

ASSESSMENT AND SURVEILLANCE OF EROSION RISK IN UNLINED SPILLWAYS

SE Pells¹

1. Associate, Pells Consulting, Sydney, Australia / Department of Civil and Environmental Engineering, UNSW Australia, Sydney, Australia

PRESENTER: STEVEN PELLIS

ABSTRACT

This paper provides a methodology for surveillance and risk-assessment of spillway erosion, and is based on the findings of detailed assessments of erosion at over 30 unlined spillways in South Africa, Australia and the USA. The proposed methodology includes recommendations for: geological inspections; hydraulic assessments; rock-mass classifications for initial assessment of potential erodibility, and; surveillance techniques to assist with predicting further erosion risk.

1. INTRODUCTION

Many dams feature spillways which are unlined, or partially lined. On large dams, these unlined sections are sited in rock which is judged at design stage to be sufficiently resistant to erosion. Some erosion may be tolerated in the design, but the expectation is that the erosion will be of limited extent and will be readily repairable, and will not introduce an unacceptable risk to dam safety.

The erosion resistance of a rock mass is difficult to judge. At the spillway design stage, the quality of the rock mass is judged using information from geological investigations and regional geology. Through the process of spillway construction, more site-specific geological information may be revealed, which may necessitate review of the design. The excavated section of the spillway may be damaged by blasting and the extent and significance of blasting damage may be difficult to quantify. The surface may be similarly obscured by loose rock and construction spoil, making geological examination difficult, or even covering important geological structures such as dykes or faults. Downstream of the excavated section, the depth of weathering and quality of the rock mass underneath surficial *insitu* material may be largely unknown.

Hence, in most cases, the true quality of the rock mass is not revealed until the first significant spill event. After removal of loose blast-effected or surficial material, significant erosion may occur, or a pattern of erosion may commence. It is at this stage, and after subsequent spillway flows, that surveillance must be undertaken and that erosion is assessed using methods as presented herein.

2. EROSION OF UNLINED SPILLWAYS – SOME OBSERVED CHARACTERISTICS

A typical long section through a side-channel spillway is shown in Figure 1 (adapted from Woodward, 1981), comprising an initial lined section, an excavated section, and a natural hillside leading back to the original river channel. Common erosion risks at the annotated sections along this spillway are described with reference to case studies.

The spillway design at Copeton Dam, in New South Wales, Australia, comprises a (gated) ogee crest, which discharges over an initial lined section before plunging over the natural hillside toward the original river channel (Figure 2). During construction, a relatively small spill event (peak discharge of $200 \text{ m}^3\text{s}^{-1}$) occurred. The flow quickly removed the existing roadway, loose debris and natural surficial material from the spillway (e.g. Region D in Figure 1). Substantial erosion of the underlying granitic bedrock then followed, creating a channel and plunge pool of 20 metres depth. The extent of erosion was unexpected by designers. Subsequent investigations on the now-exposed rock mass have explained the apparently high erodibility of the rock mass in terms of: very high residual stresses (Woodward, 1981); extensive sheet jointing parallel to the slope, providing a sliding mechanism (Fell,

et al 2015), and; the presence of a transpressional fault adjacent to the natural gully (Pells and Pells, 2015). Analysis presented in Pells (2015) demonstrated the significance of the lineal fault in amplification of hydraulic loading. The significance of this fault was not perceived during design and construction, and during subsequent spills, extensive further erosion of this fault has occurred.

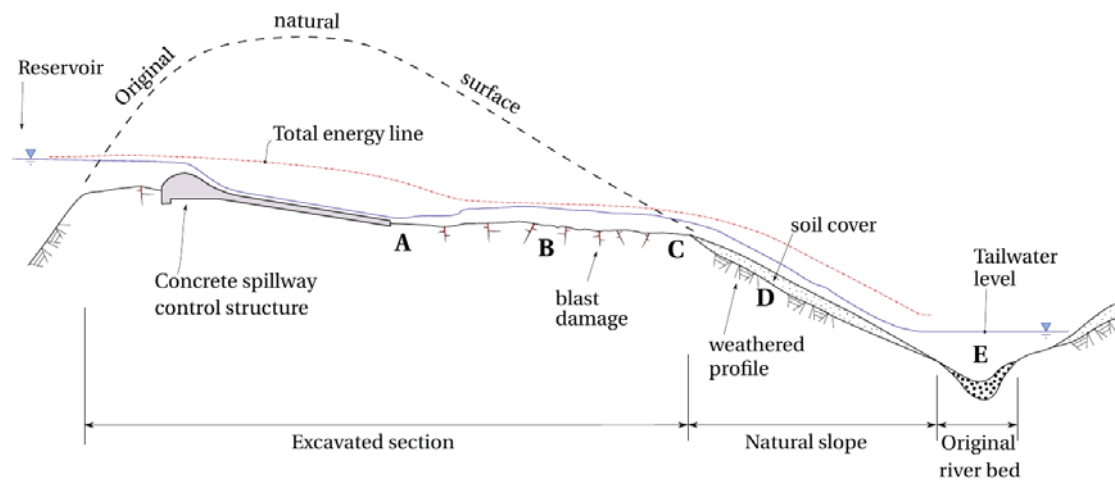


Figure 1. Typical long-section through an unlined spillway of a large embankment dam

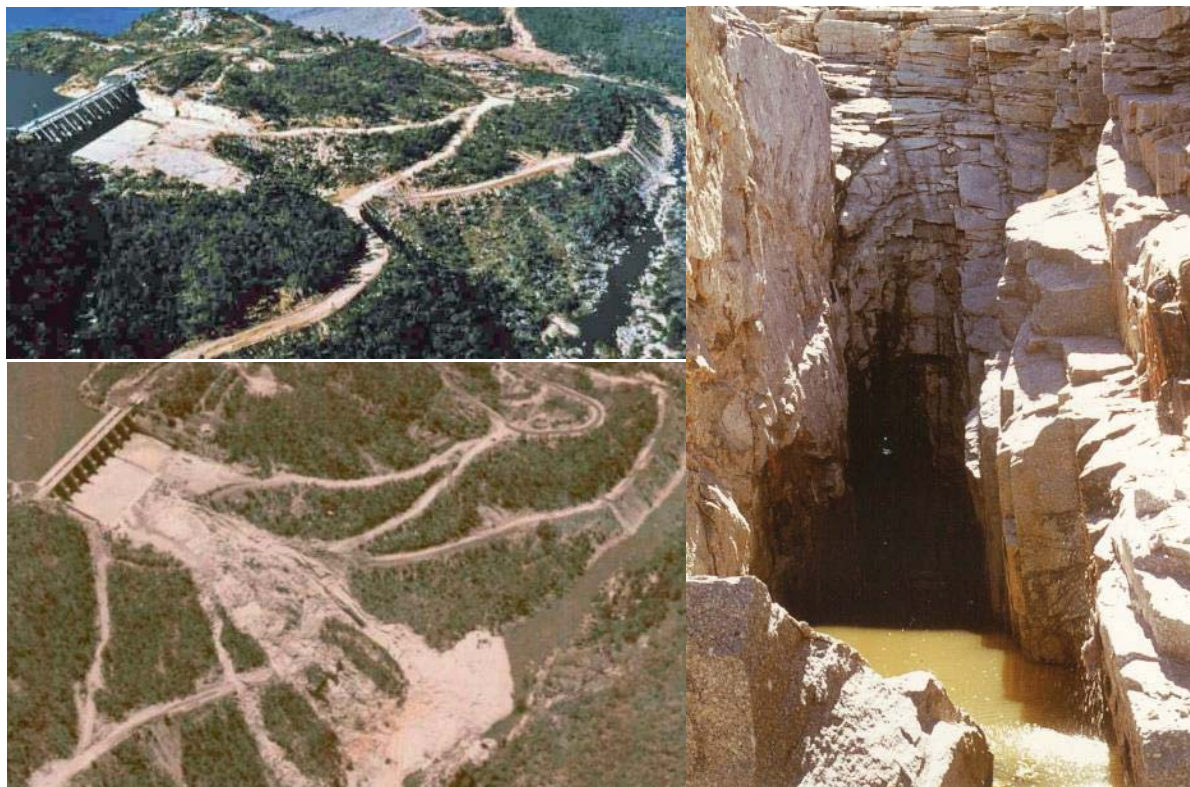


Figure 2. Copeton dam spillway. Top left: prior to spill. Bottom left: subsequent to the first spill event. Right: deep channelisation caused by erosion

At Mokolo dam, in Limpopo Province of South Africa, lineal faults are readily perceived from aerial photographs (Figure 3), but the significance of a thrust fault passing through the excavated section of the unlined spillway (e.g. Region B in Figure 1) was not appreciated during design. Erosion along the fault line, approximately 2 to 3 m depth, developed after the initial spill event in 1981 (peak discharge of $82 \text{ m}^3 \cdot \text{s}^{-1}$, Pells, 2015). Subsequent spill events have enlarged erosion along this feature, with erosion 20 to 30 m depth observed after the flood of record (peak discharge of $920 \text{ m}^3 \cdot \text{s}^{-1}$, Pells, 2015) in May 2014.

Over-blasting during construction of the spillway at Osplaas dam, in Western Cape, South Africa, was a recognised problem, and necessitated lowering of the spillway channel by removal of disturbed material, and construction of a weir to achieve the design spillway sill height (Shelley, 2013). Notwithstanding this, during the first spill, significant erosion channels formed (see Figure 4) within the blast-disturbed formations (i.e. Region B in Figure 1) which cut into the underlying formations.

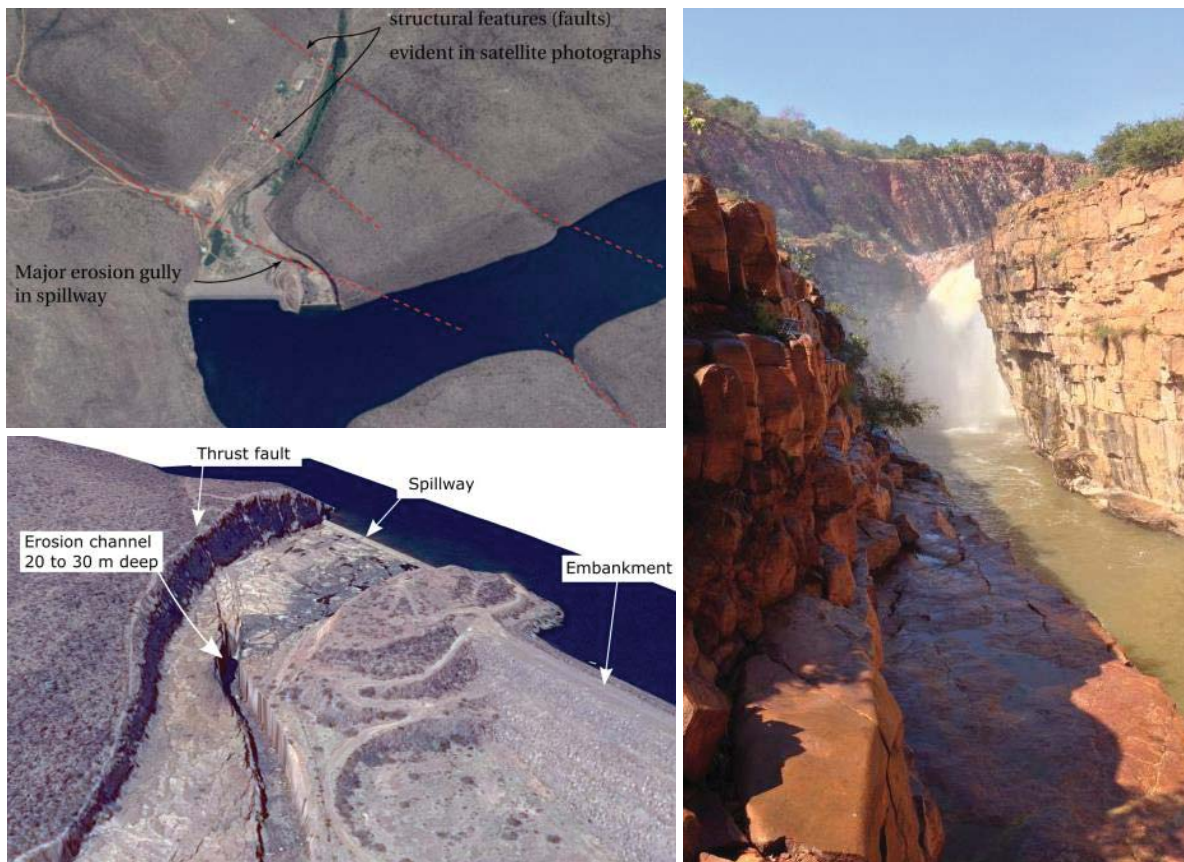


Figure 3. Mokolo dam spillway. Top left: aerial photo showing regional faults. Bottom left: perspective of current erosion slot. Right: deep erosion slot.

At Klipfontein dam, in kwaZulu / Natal in South Africa, the transition of the spillway from the excavated section onto natural materials (i.e. Region C and D in Figure 1) was marked by an increase in gradient. The upper weathered dolerite 'core-stones' were readily removed by first spillway discharges (Figure 4). Over subsequent floods, the extent of erosion found to be limited to the weathered zone, with intact formations underneath adequately resisting erosion.



Figure 4. Erosion of blast-damaged rock at Osplaas dam (left) and weathered dolerite at Klipfontein dam (right)

Soft-rock material forming the unlined spillway at Haarlem dam, in the Western Cape of South Africa, suffered major, progressive erosion through the excavated region (i.e. Regions A to C in Figure 1), initiating from the first spill events. In this case, there were no structural features revealed after the first spill which were the cause of erosion, it was primarily that the natural material was proved to be more erodible than perceived during design (Figure 5).

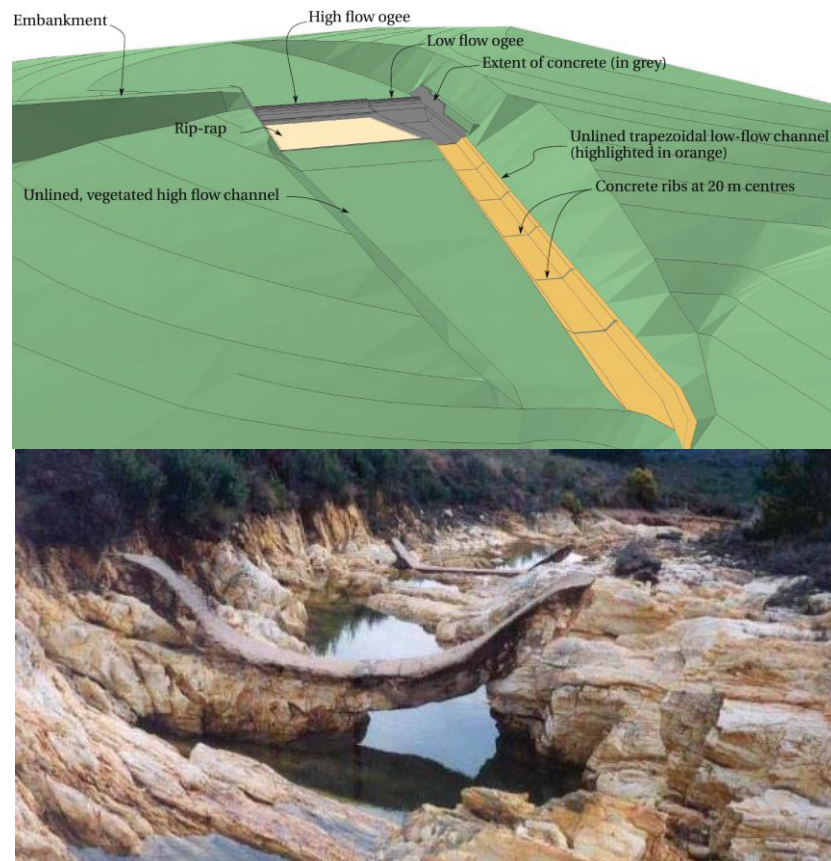


Figure 5. Highly erodible soft-rock at Haarlem dam

In these examples, the extent of erosion was subject to the nature of geological conditions that lay beneath the disturbed or natural materials that were removed during the first spills.

3. ASSESSING EROSION VULNERABILITY IN UNLINED SPILLWAYS

van Schalkwyk *et al* (1994a; 1994b) compiled case studies of erosion at 18 unlined spillways in fractured rock in South Africa, based on the work of Pitsiou (1990) and Dooge (1993). For these case studies, the severity of erosion observed at selected locations within spillways was classified, and the geological conditions at these locations were characterised using rock-mass indices. The hydraulic loading from the relevant flood responsible for erosion was characterised using the unit stream power dissipation (Π_{UD}), defined as:

$$\Pi_{UD} = \rho g \frac{Q}{B_f} \frac{dE}{dL} = \rho g q S_f \quad (1)$$

Where: Q is the discharge (m^3s^{-1}), B_f is the flow width, dE/dL ($= S_f$) is the gradient of the hydraulic grade line, and; q is the specific discharge (m^2s^{-1})

In van Schalkwyk (1994) data from erosion of unlined spillways in earth and soft-rock from the USA (from Moore, 1991) was incorporated into the dataset. The observed erosion was plotted as a function of Π_{UD} and the Kirsten Index “K”, which is a rock-mass index developed to characterise rock mass excavability (rippability) (Kirsten, 1982). A correlation was found, and was proposed as a useful means to obtain a “first pass assessment of erosion potential” (van Schalkwyk, 1994).

Pells (2015) undertook a detailed review of this erosion assessment method. To do this, detailed assessment of erosion of 30 unlined spillways in Australia, South Africa and USA was undertaken, gaining over 100 data points of erosion in fractured rock environments. The observed erosion was categorised in a similar manner to van Schalkwyk *et al* (1994a), using five classes as per Table 1. For each erosion region, interpretation of various rock mass indices (including the Kirsten index), were made, and Π_{UD} was assessed from detailed hydraulic modelling of each spillway.

Table 1. Erosion classes, as adopted by Pells, 2015.

Maximum erosion depth <i>m</i>	General erosion extent <i>m</i> ³ per 100 <i>m</i> ²	Erosion class	Erosion descriptor
< 0.3	< 10	I	Negligible
0.3 to 1	10 to 30	II	Minor
1 to 2	30 to 100	III	Moderate
2 to 7	100 to 350	IV	Large
> 7	> 350	V	Extensive

The resulting dataset was plotted as a function of Π_{UD} and the Kirsten Index “K”, and the interpreted ‘erosion classes’ were contoured. The results are presented Figure 6, overlaid on the original plot of van Schalkwyk (1994). The field data obtained by Pells (2015) confirm that erosion can be correlated with hydraulic loading, as represented by the unit stream power dissipation, and ground quality, as represented by the Kirsten index. The regions of erosion severity presented by van Schalkwyk (1994) provide an appropriate representation of the independent dataset of Pells (2015).

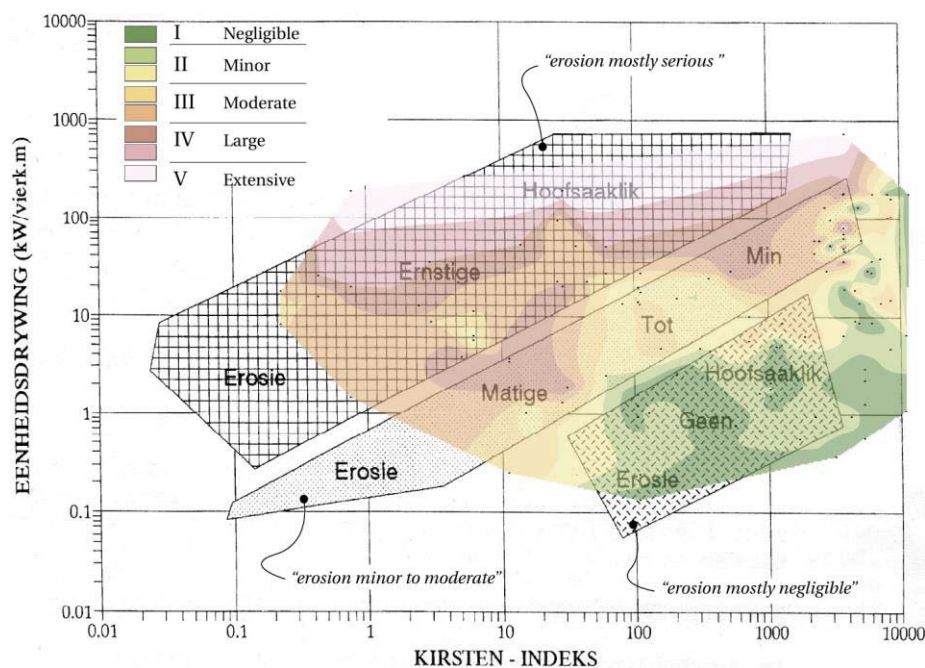


Figure 6. Interpreted erosion potential at spillway case studies, van Schalkwyk, 1994 (contours of case study data from Pells (2015) are overlaid).

Annandale (1995) and Kirsten *et al* (2000) presented similar erosion assessment methods, essentially based on the same data (for fractured rock) as van Schalkwyk (1994). Both authors interpreted the existence of a binary (but differing) ‘threshold of erosion’. Annandale (1995) described this as a “critical threshold to initiate erosion of a material” (pg 471), and recommended that the threshold could be used to progressively model erosion depth (Annandale *et al* 2000). In contrast, the more comprehensive dataset of Pells (2015) did not support either of these ‘thresholds’, but showed a gradation. Pells *et al* (2015) showed that the notion of a binary threshold was inconsistent with observations at case studies and was incongruous with the uncertainty in the dataset. The integrity of the interpretation of case data presented in Annandale (1995) was consequently questioned.

The Kirsten index has been largely forgotten within the rock-mechanics community. Pells (2015) also showed that the factors 'M_s' and 'J_s' used in the Kirsten index to represent rippability of rock do not appropriately represent erodibility of fractured rock. In Pells (2015), various more commonly used rock mass indices, including the Q-system (Barton, 1974), RMR (Bieniawski, 1973) and GSI (Hoek, 1995) were estimated at the spillway case study sites, and a correlation with erosion was found to be similar to the Kirsten index.

Of particular interest in these findings, was the efficacy of GSI in representation of erodibility. In more recent times, the determination of GSI has been shown to be effectively obtained by the simple application of lookup charts (Hoek, 2006, pg 12), such as reproduced in Figure 7. It was shown in Pells *et al* 2015 that assessment of GSI using the chart was as reliable as by calculation, and provides a more repeatable characterisation between different users. Estimation via the chart does not rely on assessment of RQD, which has been shown to be particularly culpable of inconsistent interpretation (Pells *et al* 2015; Forster, 2015), or rock substance strength (UCS), which is an inappropriate measure of erodibility for fractured rock (Pells, 2015). It is argued that the usage of the chart in Figure 8 provides an appropriate inference of accuracy for rock mass index interpretation, in contrast to indices obtained by calculation. Estimation using the chart is also significantly simpler.

GEOLOGICAL STRENGTH INDEX FOR JOINTED ROCKS (Hoek and Marinos, 2000)						
From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Quoting a range from 33 to 37 is more realistic than stating that GSI = 35. Note that the table does not apply to structurally controlled failures. Where weak planar structural planes are present in an unfavourable orientation with respect to the excavation face, these will dominate the rock mass behaviour. The shear strength of surfaces in rocks that are prone to deterioration as a result of changes in moisture content will be reduced if water is present. When working with rocks in the fair to very poor categories, a shift to the right may be made for wet conditions. Water pressure is dealt with by effective stress analysis.						
STRUCTURE	SURFACE CONDITIONS	DECREASING SURFACE QUALITY →				
	INTACT OR MASSIVE - intact rock specimens or massive in situ rock with few widely spaced discontinuities	90	80	70	60	N/A
	BLOCKY - well interlocked undisturbed rock mass consisting of cubical blocks formed by three intersecting discontinuity sets	80	70	60	50	40
	VERY BLOCKY- interlocked, partially disturbed mass with multi-faceted angular blocks formed by 4 or more joint sets	70	60	50	40	30
	BLOCKY/DISTURBED/SEAMY - folded with angular blocks formed by many intersecting discontinuity sets. Persistence of bedding planes or schistosity	60	50	40	30	20
	DISINTEGRATED - poorly interlocked, heavily broken rock mass with mixture of angular and rounded rock pieces	50	40	30	20	10
	LAMINATED/SHEARED - Lack of blockiness due to close spacing of weak schistosity or shear planes	N/A	N/A			

Figure 7. Chart for determination of GSI (from Hoek, 2006)

The GSI index does not, however, incorporate defect orientation which, based on observations at case studies, is considered to be an important factor in erodibility. A factor for representation of vulnerability to erosion from defect orientation was developed in Pells (2015), termed a “discontinuity orientation adjustment for erosion” or “E_{doa}”, giving an erosion-GSI (eGSI) index, thus:

$$eGSI = \max \left\{ \begin{matrix} GSI + E_{doa} \\ 0 \end{matrix} \right. \quad (2)$$

The pictograms presented in Figure 9 and Figure 10 are used to estimate E_{doa}. For the pictograms, rock masses were drawn, with two orthogonal joint sets at various orientations relative to the direction

of flow, and with various relative spacing's, and with the surface creating a roughness and shape that reflects the joint structure. E_{doa} values for each configuration were derived taking in consideration the kinematics of block removal and the nature and direction of hydraulic loading, based on observation at sites and analysis of model tests presented in Pells (2015).

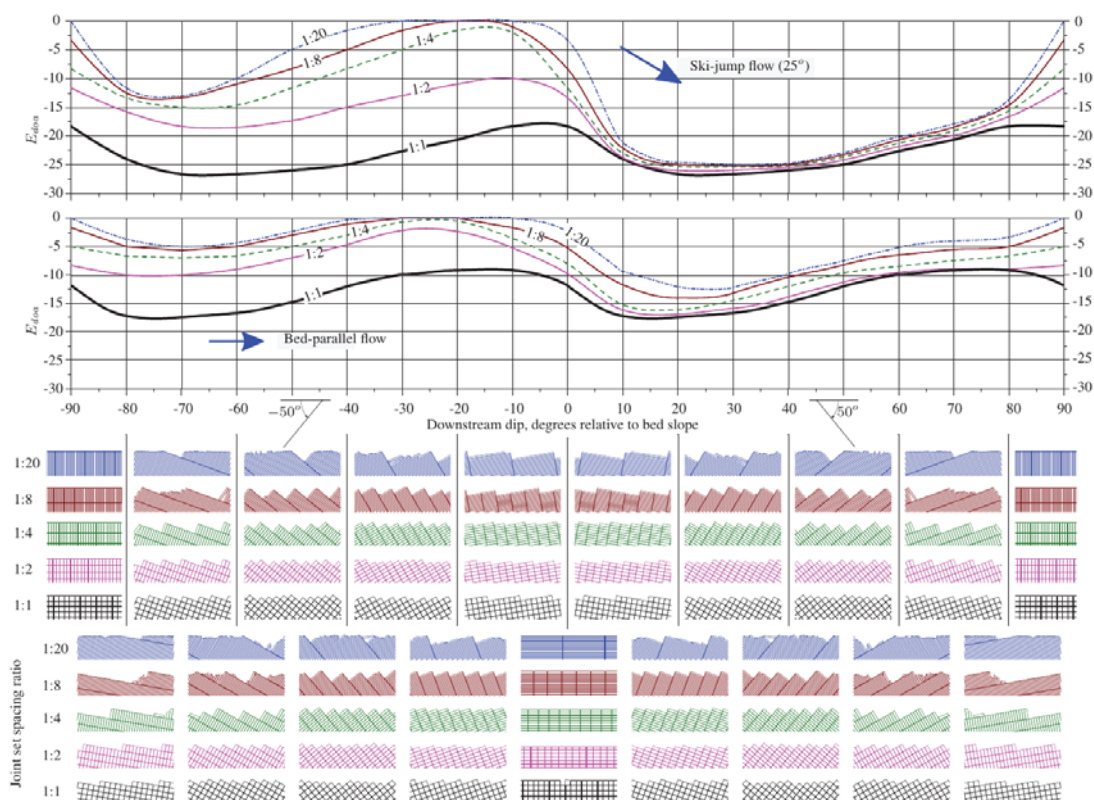


Figure 8. Erosion discontinuity adjustment (E_{doa}), bed-parallel and ski-jump flows

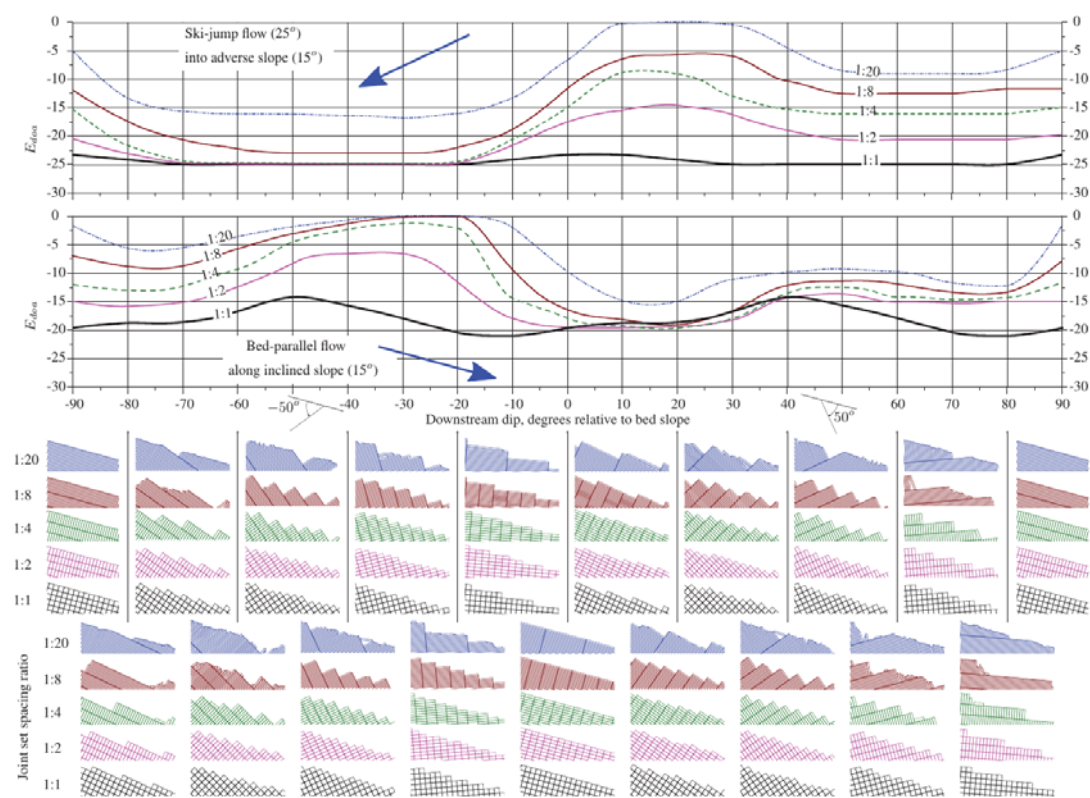


Figure 9. Erosion discontinuity adjustment (E_{doa}), inclined and adverse ski-jump flows

A plot of observed erosion, Π_{UD} and eGSI index is shown in Figure 10. The erosion classes (Table 1) were contoured manually with consideration to the quality of each data point, and allowing for the expected nature of error bars.

Erosion risk can thus be assessed, using Figure 10, in terms of the five classes given in Table 1.

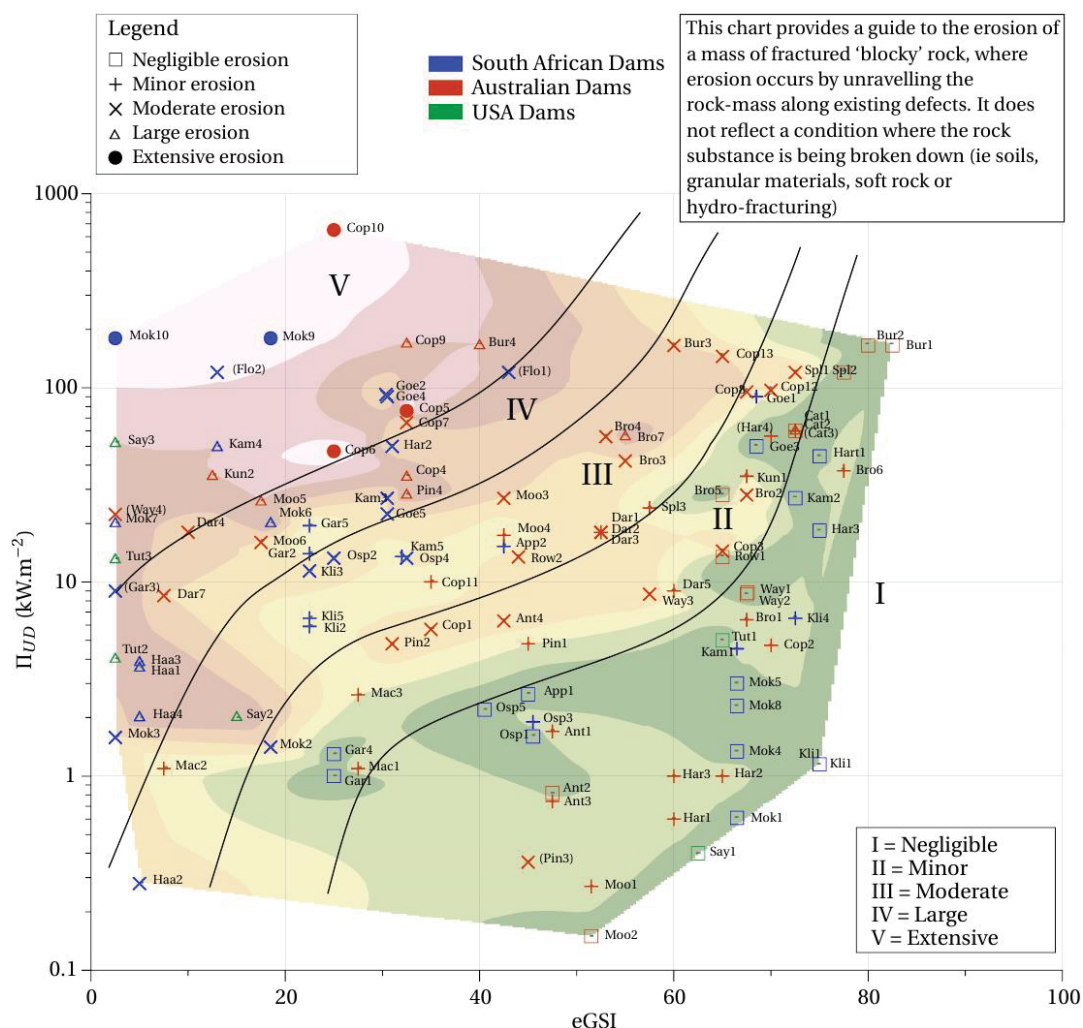


Figure 10. Comparative erodibility assessment

4. RECOMMENDED PROCEDURES FOR EROSION RISK ASSESSMENT AND SURVEILLANCE

The above case examples demonstrate that a high degree of uncertainty exists in characterising the erodibility of unlined spillways in rock. This uncertainty becomes reduced as the spillway is tested, and is 'cleaned up' by spill events. Surveillance of unlined spillways, subsequent to each spill event, therefore provides critical information.

The erodibility assessment methods presented above allow some qualification of erosion risk, based on comparison to case studies. To undertake such assessments, the following procedure is recommended:

1. A review of the site geology, by inspection and review of available data is undertaken.
2. With reference to the spillway geometry, geological regions, and areas of perceived erosion vulnerability are identified
3. For each area of interest, the eGSI index is calculated with reference to Figure 7, Figure 8Figure 9.

4. The value of Π_{UD} is estimated at each of the areas of interest for a range of flood conditions up to the design condition. This estimate may be done by analytical methods, if the geometry of the spillway allow, but should consider gradually varied flow where the spillway geometry and / or roughness is constantly changing. Steady-flow analyses are considered to be sufficient. The outputs from more detailed hydraulic models (such as physical or CFD models) may also be used, but it is cautioned that this is unlikely to provide any increase in accuracy of the estimation, as the data underpinning the comparative design chart is not of this order of complexity.
5. Using the values of eGSI and Π_{UD} , an estimate of the likely category of erosion is made with reference to Figure 10.

The erodibility assessment methods presented above have two major limitations. Firstly, they do not provide an indication of the rate of erosion. Secondly, rock-mass indices do not adequately represent *mechanisms* of erosion in fractured rock. Many of the more dramatic erosion examples examined in Pells (2015) occurred due to specific mechanisms of dismantling of the rock mass structure, which could be perceived by thoughtful consideration during site inspections, but are not necessarily represented by rock mass indices. For example, the dramatic erosion at Mokolo and Copeton dam along lineal fault structures, and in the context of and high insitu stress, was of a nature unlikely to be perceived by generalised rock-mass index assessments alone. *Surveillance is therefore undertaken* to: monitor and assess erosion damage and risks to dam safety; revise estimations of rock mass erodibility; estimate rates of erosion, based on extrapolation, and; identify possible erosion mechanisms.

For example, at Copeton dam, following the major erosion from a relatively small flood event, a series of controlled test spills were undertaken to test the erodibility of the unlined spillway, followed by detailed inspection and topographic survey. These tests indicated ongoing rapid erosion. Based on these tests, the spillway was modified to create two separate spillways – a service spillway over a region proven to be more erosion resistant, and a secondary spillway, to be used with greater caution.

At Moochalabra dam, in Western Australia, the unlined spillway suffers significant erosion during seasonal spill events. Routine ground surveys over 12 sequential years indicate a headcut advance rate in the order of 0.5 to 1 metre per year. As the headcut location is over 100 metres downstream of the reservoir, there is considered to be no immediate risk to dam safety.

The following procedure is recommended for surveillance of unlined spillways following spill events:

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-mounted LIDAR scanners provide rapid and high accuracy surveys. Due to the lack of vegetation in spillways, very cost effective, and sufficiently accurate 3D surveys can be undertaken by photogrammetry, using unmanned aerial vehicles (UAV's). 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 should be undertaken, providing synoptic profiles of hydraulic conditions throughout the spillway.
5. Reassessment of rock mass erodibility, using the methods set out above, should be undertaken.
6. Based on the above information, an appropriately attended risk-assessment workshop should give thoughtful consideration to erosion mechanisms, prediction of erosion development and assessment of risk.

5. ACKNOWLEDGEMENTS

The content of this paper is drawn from the doctoral thesis of the author, and the guidance of thesis supervisors Dr. Bill Peirson and Dr. Kurt Douglas and also Professor Robin Fell is acknowledged. The review by Dr. Philip Pells and assistance in undertaking spillway inspections in South Africa and translation of documents from Afrikaans is also acknowledged.

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