Estimating scour risks from 1D, 2D, and 3D flood model results

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Abstract

Flood models are typically run as fixed bed hydraulic simulations, without accounting for the dynamic effects of erosion or scour. In some cases, the incorporation of a mobile boundary can drastically affect simulated flood depths and inundation extents. Predicting the location and magnitude of scour can aid modellers in selecting areas requiring further analysis and risk assessment. The identification of high-risk areas can, in turn, reduce flood risk through the introduction of appropriate countermeasures or design changes.

Scour occurs where the hydraulic energy exceeds the inherent resistance of the local bed or bank material. The background equations used to predict incipient motion and estimate stable particle sizes are generally based on one-dimensional (1D) computations. In recent years, flood modelling has much more commonly been applied with two-dimensional (2D) models, and hydraulic structures are increasingly being modelled with three-dimensional (3D) computational fluid dynamics (CFD) approaches. When 2D and 3D results are extracted for the purpose of predicting erosion, adjustments may be needed to account for the inherent assumptions of the 1D approaches on which the computations are based.

Australian Rainfall and Runoff (ARR) and Austroads guidance documents for sizing erosion countermeasures reference 1D approaches that include adjustment factors to account for horizontal and vertical variation in the results. Applying localised 2D and 3D hydraulic results to 1D-based equations therefore carries a risk of double-counting the effects of bends, constrictions, changes in the flow regime, and other factors that may have been accounted for in the 1D equations. With the increasing prevalence of 2D and 3D flood modelling, previously adopted stable particle sizing criteria should be reappraised.

This paper presents recommended approaches for the prediction of particle mobility using 1D, 2D, and 3D model results for localised and averaged velocity, shear stress, and flow depth. Modelling assumptions and limitations associated with 1D, 2D, and 3D approaches are presented. Current Australian source data for scour countermeasures are also addressed, along with recommendations for updating the current guidance to reflect the latest modelling practices.

Introduction

The 2022 extreme flooding in Australia resulted in a number of erosion and scour-related failures, particularly around floodways. Scour and erosion can add substantial risk to already risky situations when vehicles cross flooded roadways. In light of the recent events, a review of the design approaches is warranted to determine whether the erosional failures were related to the occurrence of greater-than-design events or whether they were related to deficiencies in design or construction approaches.

Guidance

Australian national guidance for determination of erosion and scour countermeasures is included in Austroads (2013a, 2013b, and 2018) and in Australian Rainfall and Runoff (Ball et all, 2019). The guidance is based entirely on 1D hydraulic modelling results and empirical approaches. Hardware and software improvements have resulted in an increasing prevalence of 2D and 3D flood modelling. Australian rock sizing and erosion-related guidance has not been updated to apply to 2D and 3D modelling results.

For predicting erosion and stable thresholds for materials, Austroads generally takes a velocity-based approach drawn from 1D hydraulic modelling. A range of critical thresholds are listed depending on the application. ARR references shear stress as a relevant factor but does not specify how to apply it; velocity-based approaches in ARR rely on the same sources as Austroads.

Figure 1 shows selected Austroads rock sizing criteria. The recommended values depend on the application, with structures requiring larger rock sizes than channels. The derivation of these values is included along with additional details on the ancestry of the Australian rock sizing methods in Price (2021).

1D Assumptions and Limitations

1D hydraulic modelling approaches assume that water surface elevations are exactly flat across the cross-sectional alignment selected by the modeller, whether or not that is a realistic assumption. Velocities and energy gradient elevations are also constant across each section.

These assumptions can lead to discrepancies, particularly around skewed roadways where flow directions are not aligned perpendicularly to the roadway orientation.

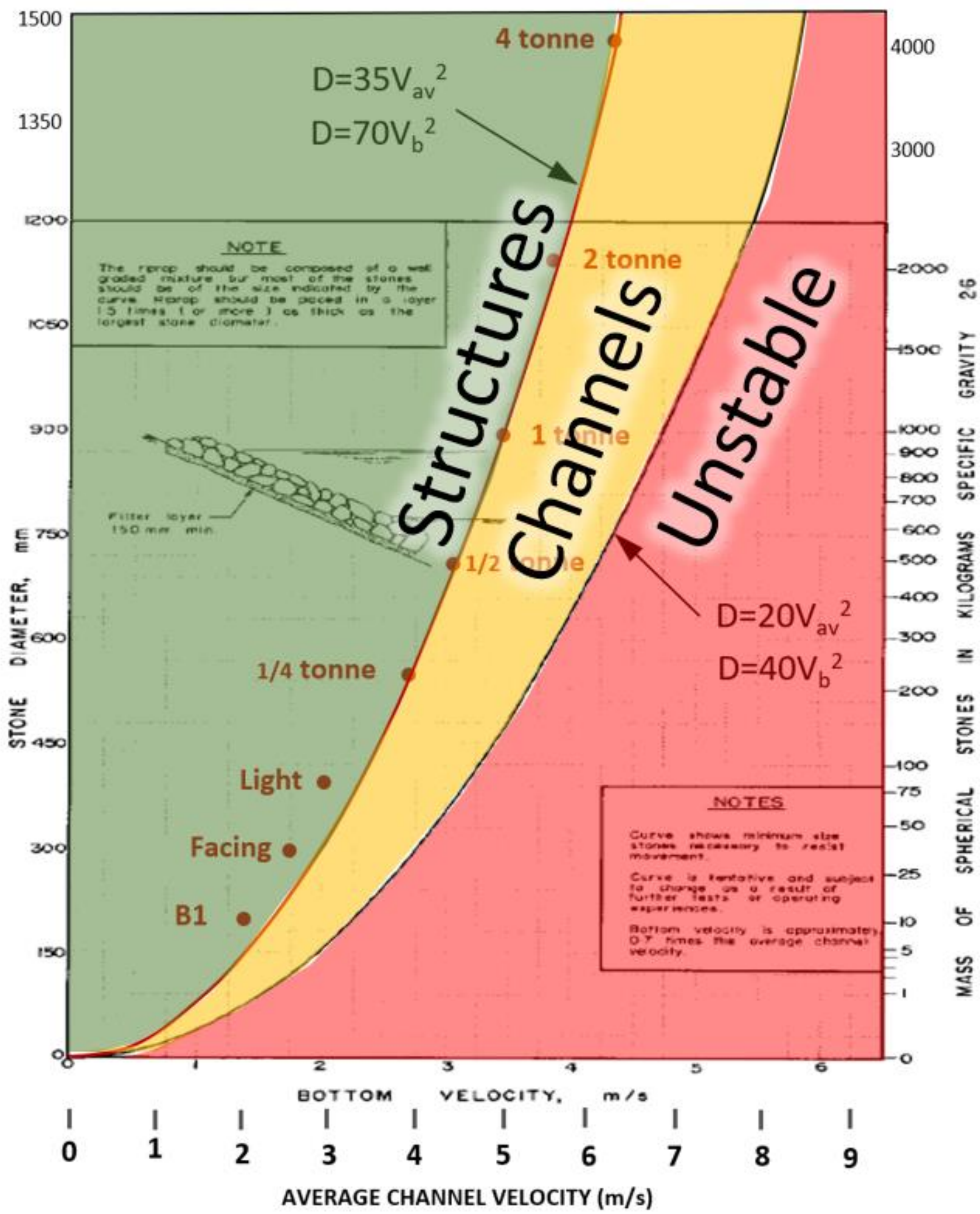

Figure 1. Austroads rock sizing criteria

2D Assumptions and Limitations

Figure 2 shows an example of a floodway analysis conducted with 2D modelling. Whereas a 1D analysis would show flat water surface elevations, the 2D approach accounts for superelevation and other effects that result in a varying water surface elevation across the floodway. Velocities and erosive potential likewise vary along the alignment. If closure criteria in this case are based on 1D results, safety thresholds may be misrepresented.

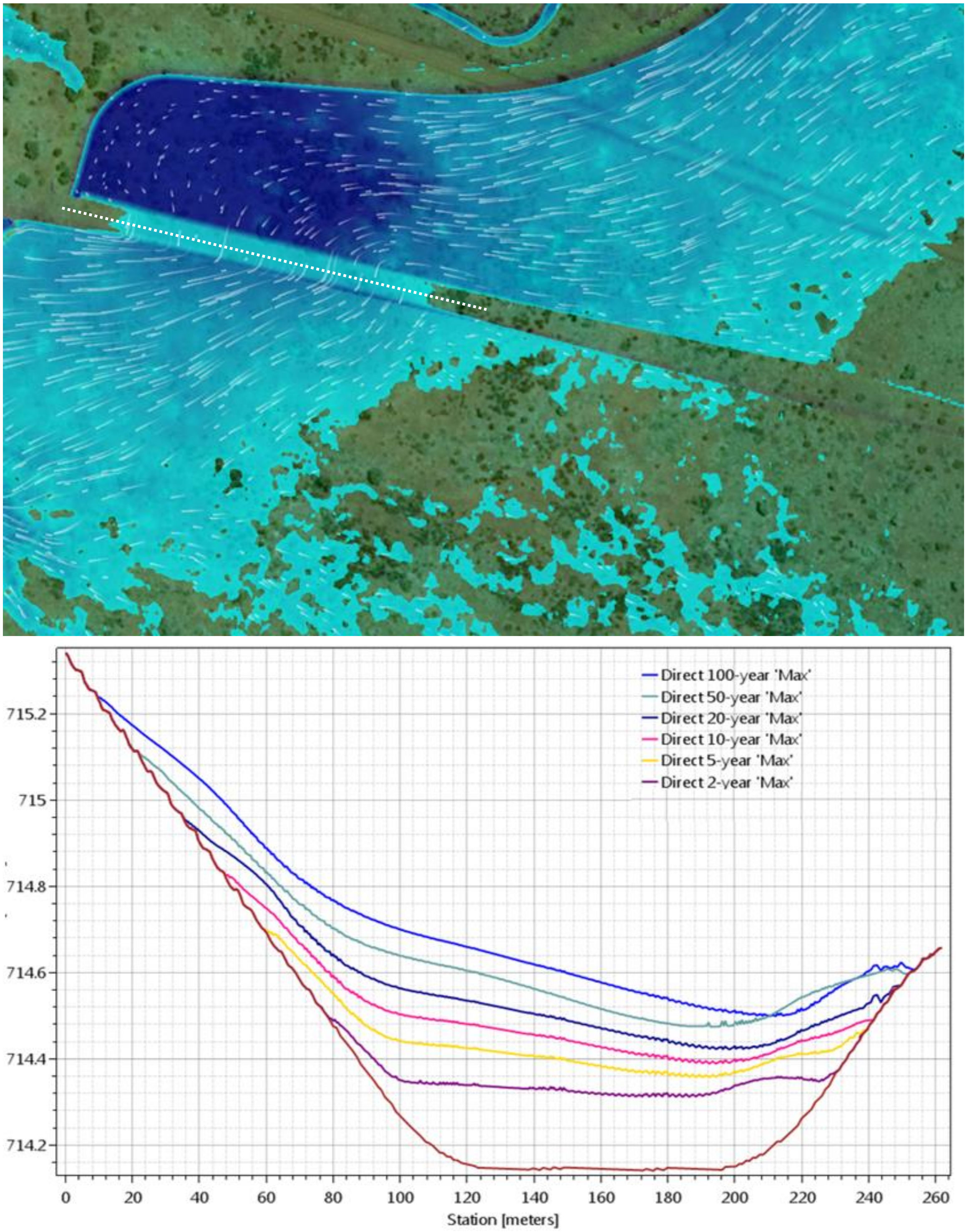

Figure 2. 2D floodway assessment example

Rock sizing methodologies are generally based on average channel velocities extracted from a 1D cross section. The original guidance that was used as the source material for Austroads methods includes the recommendation to use either 2/3 or 4/3 of the average channel velocity for rock sizing, depending whether the flow direction is parallel to or impinging on an embankment. The difference between the two scaling factors is quite extreme, with the resulting stone weight varying by a factor of 64. There is no provision in the original source material for using the average channel velocity without factoring for the flow direction; however, the recommended factoring has not been included in the most recent Australian guidance documentation.

If a 2D modelling approach is used to asses project hydraulics, no guidance is available in the current Australian sources regarding the location from which to select the appropriate velocities or how to average velocities for use in the charts or tables.

1D rock sizing methods account for both horizontal and vertical variations. Whilst 2D approaches provide horizontal variation, results are depth-averaged and there is no provision in the guidance for separating horizontal and vertical variation in the applied velocities.

Both 1D and 2D modelling approaches have limitations for the longitudinal slope. The original experiments that are cited in the source material for Ausroads guidance are based on rock dumped into flowing rivers, where the assessed slopes are not the longitudinal slope of the river bed but rather the angle of repose of the downstream batter face of the dumped material. Substantial limitations arise in 1D and 2D hydraulic models when slopes along the flow direction exceed approximately 10%.

Guidance for application of 2D results

Recognising that 2D flood modelling is becoming much more prevalent than 1D, the US Federal Highways Administration, the source agency for the current Australian bridge scour guidance, has developed guidance for two-dimensional hydraulic modelling (FHWA 2019). The guidance includes recommended approaches for applying hydraulic results to predict stable rock sizes. It should be noted that the example provided in that publication includes excessive rock sizes with diameters exceeding 4 metres due to the application of local results. Localised instabilities in particular should be avoided in interpreting 2D results and applying the extracted velocities to rock sizing approaches.

3D Advantages and disadvantages

3D CFD modelling accounts for both the horizontal and vertical effects that are limitations in 1D and 2D models. At hydraulic structures, vertical variation can significantly affect the proportion of orifice and weir flow during overtopping events, for example, and 3D models are able to simulate those effects. The critical drawback of 3D modelling countering the advantages is generally the simulation time; when catchment-wide models or multi-day events are simulated, the computing time for 3D models can be excessive. 3D sediment transport modelling can be used for estimating scour and assessing the effectiveness of countermeasures; however, guidance on parameter selection must rely on individual software criteria due to limited guidance in current Australian guidance documents.

Shear stress

The computation of shear stress is recommended in ARR for assessing bed and bank stability and other factors. The use of shear stress to predict incipient motion for a given particle size is well documented; however, most of the published methods are based on experimental results from a range of grain sizes up to approximately 100 mm. Some guidance documents apply extrapolated sizing relationships to larger riprap stones; however, these approaches should be treated cautiously as there is very little experimental data available for larger particle sizes. At the time of publication of the source data for Australian rock sizing criteria, the computation of shear stress required iterative procedures that were sometimes avoided in the guidance documentation. In light of modelling advances, shear stress results can be readily extracted from 1D, 2D and 3D models, and updated guidance on applying shear stress from each model type is recommended.

An Australian spreadsheet forms part of the Catchment Modelling Toolkit (CRC for Catchment Hydrology, 2003). The computations are based on shear stress. A comparison of shear and velocity-based methods is included in Price and Westwater (2020)

Guidance regarding multiple approaches

Realising that different methods will generally produce widely varying results, the US Bureau of Reclamation, the source agency for the rock sizing charts in Austroads, has published the recommendation to apply at least three methods when sizing rock. The velocity-based methods that are included in current Australian guidance are in some cases based on sources that have been superseded by the U.S. Army Corps of Engineers method in the meantime. The USACE method has some substantial limitations, but where applicable, it should be included as one of the applied methods.

Recommended approach

The development of new or updated rock sizing methods would require a long-term effort because it would need to be confirmed with both physical and numerical modelling. The Australian industry currently lacks guidance on where hydraulic results should be drawn from and how the results from 2D and 3D modelling ought to be averaged when used in 1D-based rock sizing methods. The proper use of the sizing criteria would require a 1D model to be developed in addition to the 2D or 3D model.

In the meantime, prior to the development of updated guidelines, applying both velocity and shear-based methods is recommended, with appropriate safety factors applied. The USACE method, which includes depth in its function, is also recommended where applicable.

Raster results layers for depth, shear, and velocity can be converted to the predicted stable particle size using a raster calculator. These layers can be combined with layers for existing grain sizes with comparisons plotted to indicate where stability thresholds have been exceeded. If stratification of substrate or bank material is crucial, or if bed mobility affects hydraulics sufficiently to produce a feedback loop, numerical mobile boundary sediment transport modelling may be considered using 1D, 2D, or 3D approaches.

The current guidelines do not provide detailed recommendations for sediment transport modelling. Several statements are included about accounting for sediment transport in sizing sediment basins, and the references state that geomorphic and sediment transport analyses are “essential” for diversion designs, bypass channels, gravel mining operations. Sediment transport is also noted as a consideration for rating curve development and temporal as well as spatial variation in roughness coefficients.

Sensitivity

Recommended stable rock sizes are highly sensitive to the applied velocity. Actual velocities during flood conditions vary both horizontally and vertically, and the extraction of the appropriate velocity from 1D, 2D, and 3D hydraulic model results is crucial in designing scour countermeasures. The sensitivity to velocity appears to be poorly understood in the industry. In a recent Australian Water School poll of practicing water professionals, all respondents underestimated the effect of increasing velocity on the design rock size.

Figure 3 shows the effect of doubling the velocity on diameter and weight of the stable particle size. As shown in the figure, the corresponding factor of increase is 64.

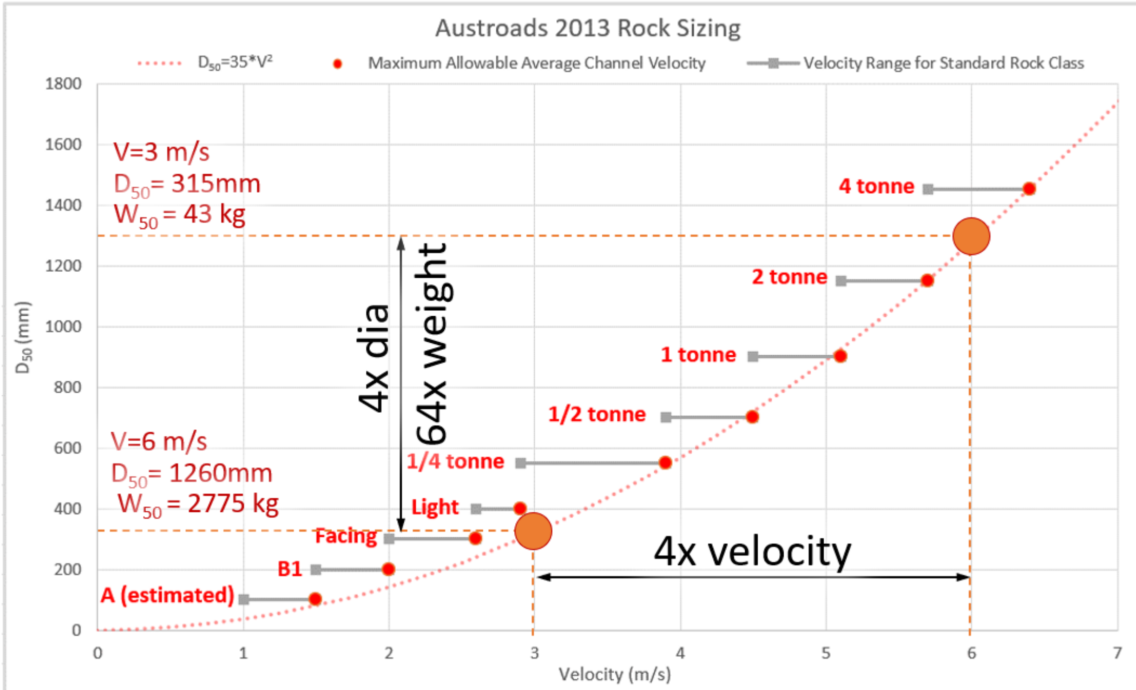

Figure 3. Effect of doubling the applied velocity on diameter and weight

In the original USBR document that published the rock sizing charts that are in the current Austroads guidance, the weight relationship is incorrectly stated as a factor of 16.

Recommendations

Further guidance is needed to allow Australian scour and rock sizing approaches to align with current modelling practices. Adoption of updated standard guidelines may help avoid some of the erosional failures experienced during recent flood events. In the meantime, scour countermeasures should be sized using at least three methods, including velocity and shear based methods, with appropriate safety factors applied to account for the limitations of the adopted modelling approach.

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