory risk reduction perspective, the very low probability of occurrence of such an extreme single design event means that fluvial processes, and hence the dynamics of the closure corridor, will be governed by multiple events with a much higher probability of occurrence. In addition, while a structure may provide a design level of protection when built, subsequent changes in the river environment such as aggradation may lead to conditions in the future where the design level of protection is not provided.

Probability of Extreme Hydrologic Events

Probable Maximum Precipitation

The probable maximum precipitation is defined as the “theoretically greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of the year” (Hansen et al. 1982). Prior to the 1950s, the concept was known as the maximum possible precipitation (MPP). The name was changed to the PMP reflecting the uncertainty surrounding any estimate of maximum precipitation (Wang 1984). There is no known way to develop the PMP from first principles (National Research Council 1994) and proposed estimation methodologies have been the subject of much debate. By another definition, the PMP is the estimated precipitation depth for a given

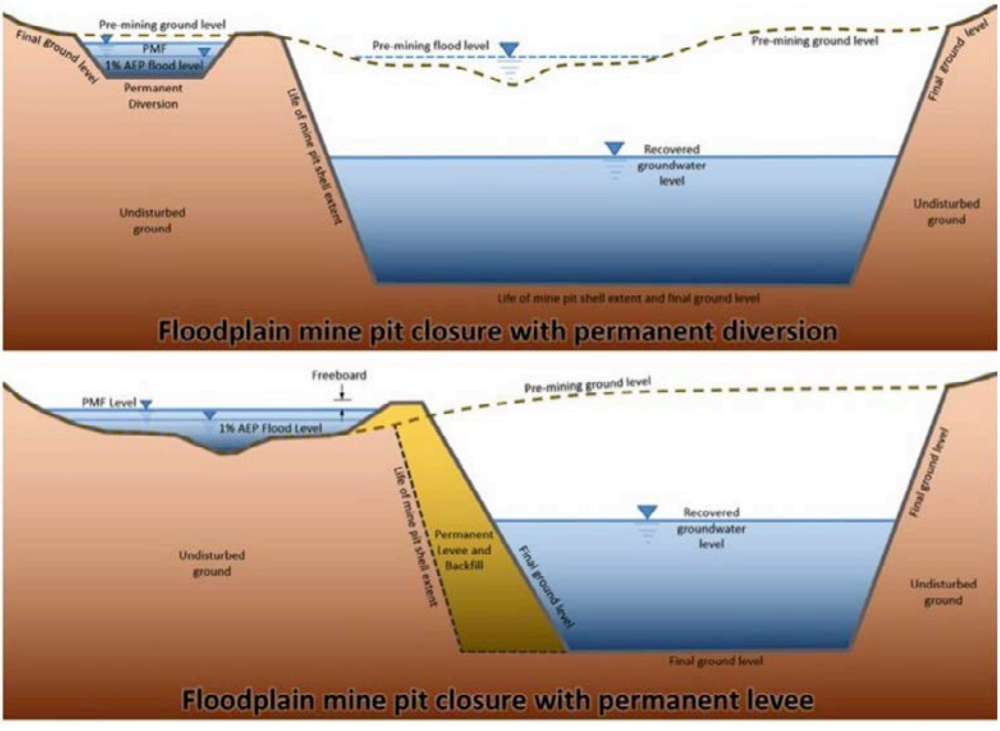

Figure 1 *Typical closure scenarios with permanent diversions and a levee for a non-backfilled pit (Price 2018).*

duration, drainage area, and time of year for which there is virtually no risk of it being exceeded (Wang 1984). However, the fact that measured rainfall depths have exceeded PMP estimates in the past clearly indicates that the PMP approach by no means implies zero risk in reality (Koutsoyiannis 1999).

The PMP estimation methodology makes the inherent assumption that the past climate will be representative of future conditions. As global climate patterns continue to change, PMP estimates from previous analyses may need to be updated. The Mine Closure Checklist for Governments (APEC Mining Task Force 2018) describes some of the challenges associated with climate change and mine closure, including changing rainfall patterns, drier climates, rising temperatures, and rising sea levels. Changing rainfall patterns may quite possibly have the greatest impact as areas have more intense and/or more frequent rainfall events or even more prolonged periods of dry weather than in previous years (IPCC 2007).

Probable Maximum Flood

The probable maximum flood (PMF) is defined as "the largest flood that could conceivably occur at a particular location, usually estimated from the PMP coupled with the worst flood-producing catchment conditions" (Douglas and Barros 2003). The temporal and spatial patterns of the predicted PMP rainfall depths, antecedent soil conditions, and precipitation losses will all impact the estimate of the PMF. Use of the PMP to generate the PMF has become the standard for dam design in many parts of the world including the United States, China, India, and Australia (Svensson and Rakhecha 1998). Estimates of the annual exceedance probability (AEP) of the PMF range from 1 in 10,000 to 1 in 1,000,000 in Canada (Smith 1988) to 1 in 1,000,000 in the eastern USA (Shalaby 1994). However, there is considerable uncertainty in estimating both the PMP and PMF (Salas et al. 2014).

Guidance in Australia (Nathan and Weinmann 2019) states that the absolute upper limit of flood magnitude under consideration is the probable maximum flood, which is a design concept that cannot be readily assigned an annual exceedance probability. However, the AEP of the PMP is considered to vary from 1 in 10,000 to 1 in 10,000,000. The stability of hydraulic features that are included in mine closure plans may be undermined by morphological changes that occur as a result of more frequent events with a higher likelihood of occurrence. Given the extremely low probability of occurrence of the PMP/PMF, designing for it is not pragmatic if the features cannot withstand the impacts of a series of more frequent events.

Fluvial Processes and Geomorphic Change

In general, fluvial processes in the Pilbara, located in the arid subtropics, tend to be driven by infrequent, high intensity and short duration hydrologic events that are related to the occurrence of Tropical Cyclones (Harvey et al. 2014). The morphology of the alluvial sections of the ephemeral-flow, gravel-bed creeks where sediment transport is episodic, tends to be a relic of the last major flow event and results in highly variable channel morphology over both space and time (Graf 1988). Graf (1988) concluded that in arid and semi-arid regions where the flows are ephemeral, infrequent and relatively short-duration hydrological events rarer than the 1 in 100 AEP are the major determinants of overall valley floor morphology, but more frequent events are responsible for defining highly variable channels (macro-channels) within the disturbed landscape. Macro-channel morphology (compound channels) is associated with regions of high hydrological variability (Croke et al. 2013). Macro-channels are characterised by a small inner channel and associated benches set within a much larger channel that operates as a conduit for high magnitude floods (Croke et al. 2016). They have large channel capacities, with bankfull capacities approaching a 1 in 50 AEP, and are laterally stable even during extreme flood events because of the presence of highly erosion-resistant clays (Fryirs et al. 2015) or calcrete and ferricrete-cemented alluvium in their banks (Harvey et al. 2014).

Tooth and Nanson (2004) demonstrated the high variance of morphologic, hydraulic and sediment transport characteristics over relatively short distances in ephemeral flow channels in central Australia and because of this high morphologic variability, it is very difficult to define either channel-forming discharges (Wolman and Miller 1960, Baker 1978, Wolman and Gerson 1978) or design discharges (Harvey and Mussetter 2005). Consequently, channel dimensions within the ephemeral flow channels are unlikely to be related to hydrologic events of any particular recurrence interval, and as such, existing channel morphology provides a very poor template for post-mining channel reconstruction in the Pilbara (Harvey et al. 2014).

International Approaches to Engineering Design and Long-Term Landform Stability

With the exception of tailings dam design where PMP/PMF criteria are prescribed (ICOLD 2013, Slingerland et al. 2018), the international literature on mine closure generally addresses regulatory goals for reclamation/closure/relinquishment rather than specific hydrologic design criteria. For example, the extensive South African Guidelines for the Rehabilitation of Mined Lands (Chamber of Mines of South Africa and CoalTech 2007) does not specify any hydrologic criteria but rather focusses on achieving post-mining landscape rehabilitation and acceptable future land use.

The U.S. Surface Mining Control and Reclamation Act (SMCRA) of 1977 aims to avoid disturbance of alluvial valley floors and their attendant hydrologic balance (both surface water and groundwater). If stream diversions are required, they must convey the peak runoff from the 1 in 100 AEP, 6-hour precipitation event. There is also an expectation that "good engineering practice" will be employed in design of the diversion structures (Office of Surface Mining and Reclamation and Enforcement 1977).

To accommodate the dichotomy of constructing landforms that are stable over the long-term and the limits of engineering practice, the U.S. Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978 requires closure measures to be effective for up to 1,000 years to the extent reasonably achievable and, in any case for at least 200 years (Nuclear Regulatory Commission 1978; APEC Mining Task Force 2018) even though they fall short of the full duration of the hazard (Nuclear Regulatory Commission 2002). These timeframes were formulated to cover periods over which climatological and geomorphic processes could be reasonably predicted given current knowledge of earth sciences and engineering (Logsdon 2013).

Canadian practice is encapsulated within the APEC Mining Task Force (2018) document and addresses the problems of prescribing extreme events as hydrologic design criteria as well as acknowledging the practical limits of engineering design

Concluding Discussion

Hydrologic design criteria provided by regulatory agencies for mine closure landforms in the riverine environment in the Pilbara region of Western Australia are not clear or recommend that landforms need to be stable under extreme, single hydrologic events such as the PMP or PMF. These extreme hydrologic design events with annual exceedance probabilities in the order of 1 in 10,000 to 1 in 10,000,000 are not appropriate for designing long-term mine closure landforms in the riverine environment of Western Australia

The use of a single extreme event as a design criterion confuses the low annual exceedance probability of a design event with the desired design longevity of the closure landform (Price 2018). A post-closure design life of 1,000 years can be considered to be in perpetuity (Department of Industry Innovation and Science 2016). However, even a design life of 1,000 years significantly exceeds the limits of engineering practice, that is generally considered to be between 100 and 200 years, and also exceeds the duration of most human institutions that would monitor and regulate closure and relinquishment (APEC Mining Task Force 2018).

Engineering analysis for long-term closure (1,000 years) needs to take into account the impacts of a series of design events that have lower magnitude but higher frequency. The cumulative geomorphic effects of multiple more frequent and lower magnitude events may well exceed that of the single extreme event.

Failure of a closure landform in the riverine environment may be dictated by non-fluvial factors such as settlement, cracking, piping or mass failure of emplaced fill or pit walls and as such are not explicitly evaluated in a hydrologic risk-based analysis. Even if the overall probability of failure can be reasonably constrained, the consequences of failure of a closure landform will tend to be location-specific, and thus, a generalised approach to establishing risk is unlikely to be particularly useful.

A more realistic approach to hydrologic design for long-term landform closure is provided by the U.S. Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978. The UMTRCA requires closure measures to be effective for up to 1,000 years to the extent reasonably achievable and in any case, for at least 200 years (Nuclear Regulatory Commission 1978, APEC Mining Task Force 2018). However, this approach also requires the development of a site-specific, long-term surveillance plan that involves annual inspections and maintenance, as required, in perpetuity. This approach would require a program to distribute dedicated funds to those groups assuming responsibility for ongoing maintenance.

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Scour Protection Design Criteria for Mine Site Infrastructure

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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

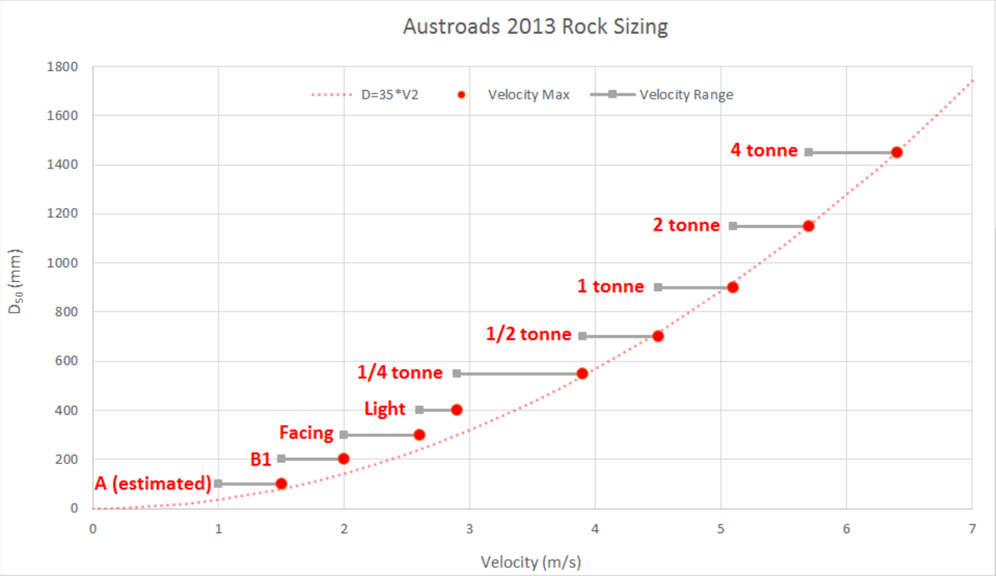

Figure 1 *Rock sizing data compiled from the Austroads Guide to Road Design (2013) and the MRWA Floodway Design Guide (2006).*

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

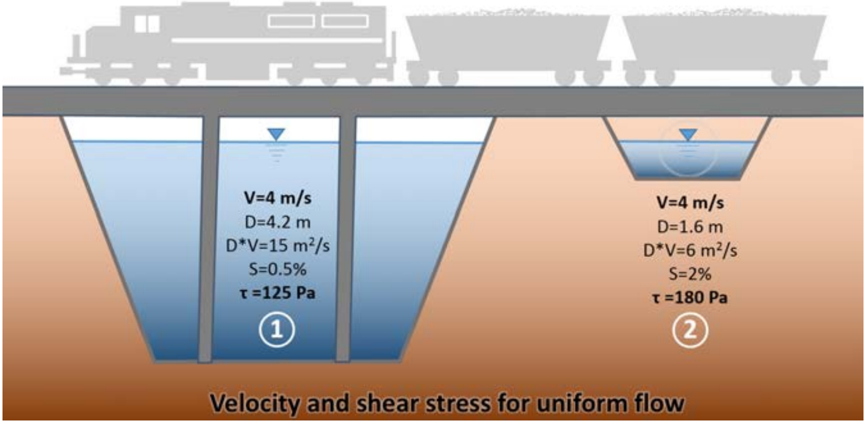

Figure 2 *Comparison of velocity and shear stress for armour rock sizing (Indicative scale for reference only).*

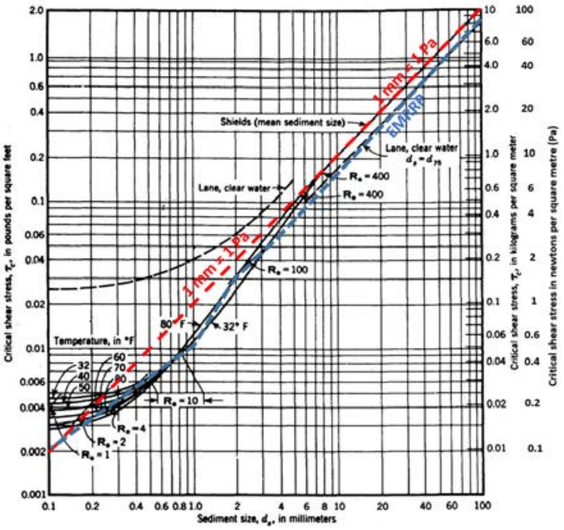

Figure 3 *Relationship between shear stress and rock diameter (Annotated from USDA SCS 1983).*

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.

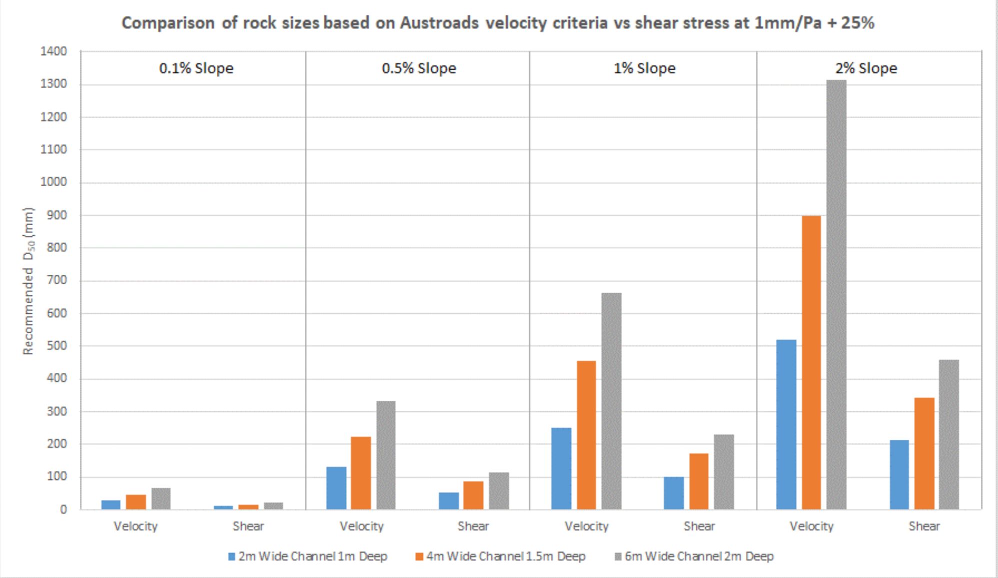

Figure 4 Comparison of channel rock sizes based on velocity criteria vs shear stress.

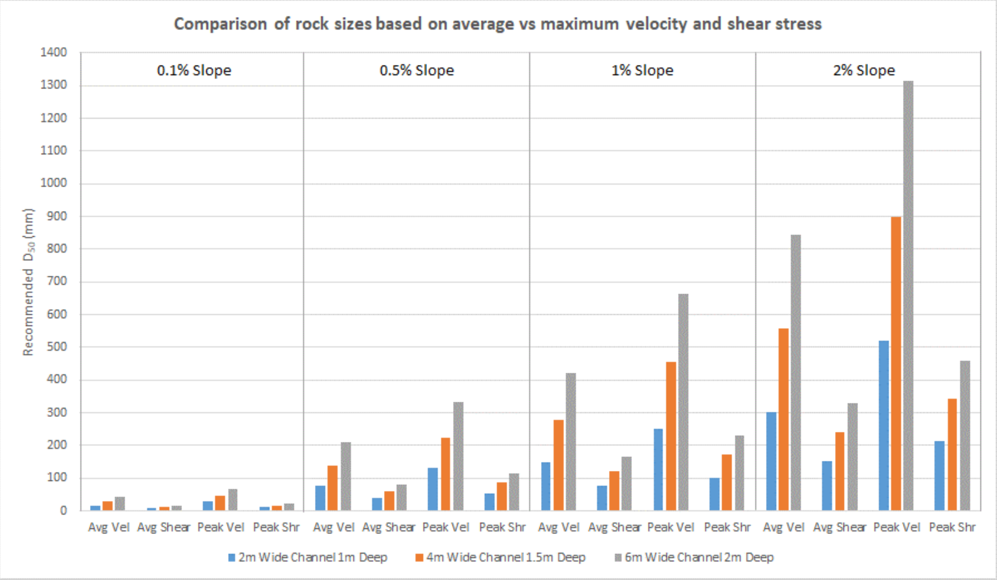

***Figure 5** Comparison of channel rock sizes based on average vs maximum velocity and shear stress.*

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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