GUIDELINES FOR ASSESSMENT OF SCOUR IN UNLINED SPILLWAYS

Dr Steven Pells
PSM Pty Limited
G3 56 Delhi Road
North Ryde
Sydney, Australia

Dr Kurt Douglas
University of New South Wales
Level 5, Room CE506
Kensington Campus
Sydney, Australia

Introduction

Spillways for dams are commonly lined with concrete to control the flow of water and to offer resistance to scour / erosion[1]. Despite this, for practical or economic reasons, many spillways may be left unlined where the local rock mass is judged to be sufficiently resistant to scour. Risk from erosion is therefore a key consideration in spillway design and surveillance, and assessment of this risk requires an assessment of erosion potential of the rock mass. Erosion of rock masses is dissimilar to erosion of earth or soil. Typically, the rock substance remains intact, but structural features of rock masses (i.e. defects within the rock mass) create distinct but interlocking units of rock, which may be unravelled by hydraulic forces. Assessment of erosion of rock masses therefore requires a multi-discipline approach, applying expertise in both rock mechanics and hydraulics.

A methodology to guide the undertaking of a “hydro-geotechnical rock scour assessment” is presented in this paper. The methodology has been formed following review of over 30 case studies of spillway scour across Australia, South Africa and the USA, and with consideration to current best-practice techniques in both rock-mechanics and hydraulics. This paper presents an abridged summary of the methodology prepared for the European Group of ICOLD and the French Committee on Dams and Reservoirs following an international workshop in Aussois, France, December 2017.

Methodology for a ‘hydro-geotechnical rock scour assessment

A “hydro-geotechnical rock scour assessment” is considered to conform to the flowchart presented in Fig 1 below. Each of the steps (1. to 8.) in the flowchart are discussed in turn below.

Step 1 - Geometry and topology

In the assessment of spillway scour, the entire spillway is usually considered, extending from the reservoir through to a location on the natural river bed downstream of the spillway where flow conditions are returning to their natural (pre-dam) condition. The topography of this entire region must be compiled and presented in maps, with reference to available ground-survey data and dam design or as-constructed drawings. It is recommended, based on case study observations, that 3D representations of the geometry are constructed as this communicates a clear perspective of the problem.

Step 2 - Historical performance

Where historical erosion has occurred, detailed ground surveys, ideally successive, should be obtained to allow examination of the extent and form of erosion. The available information on design flood conditions should be obtained. For existing dams, a record of historical spills should be compiled and should be related to the available topographic data, correlating any historical erosion with past events. Where recorded reservoir levels are available, it is recommended to plot data as a timeseries, showing crest elevations of spillway inlets or overflow points.

Historical photographs of the dam should also be compiled, including photographs of the rock mass during previous inspections or during construction and any available photographs of the spillway in operation.

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[1] The terms ‘scour’ and ‘erosion’ are considered synonymous for the purposes of this paper

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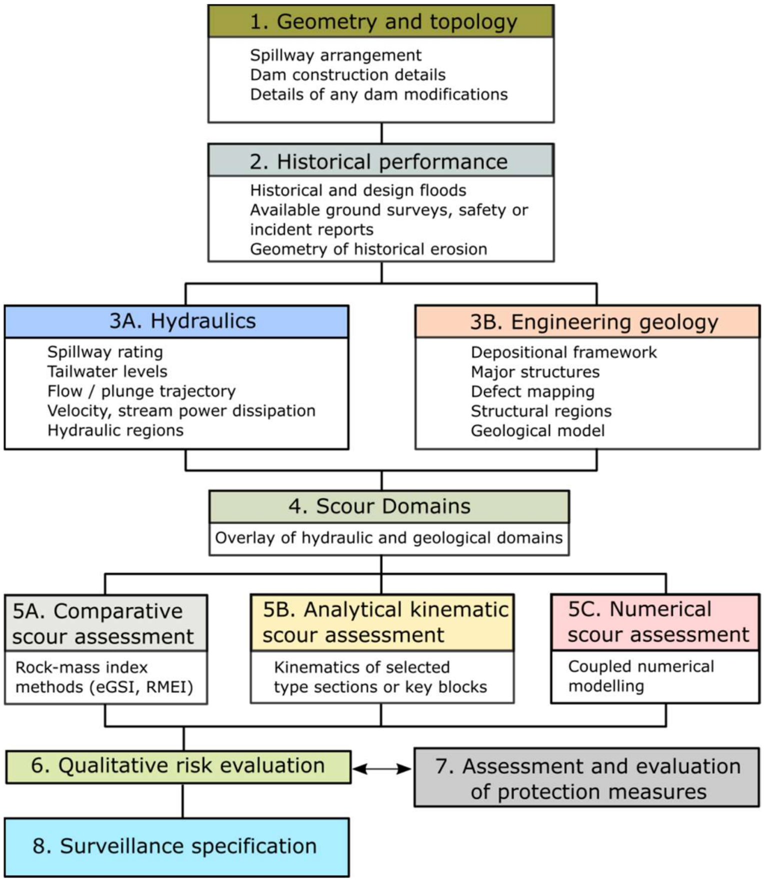


Fig 1. Flowchart for hydro-geotechnical assessment of erosion of unlined spillways

Step 3A - Hydraulics

It is necessary to characterise the hydraulic loading that the spillway is subject to, under historical or design flood conditions. Ultimately, it is the differential in hydraulic pressures between opposing faces of a rock unit that is responsible for scour. Integration of these pressures around the perimeter of a rock unit will resolve forces termed hydraulic 'drag' and 'lift', where drag is the force resolved parallel to the flow direction and lift is perpendicular. Calculation of these forces (in Step 5B.) requires knowledge of the flow velocity field, and for this reason it is necessary to assess flow velocity over the spillway domain. The 'comparative' scour assessment method in Step 5A utilizes the unit stream power dissipation (Π_{UD}) defined as:

$$\Pi_{UD} = \rho g \frac{Q}{B}\frac{\Delta E}{\Delta L} = \rho g \frac{Q}{B} S_e \qquad (1)$$

ρ is density of water (~1000 kg.m^{-3}); and B is the width of flow (m).

The flow discharge is usually known a priori, as a historical record or a design condition. Estimations of flow area, velocity and unit stream power dissipation can be made using standard open-channel flow techniques, keeping in mind the following:

1. Standard open-channel analyses assume that flow is 1-dimensional – ie. depth-averaged, width-averaged and of a single streamwise direction. The 1D assumption is often appropriate because spillway channels are usually clearly defined.
2. Spillways are typically relatively short, and the flows are rapid. Hence, a steady flow condition is usually a suitable assumption (that is, analysis can assume a constant discharge).
3. For analysis, hydraulic conditions can be usefully categorized as being: uniform, gradually varied (GV) or rapidly varied (RV).
4. For uniform and GV flows, the flow velocity and depth are controlled dominantly by friction forces – a relationship that is solved through 'hydraulic roughness equations', such as "Manning's" or "Darcy-Weisbach" equations. Manning's n values are typically estimated from published guidance in hydraulics texts. However, such guidance is typically given for cases of relatively quiescent river flows. There is a

paucity of published guidance for high-energy spillway flows. Darcy f values can be estimated from absolute roughness (k_s') values via the Colebrook-White equation – a more arduous analysis. Mannings 'n' and k_s values for high-energy unlined rock chutes require further research.

5. Uniform flows are an equilibrium condition where the energy slope S_e is parallel to the bed slope S_o, making the analysis somewhat simpler. However, uniform flow conditions seldom occur over the short and changing geometry typical to spillways.
6. GV flow analysis requires integration of the energy balance over the channel alignment. Depth-averaged GV flows can be resolved simply within 1D numerical software, such as HEC-RAS.
7. For GV flows, changes in channel shape and bed roughness will result in peaks in Π_{UD} values, due to a local increase in energy gradient. These changes should be judiciously represented.
8. For RV flows, energy losses are dominated by turbulent effects, and the depth profile cannot be resolved from a hydraulic roughness equation. Classical analytical solutions based on momentum considerations exist for some idealized flow conditions, such as for hydraulic jumps or drop structures (e.g. Henderson, 1966).
9. Analytical solutions and 1D and 2D numerical hydrodynamic models will resolve the total energy at locations upstream and downstream of a RV flow section, but the rate of energy loss within the RV flow section will not be represented. For RV flows, the length ΔL is the primary source of uncertainty in estimation of Π_{UD}.
10. Contrary to some practices, for plunging conditions, the dissipation length ΔL should not be taken as the thickness of the jet, as the energy is dissipated over a larger area, and much energy can remain after impact. In the experience of the present writers, when the 1-dimensional hydraulic conditions are analytically interpreted for spillways, the slope of the energy line rarely exceeds 3, and, except under extreme design events, the unit stream power dissipation (Π_{UD}) rarely exceeds 1000 kW.m^{-2}.
11. In cases where suitable analytical estimations do not provide the necessary confidence, refined estimates may utilise physical scale modelling, prototype measurements or detailed turbulent numerical (i.e. CFD) modelling. CFD simulations are not depth and width averaged and show spatial variation in Π_{UD} estimates, including regions of greater Π_{UD}than the averaged values estimated from 1-D analytical techniques presented above. The comparative assessment techniques presented in Section 5A below were developed using 1D assumptions. Hence, spatial averaging of CFD results may be required to derive suitable comparison values.

It is recommended that these analyses are used to plot continuous profiles of depth, velocity and energy slope across the spillway domain for a range of design discharges. This clearly presents the findings and also ensures that calculations maintain conservation of energy across the spillway domain. An example presentation of spillway hydraulics based on 1D hydrodynamic models is presented in Fig 2.

Step 3B - Engineering Geology

Appraisal of the geology of the unlined spillway should seek to demarcate regions of rock masses with common structural properties, referred to herein as "geological domains".

The broad discipline of geology has various ways of demarcating geological types. Of primary interest here are the structural or engineering characteristics, as evidenced by the nature of defects (ie defect type, orientation, frequency and persistence), the interaction between defect sets and the characteristics of the rock substance – its composition and strength. In some sites, different regions may be clearly apparent, but others may require detailed consideration of rock mass mapping and testing. For example, a large structural feature, such as an intrusive dyke, is clearly distinguishable from the parent rock mass. In other cases, careful consideration of fracture frequency and orientation may guide a decision to consider demarcation of regions.

Geological field investigations need to collect sufficient information to support the type of erosion assessment undertaken (ie. 5A, 5B and / or 5C) as described below. This would typically include for each of the geological domains identified:

- Development of defect stereoplots.
- Identification of characteristic defect sets.
- Measurements and/or interpretation of defect strength, frequency or spacing, persistence, roughness, aperture and infilling.
- Characterization of typical rock unit shapes and orientations (as defined by defect set interaction).
- Documentation of any structural features that may be present, albeit of insufficient scale to be warranted as a separate 'domain'.

- Measurement or estimation of rock substance strength (eg UCS).
- Collation of sufficient data for estimation of rock-mass indices (see Section 5A below).

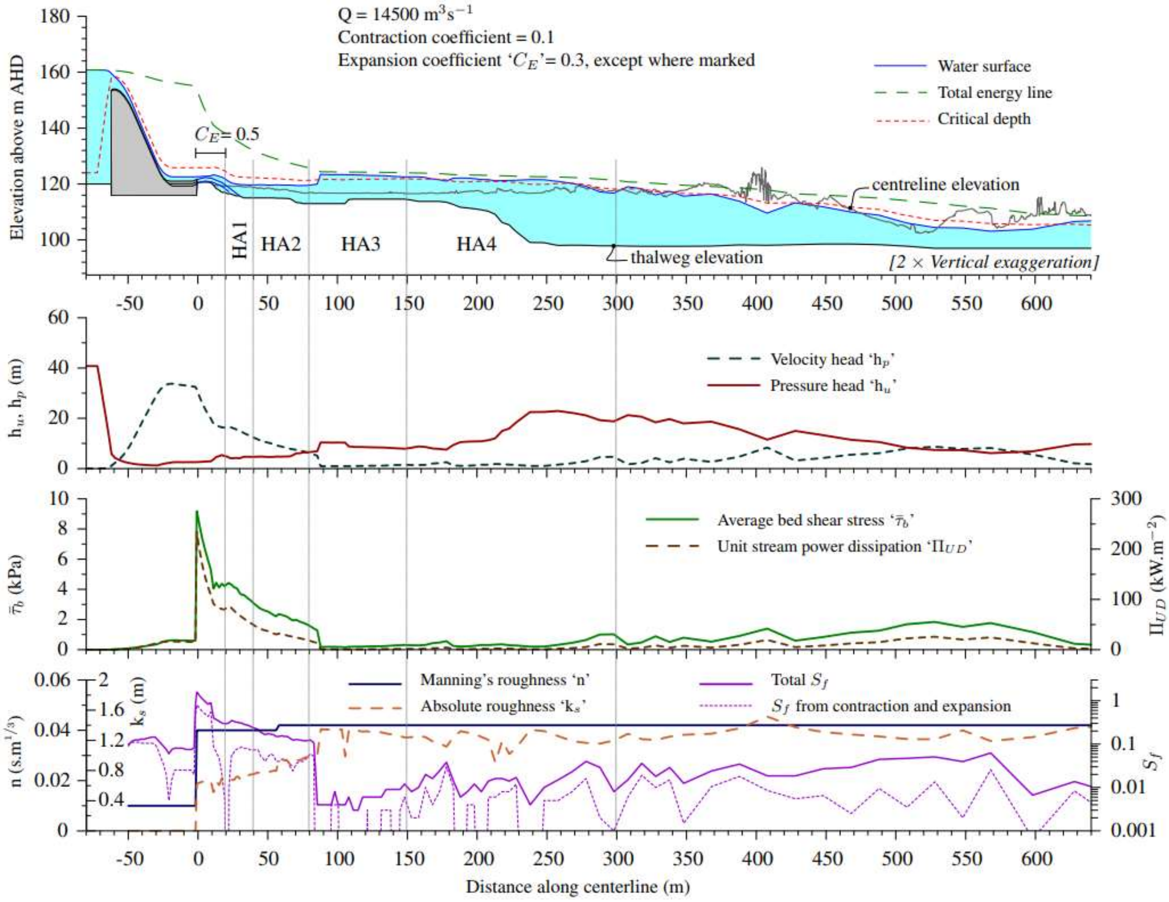


Fig 2. Example presentation of hydraulic analyses at an ogee crest spillway

It is recommended that conceptual geological type-sections are prepared (eg Fig 3) to clearly present the interpreted geological conditions. These type-sections permit the visualisation of potential erosion mechanisms and are required to support the analytical erosion analyses discussed in Section 5B.

Spillways with a higher risk profile may warrant more critical analysis and therefore require more detailed geological models to be developed. For existing spillways 3D numerical geological models can be prepared using specialist interpretation of photogrammetric data and include 3D mapping of individual defects. For spillways for proposed dams, 3D geological models can be developed from geotechnical investigative data using Discrete Fracture Network (DFN) modelling techniques. It is important to remember that the DFN technique must be capable of replicating the actual interaction between defects sets (i.e. the rock mass fabric) as it directly impacts the shape of potentially erodible blocks.

Step 4 - Scour domains

Scour domains are regions of common geology and hydraulic loading. These are determined as the intersection of hydraulic domains and geological domains. It is only necessary to define scour domains where the onset of scour would be of possible consequence to dam safety.

Significant reshaping of the spillway from scour may create new hydraulic conditions, such as plunging or channelization, which may require recognition of new domains subsequent to erosion. For example, erosion of the fault zone at Mokolo Dam (South Africa) created channelized and plunging flow conditions, which incurred greater hydraulic loading, leading to further scour and so on (Pells et al,2016). The possibility of such an occurrence, particularly for lineal geological structures, should be perceived in the process of defining scour domains.

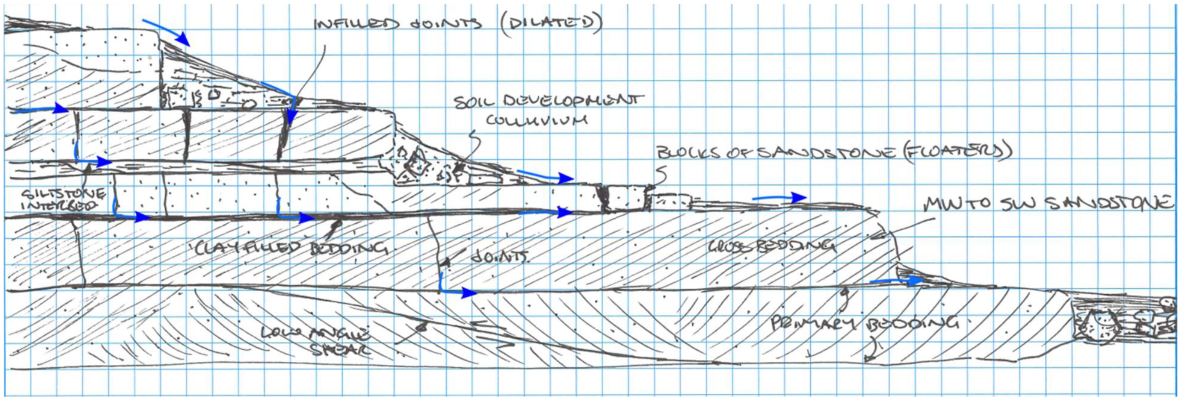


Fig 3. Example of a geological type-section (courtesy T. Nash, PSM) Note: grid is a 1m scale

Step 5A - Comparative scour assessment

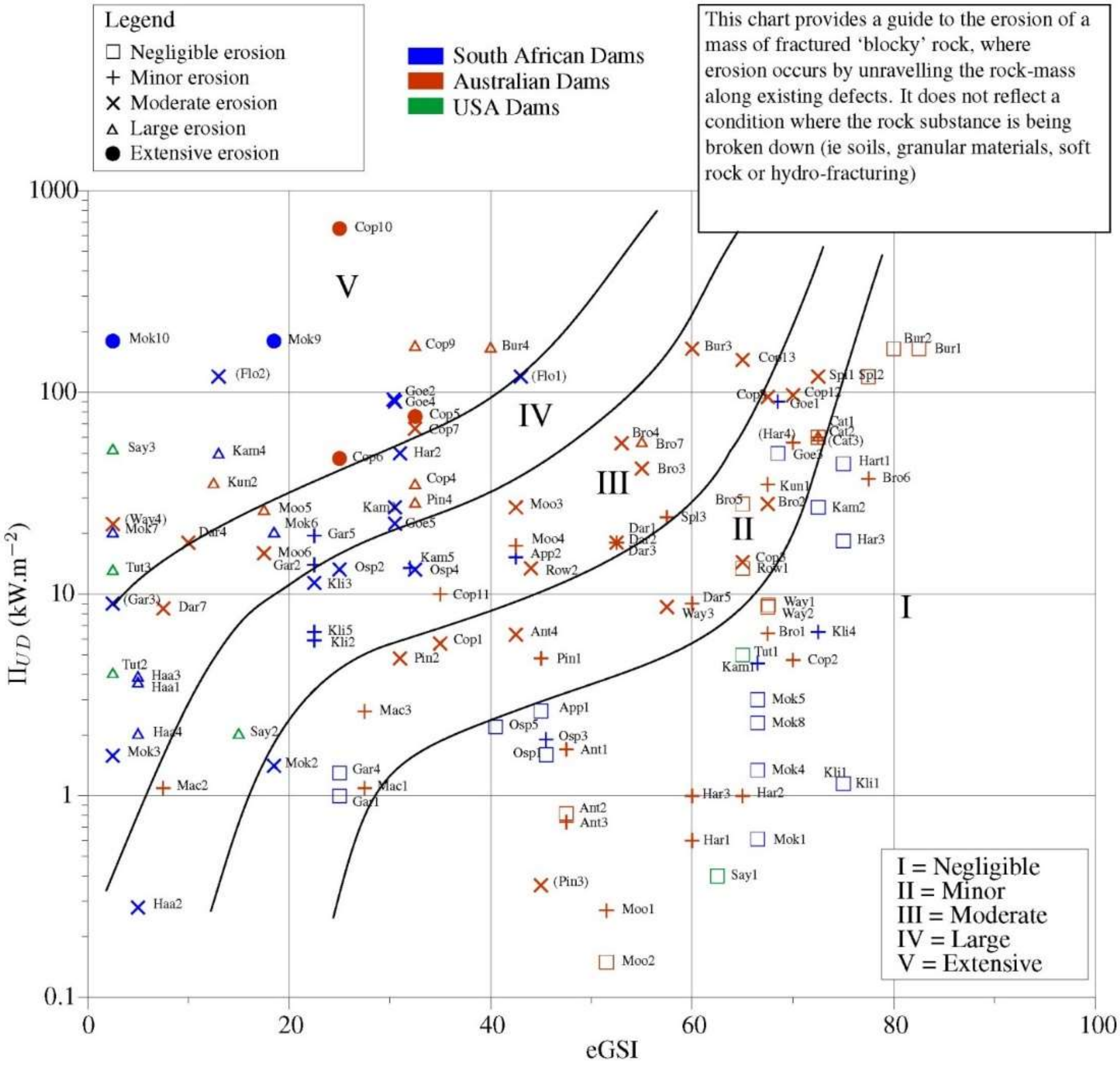
Three methodologies for assessment of rock scour are discussed in Section 5A, 5B and 5C. The first, discussed here, has been termed by the present writers as a 'comparative' method, because it assesses erosion through comparison to case studies, where the rock mass conditions are compared using a rock mass Index, and the hydraulic conditions using the unit stream power dissipation. Neither the rock-mass index nor the stream power dissipation describes the problem completely, but have been found to be useful indicators, or proxies, of general conditions.

A rock-mass index is a system that attempts to describe the engineering characteristics of a rock mass with a single number. A numerical rating of the rock-mass is obtained from the sum or product of various numbers which are chosen (with reference to specific guides and tables) to represent the orientation, quantity and condition of joints in the rock mass and the strength of the rock substance. Two early examples of rock-mass indices are the Rock Mass Rating (RMR) system (Bieniawski, 1973) and the "rock-tunnelling quality index" (the Q-system) (Barton et al 1974). Numerous other rock-mass indices have since been developed for other applications, most of which are extensions or modifications on RMR or Q-system. The Geological Strength Index (GSI) (Hoek et al, 1995) is a modification to the RMR system which also enjoys wide usage within the discipline of engineering geology.

Various researchers have used rock mass indices as an indicator of erodibility (Kirsten and Moore, 1988; Pitsiou, 1990; Moore, 1991; Dooge, 1993; van Schalkwyk, et al 1994; Annandale 1995; Kirsten et al 2000). In most of these cases, the researchers utilized the Kirsten Index, which is a rock mass index based on the Q-system (Kirsten 1982), modified to represent excavatability of rock masses. Rock mass indices have been developed specifically to represent rock mass erodibility, as presented in Pells et al (2017) (erosion GSI , or eGSI) and Douglas et al (2018) (the Rock Mass Erodibility Index, or RMEI). These methods were based on erosion at 118 locations at dam spillways in Australia, South Africa and USA as documented in Pells (2016a). Each case was assessed in terms of five classes, as described in Table 1, reflecting the nature of erosion as observed at these case study sites. The methods of Pells et al (2017) and Douglas et al (2018) each presented a design chart which can be used to assess erosion risk, using estimations of unit stream power dissipation (Π_{UD}) plotted against the relevant rock mass erodibility index. An example of the design chart from Pells (2016a) is presented in Figure 4. The Rock Mass Erodibility Index (RMEI) (Douglas et al 2018) attempts to identify the presence of mechanisms of erosion in unlined spillways based on defect characteristics and spillway geometry.

Table 1 – Erosion risk classes

Class	Erosion descriptor	Maximum erosion depth (m)	General erosion extent (m3 per 100 m2)
I	Negligible	< 0.3	<10
II	Minor	0.3 - 1	10-30
III	Moderate	1 - 2	30-100
IV	Large	2 - 7	100-350
V	Extensive	> 7	>350



This chart provides a guide to the erosion of a mass of fractured 'blocky' rock, where erosion occurs by unravelling the rock-mass along existing defects. It does not reflect a condition where the rock substance is being broken down (ie soils, granular materials, soft rock or hydro-fracturing)

Fig 4. Rock-mass erodibility assessment chart using eGSI (Pells, 2016?)

Step 5B - Analytical scour assessment

Within the discipline of rock mechanics, techniques are used to analytically assess the stability of rock slopes, tunnels or high-wall excavations. This involves resolving the force freebody for an identified rock (eg a 'key block') or particular section, and usually considers water pressures arising from seepage of groundwater. These types of analyses can be appropriated for examination of stability of spillways by incorporation of water pressures arising from spillway flows.

It is well known that the total energy embodied in a moving mass of water includes its kinetic and potential energy components. When a fluid is caused to slow down when impacting against a bluff object, the kinetic energy is transformed to a potential head or 'stagnation pressure' that acts against the object (referred to in literature as `form drag'). Laboratory experiments (e.g. Reinus, 1986; Coleman *et al* 2003; Bollaert, 2003; Frizell, 2008; Pells 2016) have shown that stagnation of high velocity water against protrusions not only gives rise to locally high pressures, but that these pressures can be translated through adjacent rock defects, effectively penetrating into a rock mass. It has also been observed within these above cited experiments that turbulent fluctuations give rise to fluctuating pressures. It is the pressure differential between exposed and sheltered faces of a block of rock that give rise to the drag forces that are responsible for erosion.

Laboratory experiments have been undertaken to allow estimation of the proportion of velocity being converted to pressure head for various geometric conditions, with the proportionality constant, denoted "C_p". *Average* pressure coefficients (denoted $\overline{C_p}$) are assessed from laboratory experiments with the following expression:

$$\overline{C_p} = \frac{\overline{P}_{\text{test}} - h_p}{\bar{u}^2/2g} \qquad (2)$$

where: $\overline{P}_{\text{test}}$= the mean pressure (Pa) recorded by a pressure transducer
h_p = the static pressure head (m) at the observation point in the test (hydrostatic pressure normal to the slope assumed)
$\bar{u}$ = the time and depth averaged flow velocity

Design average pressure $\overline{P}$ is thus calculated at a point on an element in any prototype by rearrangement of Equation 2:

$$\overline{P} = \overline{C_p}\rho\frac{\bar{u}^2}{2} + \rho g h_p \qquad (3)$$

$$= \overline{P}_{\text{dyn}} + P_H \qquad (4)$$

where: $\overline{P}$= the mean pressure (Pa) acting on the prototype
h_p = the static pressure head (m) at the observation point in the prototype (hydrostatic pressure normal to the slope assumed)
$\overline{P}_{\text{dyn}}$= the mean dynamic pressure (Pa) acting on the prototype
P_H = the static pressure head (m)

Turbulence causes velocities to fluctuate, resulting in fluctuating stagnation pressures. It can be said that the total pressure (P) at any time is the sum of mean ($\bar{P}$) and fluctuating (P') components, ie:

$$P = \bar{P} + P' \qquad (5)$$

Detailed analysis of laboratory measurements presented in Pells (2016a) demonstrated that the observed fluctuating pressures P' could be represented by a normal statistical distribution. The standard deviation of pressure fluctuations (denoted σ_p) can be calculated at a point on an element as:

$$\sigma_p = C_{p,\sigma}\rho\frac{\bar{u}^2}{2} \qquad (6)$$

where: $C_{p,\sigma}$= a fluctuating pressure coefficient (determined through experimentation)

As such, the probability of a certain total pressure P acting on a face at any time is assessed in accordance with a normal statistical distribution:

$$Prob(P) = \frac{1}{\sqrt{2\pi}\sigma_P} e^{\frac{-(P-\bar{P})^2}{2\sigma_P{}^2}} \qquad (7)$$

As such, the mean and fluctuating pressures can be described using two coefficients: $\overline{C_p}$ and $C_{p,\sigma}$. Coefficients for a range of geometric and flow conditions were developed from detailed analysis of the test data presented in Pells (2016a, Table 6.3). These pressure coefficients can be used by a practitioner to estimate pressures acting on any element - the coefficients are distributed around the surface area of the element in accordance with observations made, and the principle force can be resolved by integrating the product of pressure and area.

Rock masses are complex materials and are unique to each site. It is not appropriate to develop a single 'black box' approach for generic analysis of stability of all unlined spillways. Rather, practitioners need to apply first principles physics to estimate a force freebody on a selected rock unit or section of slope.

Where the average pressures on a rock are sufficient to cause detachment of a block, erosion of the rock mass could be said to occur rapidly. However, even where the mean pressures are insufficient to cause instability, erosion may occur under the action of pressure fluctuations that are higher than the average. Each fluctuation can be considered to cause a small movement, and hence a time-scale of erosion is inferred by considering the probability distribution function of pressure fluctuations. An example of such analysis is presented in Pells (2016a).

Step 5C - Coupled numerical scour assessment

The analytical methods presented above are somewhat arduous, and it falls upon the practitioner to perceive an appropriate section of the spillway, or representative key block, to analyse and to write and solve analytical equations as suitable. As shown in Section 3B above, current techniques of rock mass mapping and rock mass analysis can allow for detailed 3D models of rock masses. It follows then, that numerical analysis of erosion of rock masses can be achieved through coupled rock mass and hydrodynamic modelling.

At the time of writing, even advanced 3D computational fluid dynamic (CFD) models running on advanced computing platforms cannot practically simulate fluid dynamics at a resolution that would allow direct simulation of stagnation pressures on each individual protrusion over the spillway domain, nor the propagation of these pressures into each identified defect. At the current time, a practical way forward for such coupled modelling is to include a level of code which indirectly estimates stagnation pressures upon the rock mass from the flow depths and velocities determined from hydrodynamic models. Such an estimation would rely upon experimentally determined Cp values as applied in the analytical solutions presented in Step 5B above. The present writers know of no presently available commercial software package that does undertake this complete analysis. The dismantling of a 3D rock mass model can be achieved in various commercially available finite-element analysis software packages, and can be modified to incorporate hydraulic loading, taking outputs from hydrodynamic modelling. Results from CFD analysis are preferable for this application, as they provide spatially distributed results over the entire domain and can utilise non-depth-averaged velocities for better examination of conditions close to the water-rock interface. This type of analysis offers great promise for detailed examination of rock mass erosion but is an area requiring further development.

Step 6 - Risk evaluation

In dam engineering, risk is typically considered as the product of likelihood of occurrence and consequence. When undertaking the erosion assessment methods as set out above, the likelihood of occurrence is inferred by the return period associated with the flood conditions that are assessed. The consequence of erosion is typically unique to each dam. In severe cases, the predicted erosion may lead to a dam breach. In other cases, the predicted erosion may incur expenses for repair. Risk from erosion should also consider the uncertainty in the prediction. All methods for erosion estimation presented above rely on interpretation. As such, following the analysis techniques set out above, an appropriately attended risk-assessment workshop should give thoughtful consideration to erosion mechanisms, prediction of erosion development and assessment of risk.

Step 7 - Assessment of protection measures

Where the risks from erosion are unacceptable, solutions for mitigation will be considered. Pragmatically, the only solutions that exist are either to reduce the hydraulic loading, or to decrease the erodibility of a rock mass.

Hydraulic loading may be reduced by redirecting flow away from a region, modifying release conditions or design of energy dissipators. The unit stream power dissipation (Π_{UD}) is a function of flow width and, inasmuch as Π_{UD} is a suitable indicator of hydraulic loading, it is evident that distributing the flow over a larger area will reduce the erosive capacity of flow.

Techniques to increase the erosion resistance of the rock mass may include concrete lining, dental concrete or rock-bolting. Rockbolts can be effective in decreasing the erodibility of rock masses by locking together individual units to form an effectively larger intact mass. Hence, the rockbolt spacing should be commensurate with the block size. Where closely spaced defects form smaller blocks, rock bolting may be tied into a surface mesh or surficial lining.

With reference to the structure of the flowchart in Fig 1, it is recommended that assessment of suitable protection measures is undertaken as part of the risk assessment process.

Step 8 - Surveillance

Surveillance should be undertaken following spill events. This is not only necessary to assess the significance of damage that may have occurred, but also provides some validation of the performance of the unlined spillway, against which the risk assessment can be compared. The following procedure is recommended for surveillance of unlined spillways following significant spill events (from Pells 2016b):

1. Documentation of the spill event, including the time of peak reservoir levels and discharges.
2. A site walkover attended by both engineering geologists and experienced hydraulics engineers. The walkover should formally document observed erosion (or lack thereof) using mapping and photographs.
3. The site inspection should be supported by detailed ground surveys. Techniques that allow rapid and cost-effective 3D mapping of terrain which are now available and are recommended. Land or aircraft mounted LIDAR scanners can provide rapid and high accuracy surveys. Due to the lack of vegetation in spillways, very cost effective, and accurate 3D surveys can be undertaken by photogrammetry, using unmanned aerial vehicles (UAV's). An advantage of such photogrammetric surveys is also the provision of high-resolution aerial photographs, which can be used to map rock mass structure and for the preparation of 3D geological models. Comparison of 3D surveys before and after spill events can be used to prepare isopachs of erosion, which allow quick identification of erosion regions and patterns, as well as

calculation of headcut advance and erosion volumes. Digital terrain models assembled from 3D surveys can also form the basis for rapid construction of revised spillway hydraulic models.

4. Where significant erosion that may modify flow characteristics has occurred, revised hydraulic analysis can be undertaken, providing synoptic profiles of hydraulic conditions throughout the spillway.
5. Where observed erosion does not reflect existing predictions, reassessment of rock mass erodibility, using the methods set out above, should be undertaken.
6. Based on the above information, the findings of previous risk-assessments should be reviewed, giving thoughtful consideration to observed erosion mechanisms, prediction of erosion development and assessment of risk.

In the experience of the present writers, a detailed review of erosion is often only undertaken after significant erosion has occurred so as to raise concerns for dam safety. In many of these cases, the effectiveness of the review was limited by the lack of suitable baseline data. Dam owners / operators are urged to undertaken routine spillway inspections, utilising cost-effective UAV survey techniques.

Summary

In this paper, guidelines for undertaking a “hydro-geotechnical rock scour assessment” are proposed, conforming to the flowchart presented in Fig 1. The proposed procedure uses current state-of-the-art techniques, which are illustrated with various examples. It is also recognized that ongoing research on this topic is active and is required. The proposed methodology provides a framework that can readily include new techniques or advances as they become available.

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The Authors

Dr Steven Pells spent his formative years constructing physical scale hydraulic models to support consulting services in civil engineering. In 2016, Steven completed PhD studies at the University of New South Wales, examining erosion and scour within chutes and channels, with particular focus on rock materials in dam spillways. Steven currently acts as principal engineer at PSM, Sydney , Australia, offering consulting and design solutions in water and geotechnical engineering. His particular specialisation is in applying water engineering principles to geotechnical and civil engineering problems, whether in water resources, mining, environmental, dams, groundwater or civil design. Steven has authored/co-authored over 30 papers in various fields of civil engineering, including hydraulics, hydrology, groundwater and rock mechanics. He undertakes adjunct lecturing on open channel flows and river systems at Sydney University.

Dr Kurt Douglas is the Pells Sullivan Meynink Senior Lecturer of Rock Mechanics in the School of Civil and Environmental Engineering at UNSW Sydney. His research focuses on predicting field-scale behaviour of rock masses for slopes, tunnels and dams. Dr Douglas also has research interests in backward erosion and suffusive behaviour associated with large dams and levees.