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The influence of geological conditions on erosion of unlined spillways in rock

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Abstract: Erosion in 33 unlined spillways in rock has been studied for dams in Australia, South Africa and the USA. Geological factors which influence the amount of erosion have been identified using published and project data and spillway site inspections by the authors. These are the orientation, persistence, spacing and nature of rock defects including bedding partings, joints, foliation and shears. The presence of kinematically viable blocks which can be detached and the persistence of the basal defect for these blocks are the most important factors.

Where spillways discharge on to a natural slope the presence of valley stress relief features, such as sheet joints parallel to the slope, or kinematically viable blocks, often with open sub-vertical defects, can lead to significant erosion even with small spillway discharges. The mechanism can be one of slope instability rather than erosion as water pressure destabilizes the slope.

A rock mass characterization index, the ‘Rock Mass Erodibility Index’ (RMEI), which considers spillway flow conditions and erosion mechanisms, has been developed. It can be used as a guide to spillway erosion and, when coupled with stream power for spillway flows, provides a method for preliminary assessments of likely amounts of spillway erosion.

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Many dam spillways in rock are unlined to save on construction costs. Some of these discharge on to natural slopes. In some of these, large amounts of erosion have occurred for relatively small spillway flows, requiring substantial remedial works to ensure the safety of the dam.

This paper describes the outcomes of investigations of 33 unlined spillways in Australia, South Africa and USA to determine the geological factors that control erosion. The RMEI is proposed which, with spillway stream power, allows prediction of the amount of erosion in unlined spillways in rock.

Case data

Case studies included spillways where large amounts of erosion had occurred and also cases where erosion was only minor, despite the spillway having been subject to large flows. Case study investigations focused on 19 spillways for dams owned or operated by the sponsors of the study (see Acknowledgements). These were selected based on advice from the sponsors and a review of data held at their respective offices. Also included were 10 spillways for dams in South Africa that had supported previous erosion assessment techniques (van Schalkwyk *et al.* 1994*a*, *b*; Annandale 1995; Kirsten *et al.* 2000). Lastly, two cases studies from the USA are included, based on desktop review only, as the nature of head cutting erosion was clearer in these. In total, 33 case studies of spillway erosion were used. Of these, 23 were examined in more detail and used for development of the RMEI.

The following methodology was adopted for documentation of the geological conditions at each spillway.

1. Published and owners’ project data on geology relevant to the site were reviewed, including geological mapping, rock mechanics testing, construction records and photographs and any relevant previous geotechnical site investigations.
2. Geological ‘domains’ (structural regions) and key structural features (e.g. faults, dykes) on each spillway were identified from available mapping data and/or from inspection of the spillway.
3. Erosion domains within spillways were selected based on the evidence of erosion and where rock mass properties were readily examined. For each spillway at least two and up to 13 domains were used, as detailed in Table 1, giving a total of 101.
4. An assessment of rock substance and rock mass characteristics was undertaken by inspection of each domain, including mapping of defect orientation and spacing.
5. Terrestrial and (in some cases) low-level aerial photography from a drone was undertaken to assist in this process.
6. A classification of the extent of erosion was made, based on observed erosion depth and extent. For one spillway erosion was estimated for more than one time frame to allow consideration of the effects of several floods through spillways.
7. Consideration was given to the structural mechanism of erosion at each erosion domain including consideration of the kinematics of block removal at the erosion area.

The erosion at each domain was classified qualitatively, according to the five classes presented in Table 2. In general, the ground survey data for dam spillways were insufficient to allow accurate assessment of erosion volumes, but an estimate erosion volume was made, primarily on visual assessment and project records.

Reservoir-level records were obtained from the dam owners. From these the number of times the spillway had operated and the flows could be determined as detailed below.

The geological information recorded from this methodology was documented into separate reports for the Australian, South African and USA cases, respectively. These reports, along with interpreted rock mass indices, hydraulic indices and interpreted erosion classes, are included within Appendices to Pells (2016).

Table 1. *Case study sites at which RMEI indices were appraised*

Country	Dam name	Location (WGS84)	No. erosion areas	Geology	Maximum historical discharge (m^3 s^{-1})
Australia	Anthony	41° 52′ S 145° 37′ E	4	Conglomerate	40
	Brogo	36° 29′S 149° 44′E	7	Porphyritic granite	1000
	Burdekin Falls	20° 38′S 147° 8′E	4	Ignimbrite	14 500
	Catagunya	42° 27′S 146° 36′E	3	Dolerite	879
	Copeton	29° 54′S 150° 55′E	13	Granite	1400
	Dartmouth	36° 34′S 147° 32′E	7	Granite gneiss	110
	Harding	20° 59′S 117° 6′E	4	Dolerite	475
	Kununurra	15° 48′S 128° 42′E	2	Quartzite, shale	900
	Mackintosh	41° 42′S 145° 39′E	3	Greywacke, shale	334
	Moochalabra	15° 37′S 128° 6′E	6	Sandstone, siltstone	212
	Pindari	29° 23′S 151° 15′E	4	Rhyolitic porphyry	1300
	Rowallan	41° 44′S 146° 13′E	2	Quartzite, schist	120
	Split Rock	30° 34′S 150° 42′E	3	Greywacke, siltstone	475
	Wayatinah	42° 24′S 146° 30′E	3	Dolerite	968
South Africa	Applethwaite	34° 12′S 18° 59′E	2	Feldspathic sandstone	250
	Garden Route	33° 58′S 22° 31′E	2	Schist and phyllite	127
	Haarlem	33° 46′S 23° 19′E	2	Partly metamorphosed sandstone	170
	Kammanasie	33° 39′S 22° 25′E	4	Micaceous feldspathic proto-sandstone	1310
	Klipfontein	27° 50′S 30° 49′E	5	Dolerite	756
	Mokolo	23° 59′S 27° 43′E	10*	Partly metamorphosed sandstone	400
	Osplaas	33° 27′S 19° 44′E	5	Sandy shale, siltstone and sandstone	27
USA	Saylorville	41° 42′N 93° 41′W	3	Limestone, shale	475
	Tuttle Creek	39° 16′N 96° 35′W	3	Limestone, shale	1700

*There were four erosion domains, three of which had data for three floods.

Spillway flows for the cases investigated

The historical spillway discharge (Q) for each site was obtained from reservoir-level records, and was used to calculate mean flow velocity (u), average bed shear stress (τ_0) and unit stream power dissipation (Π_{UD}) at each of the identified examination areas using a combination of analytical hand calculations and 1D numerical modelling using HEC-RAS (USACE 2010). The numerical modelling provided a more detailed view of the gradient of the total energy line 'S_f' in the context of changing channel width, slope and roughness that was characteristic of the study sites. The numerical model also reported the total energy upstream and downstream of prominent features such as drops and hydraulic jumps, from which an assessment of energy slope over the feature was made. HEC-RAS reported the total energy at the upstream and downstream extents of hydraulic jumps, but was found to produce an unreliable estimate of the length of the jump (the reported length was a function of the computational spacing). In such instances, the jump length was taken as $6y_2$, where y_2 is the water depth downstream of the jump (after Henderson 1966). As the rate of energy dissipation over the jump may not be linear, an upper bound estimate of the friction slope over the jump was also made, assuming that 80% of the energy was lost over the first 50% of the jump length. Only in some cases, where limited topographic data were available, were analytical estimates preferred to the HEC-RAS output. Classical analytical representations of non-uniform flow scenarios, such as head cuts, hydraulic jumps and knickpoints, relate to idealized flow geometry and back-water conditions, and were found to be rarely applicable to real-world case data.

For the determination of RMEI the peak historical discharge was used. The records of erosion were generally not adequate to allow any correlation of erosion with the number of spillway operations, flow rates and duration of flows. The exception was for Mokolo Dam spillway where data were available for three specific floods.

Table 2. *Erosion classes*

Max. erosion depth (m)	General erosion extent (m^3 per 100 m^2)	Erosion class	Erosion descriptor
<0.3	<10	I	Negligible
0.3–1	10–30	II	Minor
1–2	30–100	III	Moderate
2–7	100–350	IV	Large
>7	>350	V	Extensive

Rock mass indices

Interpretation of rock mass indices, and the extent of erosion at each of the erosion areas was undertaken. The indices that were evaluated were:

(a) the Q-system, after Barton *et al.* (1974);
(b) the Kirsten index, after Kirsten (1982);
(c) the Geological Strength Index ('GSI') (Hoek & Bray 1981), using RMR values from Bieniawski (1976); and
(d) GSI using the GSI look-up chart as per Marinos & Hoek (2000).

Analyses of these data, presented in Pells (2016) and Pells *et al.* (2015), confirmed some correlation between the Kirsten index (an index of rock excavatability, after Kirsten 1982) and erosion, as has been demonstrated by various researchers (Moore & Kirsten 1988; Dooge 1993; Moore *et al.* 1994; van Schalkwyk *et al.* 1994*a*, *b*; Annandale 1995; Kirsten *et al.* 2000; USSD 2006). However, the data did not support the various 'binary' thresholds of erosion as interpreted by the above-cited authors, but rather showed a gradation. Furthermore, some correlation was equally found to exist for the other published rock mass indices listed above. For a range of operational and technical reasons, the GSI index, as calculated by chart method (Marinos & Hoek 2000), and with a small adjustment to represent defect orientation (termed 'eGSI'), was shown by Pells (2016) to be a preferred index for representation of rock mass erodibility. The eGSI method (Pells 2016; Pells *et al.* 2017) is suitable for rapid initial assessment of rock mass erodibility, being particularly suitable in the investigation phases of a new spillway when the final spillway geological conditions have not been exposed.

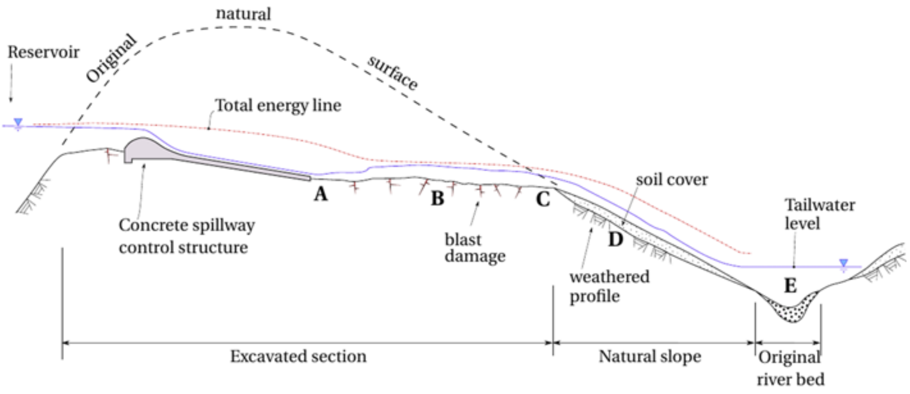

Fig. 1. Conceptual cross-section through side-channel spillway (adapted from Woodward 1981).

However, it was found that existing rock mass indices do not give representation of the mechanisms of erosion that were observed in the field investigations and include a weighting for the unconfined compressive strength of the rock which, for flows in unlined spillways, is judged from the case data to be not a significant factor. To this end, efforts were expended to conceive of a new rock mass index which represented these observed mechanisms, as discussed below.

Hydraulic and geological conditions controlling erosion within the spillway channel

In Figure 1 a conceptual cross-section through a typical side-channel spillway chute is shown. Typically, the side-channel chute is excavated through the ridge or abutment adjacent to the dam. The chute typically has a gradient <10°. A concrete sill is usually constructed to control the reservoir level and discharge characteristics, and an initial section of the spillway may be lined so that the possibility of erosion is moved away from the control section. A flip bucket will often be placed at the end of the lined section (not shown). The excavation will typically ‘daylight’ on to a natural slope, where flows are directed back to the original river bed. The areas marked A to E in Figure 1 are discussed in turn.

A. The smooth lined section facilitates development of high-velocity flows with relatively small head losses (the gradient of the total energy line takes a long distance to approach the gradient of the channel). These high-velocity flows strike the unlined section at point A (or slightly further downstream if a flip-bucket exists) and rapid energy dissipation occurs (the total energy line steepens) over the sudden change in roughness. These flow conditions may induce erosion at point A, particularly where the rock has remnant damage from the blasting for the spillway chute excavation. This erosion may be a hazard to dam safety if a plunge pool or head cut develops, which begins to progressively undermine the lined chute.

B. The excavated, unlined, section of spillway at point B may have a lower gradient and higher roughness, causing slowing and deepening of flows, reducing the erosive power. However, some transport of remnant blocks or blast-damaged rock may occur, and further erosion may develop depending on the geological conditions exposed below. The rock mass defects that control erosion are bedding (if present); joints of tectonic origin; and shears and faults, often with associated closer jointed rock adjacent.

C. Point C marks the knickpoint between the end of the excavated section and the start of the natural slope. The hydraulic conditions here are also transitional, with the gradient of the total energy line steepening in the approach to the steeper natural slope. Upstream migration of this knickpoint is possible if head cutting occurs.

Fig. 2. Photographs of the abutment of Shannon Creek Dam, showing in-filled stress relief joints. The joints are up to 80 mm wide and terminate on shale beds. Photographs courtesy of L. McDonald and Clarence Valley Council (Fell *et al*. 2015).

Fig. 3. Moochalabra Dam spillway showing erosion controlled by sub-horizontal bedding and valley stress relief joints in the near surface.

D. The soil cover on the natural slope at point D is quickly removed by the first flow events down the spillway. Higher rates of energy dissipation on this steeper slope may cause erosion to continue into an upper profile of colluvium, residual soil, and extremely weathered rock. The extent of erosion at this point is subject to the nature of geological structures that lie beneath. Weathering and defects related to valley stress relief dominate to control erosion, typically in the manner below.

In sedimentary rock environments, stress relief on valley formation can result in displacement of blocks of rock and open or soil in-filled joints (Figs 2 and 3). The water from the spillway may penetrate into the joints and displace the blocks by water pressure in the joint and beneath the block. The erosion may progress as head cutting, such as shown in Figure 4.

In igneous and metamorphic rock environments, stress relief on valley formation may result in sheet joints roughly parallel to the ground surface. Sheet joints are most common in massive igneous rocks such as granite and dolerite (Fig. 5) but also occur in metamorphic rocks as shown in Figure 6. Water may penetrate sheet joints, providing uplift and destabilizing the rock above the joint. The erosion process is actually one of slope instability so large amounts of rock can be eroded under small spillway flows.

E. The existing river at point E is typically a lower gradient, and deeper, slower, tailwater conditions may develop. The existing river bed may be armoured from a longer history of flow exposure. Erosion at point E is typically of less concern to dam safety due to its distance from the dam structure.

Fig. 4. Moochalabra Dam spillway showing head cutting in sub-horizontally bedded sedimentary rocks exhibiting head cutting at the downstream faces, but resistance to erosion elsewhere.

Fig. 5. Copeton Dam spillway showing sheet jointing in granite sub-parallel to ground surface controlling erosion.

At any of locations A to D, greater erosion is likely to occur if localized channelling develops, progressively focusing the flows, or if the erosion exposes and follows vulnerable geological structures, such as shears, faults and associated closely jointed rock. The process is quite common and is exacerbated by the flow energy localizing in the deeper eroded areas. This can result in major erosion, as was observed in granite at Copeton Dam (Fig. 7) and in slightly metamorphosed sandstone at Mokolo (Fig. 8) (Pells 2016; Pells *et al.* 2016). At these spillways erosion has followed along faults. The faulting has resulted in closely spaced vertical joints which have combined with sub-horizontal joints to form blocks, which are readily eroded. In each of the case studies, it was observed that erosion of fractured rock could only occur where there was a viable mechanism for the removal of rock blocks, and where hydraulic stagnation pressures acting against or adjacent to a joint caused intrusion of high water pressures around blocks. Where the rock defects did not create isolated blocks, erosion was not seen to occur under the hydraulic conditions experienced at the sites. Where defects were tight and the potentially eroding surface smooth, high water pressures could not be transferred into the defects around the blocks and thus erosion did not occur. These geological and hydraulic mechanisms are discussed in turn.

Fig. 6. Kangaroo Creek Dam site showing persistent valley stress relief sheet joints parallel to ground surface and resulting loosening of the rock with open joints. The sheet joints cross-foliation and tectonic joints within the schist and gneiss. Photograph courtesy of GHD and SA Water.

Fig. 7. Copeton Dam spillway showing deep erosion in closely jointed fault zone. Toppling observed in the photo is understood to have occurred post the spilling event. Sheet joints are shown in the walls.

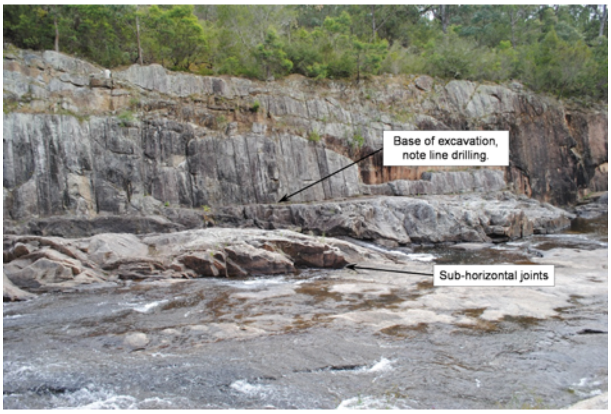

Fig. 9. Brogo Dam spillway showing erosion controlled by persistent sub-horizontal joints.

Mechanisms controlling erosion

Geological factors

From the case data it became apparent that erosion within the spillway channel was controlled by a number of geological factors.

(a) The presence or absence of a persistent basal defect (bedding, joint) favourably oriented to allow detachment of blocks of rock. Blocks bounded by defects sub-parallel to the spillway floor were most likely to be detached. In particular, detachment was likely if these day-lighted either downstream or upstream to give a kinematically viable mechanism. This was commonly present at the downstream end of spillways sited in sub-horizontally bedded sedimentary rocks, e.g. Saylorville and Tuttle Creek (Pells 2016, Appendix C; USACE 1989*a*, *b*, *c*, *d*), Moochalabra (Fig. 4), and spillways which have persistent tectonic or sheet joints paralleling the floor of the spillway, e.g. Brogo, (Fig. 9) and Burdekin Falls (Figs 10 and 11). At Burdekin Falls Dam the area bounded by the closely jointed rock shown in Figure 10, and the spillway eroded to a depth of several metres on first spilling because kinematically viable mechanisms were available, formed by the sub-horizontal defects and the channels in the original river bed, formed by erosion along the closely jointed rock.

(b) Shears and areas of closely spaced joints, often associated with shears which cross the spillway channel, are susceptible to erosion and, once eroded, allow formation of kinematically viable mechanisms to displace blocks in the adjacent rock mass. Examples are Copeton and Mokolo spillways (Figs 7 and 8; Pells 2016; Pells *et al.* 2016).

(c) The nature of the surface of the spillway and whether this facilitated the development of high water pressures in the defects around the blocks of rock. Protruding surfaces with joints open (e.g. from blasting of rock from the spillway during construction) allow the velocity head of the water to be converted to pressure in the defects, assisting in displacing the blocks of rock. Smooth surfaces such as created by glaciation or water and transport of sediment in the beds of rivers were least likely to detach, e.g. Burdekin Falls (Fig. 11). Flow parallel to bedding also was unlikely to detach within the spillway chute, e.g. Saylorville and Tuttle Creek dams (Pells 2016), and Moochalabra (Fig. 4). These geological conditions are, however, subject to head cutting from the downstream slope where the blocks of rock are not constrained on the downstream side.

(d) The nature of the defects forming the blocks of rock in relation to the defect opening and whether these allowed ready movement of the block. Defects bounding the blocks, which are rough and have small aperture, require dilation to displace the block and may require shearing of intact rock to allow the block to detach so detachment is unlikely. Blocks bounded by smooth, open defects or defects infilled with soil are readily detached. The unconfined compressive strength of the defect walls was a secondary factor except for very low strength rock (<1 MPa), soil-infilled defects, and shears.

(e) The spacing of the basal defect has some influence on the likelihood of detachment with wide spacing (large blocks) being less likely to detach than closely spaced basal defects.

(f) The shape of the potentially displaced blocks. Blocks which were tall relative to their width were seen to be less likely to detach.

It was noted that the unconfined compressive strength of the rock was not a significant factor in characterizing rock mass erodibility. For example, large erosion events occurred in high strength rock at

Fig. 8. Mokolo Dam spillway showing erosion up to 25 m deep in fault zone.

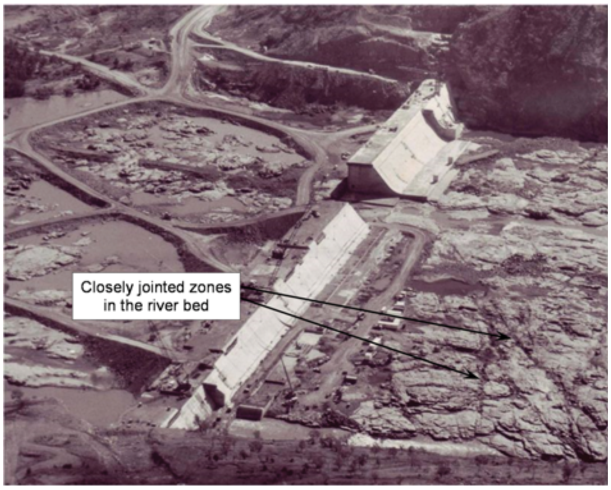

Fig. 10. Burdekin Falls spillway during construction. Protruding blocky rock masses were removed on first spilling due to kinematically viable mechanisms resulting from closely jointed zones in the original river bed.

Fig. 11. Burdekin Falls spillway showing remnant jointed rock, and persistent sub-horizontal defects in ignimbrite. The non-eroded area is characterized by having widely spaced tight joints with no free faces to form kinematically viable blocks.

Copeton Dam and Mokolo Dam, but at Burdekin Falls Dam, also in high strength rock, only minor erosion has occurred, despite regular high energy floods. In the cases of Copeton and Mokolo dams, fracturing associated with lineal fault features allowed rapid dismantling of the rock structure when subject to flows, creating deep erosion gullies. In these cases, high *in-situ* stresses were understood to have contributed to erosion vulnerability due to the formation and opening of persistent sub-horizontal joints by stress-relief and contributing to toppling of rock structures into the gullies (Pells 2016; Pells *et al.* 2016). However, it is noted that high stresses also occur at Burdekin Falls Dam, and have not led to such a mechanism of erosion.

Hydraulic factors

Pells (2016) examined the nature of hydraulic loading imposed upon joint-bound rocks from high-energy flows through extensive physical laboratory testing. It was found that forces able to detach blocks of rock arose at stagnation points where high velocity flows impacted against rock faces protruding into the flow, and the resulting pressures induced within rock defects bounding the blocks. It was found that hydraulic tangential shear-stresses contribute very little to the erosion process. Key findings of interest to erosion of rock masses were that: large stagnation pressures were observed to develop from even a very small protrusion of a rock, or part of a rock, into the flow; and stagnation pressures were readily translated through defects adjacent to exposed faces.

It is the differential in pressure between exposed and sheltered defects defining a block that leads to hydraulic forces on rock elements. It was also observed that turbulent fluctuations in the flow field lead to fluctuation in direction and magnitude of these forces, capable of ‘shaking’ a rock block out of its position.

A methodology for the prediction of these fluctuating forces on defect-bound blocks of various known geometric configurations is presented in Pells (2016).

To provide a generalized assessment of hydraulic loading, where the rock defect geometry is not defined in detail, a hydraulic index can be used as a proxy. That is, even if the precise geometry and orientation of a rock mass structure is not represented, the potential for high hydraulic forces is correlated with the magnitude of

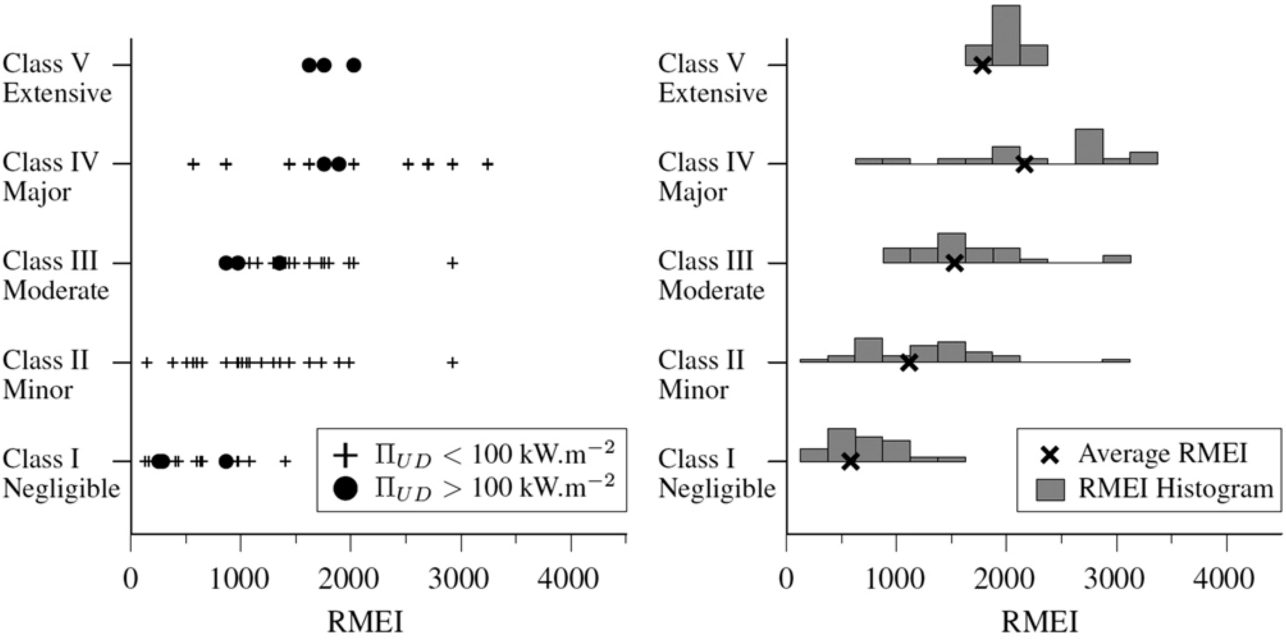

Fig. 12. RMEI v. observed erosion class.

hydraulic energy dissipation. Stream power dissipation has been used in this way as an index of erosive power in sediment transport studies (Bull 1979) and has been adopted as an index of erosive power for fractured rock structures by Moore & Kirsten (1988), Dooge (1993), van Schalkwyk *et al.* (1994*a*, *b*) and Annandale (1995, 2005). The efficacy of stream power dissipation as an index of erosive power was confirmed in Pells (2016). The unit stream power dissipation (i.e. power dissipation per unit of area), denoted herein as Π_{UD}, is defined as:

$$\Pi_{UD} = \rho g q \frac{dE}{dx} \qquad (1)$$

Π_{UD} is the dissipation of hydro-mechanical energy per unit area (W m^{-2}); ρ is the density of water (kg m^{-3}); g is the acceleration due to gravity (m s^{-2}); q is the specific discharge (m^2 s^{-2}) (i.e. total discharge per channel width) and; dE/dx is the total energy head (metres) expended per unit length (for uniform flow this is equivalent to the bed slope 'S_0', and for gradually-varied flows it is approximately equal to the 'friction slope' S_f).

Development of the Rock Mass Erodibility Index (RMEI)

The RMEI has been developed by the authors based on their observations from the case studies of the geological factors controlling detachment of blocks in unlined spillways in rock. The method was developed progressively with trials using the Australian spillway data with several refinements of the factors and their description. This was done initially with little account of the history of spillway flows and resulting hydraulic loads. Later in the development process these loads were introduced as stream power. The structure of the system was based upon that used in Fell *et al.* (2009) for estimating the probability of internal erosion and piping in dams and found there to be useful for combining multiple qualitative factors to assess likelihoods, in this case for predicting the likelihood of detachment of blocks of rock from the spillway floor.

Table 3 presents the erosion vulnerability factors, their relative importance (RF), as judged by the authors, and likelihood factors (LF), which are described for each of the vulnerability factors. Table 4 provides a suggested method for estimating the nature of the defects (erosion vulnerability factor F3). The erosion is quantified as erosion classes as detailed in Table 2.

It should be noted the method is not designed to be binary, i.e. erosion occurs or does not occur. The observations in the case data are that erosion has occurred in all of the spillways and even within one spillway several erosion classes may apply to different erosion domains.

As described in Pells (2016), two expressions for RMEI were trialed based on alternative mathematical operations of RF and LF. One expression was:

RMEI = ∑ (Relative importance factor) × (Likelihood factor) for all five factors.

The adopted RMEI in equation (2) gives a somewhat better outcome and the expression fits better to a risk-based logic and gives a wider spread of RMEI values so has been adopted.

$$\begin{aligned} \mathrm{RMEI} = {} & [\mathrm{RF}_{P1} \times \mathrm{LF}_{P1}] \times [\mathrm{RF}_{P2} \times \mathrm{LF}_{P2}] \times [(\mathrm{RF}_{P3} \times \mathrm{LF}_{P3}) \\ & + (\mathrm{RF}_{P4} \times \mathrm{LF}_{P4}) + (\mathrm{RF}_{P5} \times \mathrm{LF}_{P5})] \end{aligned} \qquad (2)$$

The possible range of RMEI values calculated from equation (1) is 36 to 4500. Low RMEI indicates geological conditions are resistant to erosion whereas high RMEI indicates geological conditions are conducive to erosion.

RMEI values were assessed at erosion domains at 23 dam spillways, representing 101 data points, as presented in Table 1. A plot of RMEI v. observed erosion is presented in Figure 12. Distinct symbols are used to distinguish high stream power (Π_{UD}) case data. It can be seen that there is a reasonable correlation between the observed erosion class and the RMEI without taking stream power into account. The exception is Class V erosion, which has three high stream power data points indicating that when hydraulic loading is high the stream loading dominates the amount of erosion over the geological factors. For lower stream power flows, it is the rock mass – as represented by RMEI – that distinguishes between large and small erosion. Rock masses may be resistant to high energy flows if no kinematically viable mechanisms for detachment exist.

In Figure 13 the case study data are plotted as a function of RMEI and Π_{UD}, and contours were drawn with respect to the observed erosion class.

The erosion class contours in Figure 13 have been modified from what was presented in Pells (2016). This is to allow for the following:

(a) from sediment transport/geomorphological studies, the stream power associated with initiation of sediment movement is in the order of 100 W m^{-2}. Hence the curves have been assumed to asymptote to this value even for rock with high RMEI;
(b) for RMEI = 0, intact rock studies by Kirsten (1995) indicated values of 10 000 to 100 000 kW m^{-2} for erosion of intact materials – the contours' upper range reflects this;
(c) the quality of the data points near the erosion class boundaries.

It can be seen that the erosion class contours correlate reasonably well with the data for erosion classes I, II and III and less so for classes IV and V. The boundary for class V is least well defined as there are fewer data points.

This reflects the accuracy of the data, the complexity of erosion prediction, and the fact that variables included in RMEI and stream power do not capture all the factors involved, including duration of flows in the spillway.

Methodology for assessment of erosion vulnerability using RMEI

The recommended methodology for assessing erosion in existing or planned spillways is to undertake geological investigation; hydraulic analysis and estimation of unit stream power dissipation; and categorization of erosion vulnerability.

Geological investigations

Geological/geotechnical assessments of unlined spillways should be carried out by suitably qualified personnel, who have an understanding of engineering geology and rock mechanics.

For existing spillways, site inspection, including geological mapping and photography should define both geological and erosion domains across the spillway. Within these areas the information required to use the RMEI, as detailed in Tables 3 and 4, should be gathered. The inspections should identify any areas with geological factors which could lead to easy detachment of blocks. These will include faults or other localized areas of sheared or closely jointed rock that could more easily erode and that would, if they erode, cause concentration of water flow and progressive erosion, which may result in kinematically viable mechanisms forming for the rock mass in adjacent areas. These areas should be identified and assessed separately.

For spillways that are still in the design phase, the intent is to obtain the same data. This must be done based on interpretation of a geotechnical model, developed from a geological understanding of valley processes and what to expect in different stratigraphic environments, for example as outlined in Fell *et al.* (2015).

It will be important that investigations include mapping of exposures of rock where exposed and in trenches and pits, as the information required to assess RMEI is not obtained in drill core.

Table 3. *RMEI relative importance (RF) and likelihood factors (LF)*

Erosion vulnerability parameter	Relative importance factor (RF)	Likelihood factor (LF)				
		Very unlikely	Unlikely	Likely	Highly likely	Almost certain
		1	2	3	4	5
F1: Kinematically viable mechanism for detachment*	3	Rock with three defects, basal defect sub-parallel to spillway floor, and no day-lighting basal release surface; or massive rock with effectively only two defect sets and no basal release surface.	Rock with three or more defects, with: basal defect sub-parallel to spillway floor, joint 2 protruding from surface; or basal defect inclined upstream or downstream at >30° relative to spillway floor.	Rock with three or more defects, with: persistent basal defect dip 10 to 30° upstream relative to the spillway floor; or persistent basal defect dip 10 to 30° downstream relative to the spillway floor.	Rock with three or more defects, with: persistent basal defect dip ≤10° upstream relative to the spillway floor; or persistent basal defect dip ≤10° downstream relative to the spillway floor.	Persistent basal defect sub-parallel to the spillway floor, day-lighting upstream or downstream; or persistent shear and/or closely jointed rock which erodes readily forming a release surface into the shear.
F2: Nature of the potentially eroding surface	3	Smooth water or glacier worn, with no protrusions of joint 2, no opening of defects	Bedding surface with protrusions of joint 2 < 1 mm, and little or no opening of defects	Relatively small protrusions and defect openings (e.g. pre-split, or ripped and bulldozed)	Irregular surface following defects, little opening of defects (e.g. blasted rock)	Irregular surface following defects, extensive defect opening (e.g. heavily blasted rock)
F3: Nature of the defects[‡]	2	Very rough surfaces, e.g. JRC ≥12 No separation UCS[‖] >50 MPa	Rough surfaces, e.g. JRC 8–10 Aperture <1 mm UCS 20–50 MPa	Slightly rough surfaces e.g. JRC 4–8 Aperture 1–2 mm UCS 5–20 MPa	Smooth surfaces e.g. JRC <4 Aperture 2–5 mm UCS 1–5 MPa	Smooth or slickensided surfaces Aperture >5 mm UCS <1 MPa, or soft gouge >5 mm thick
F4: Spacing of basal defect[‡]	1	>3 m	1–3 m	0.3–1 m	0.1–0.3 m	<0.1 m
F5: Block shape[§]	1	≤0.5	0.5–1	1–2	2–5	>5

*Defects include joints, bedding surfaces, shears, and foliation partings.

†Select class which best fits the data taking into account the kinematically viable mechanism and which defects control the displacement of the block of rock from the spillway.

[‡] Joint 1 is basal defect of a block or region (bedding or joint).

[§] Block shape = joint 2 spacing/joint 1 spacing; joint 2 is sub-vertical defect normal to the flow in the spillway. JRC, Joint Roughness Coefficient.

[‖] UCS, unconfined compressive strength of the intact rock in the vicinity of the defect surfaces.

Table 4. *Suggested method for estimating F3 'Nature of defects' (Table 3)*

Separation*,‡	Joint Roughness Coefficient (JRC)‡ >12	 8–10	 4–8	 <4	 Smooth and/or slickensided
Tight, no separation	1	1	1	2	2
<1 mm	1	1	2	3	3
1–2 mm	1	2	3	4	4
2–5 mm	2	3	4	5	5
>5 mm	3	4	5	5	5

*If joint is in-filled with soil, or is weathered to UCS <1 MPa, assume in-fill and/or soil is eroded and use eroded opening as separation.

†If joint walls have UCS 1–5 MPa, increase relative importance factor by 1, with a maximum of 5.

‡Joint Roughness Coefficient to be estimated from Barton & Choubey (1977).

There will be greater uncertainty in erosion predictions at the design phase and it will be essential that as the spillway is excavated during construction the area is mapped by engineering geologists and the erosion modelling updated.

The outcomes of these investigations should be shown on plans and sections which can then be related to the stream power estimates for assessing likely erosion.

Hydraulic analysis and estimation of unit stream power dissipation

Estimation of stream power Π_{UD} at each of the erosion domains identified by the geological investigations is undertaken by application of equation (1). Usually the total discharge for a given annual exceedance probability flood is known as a design input, and the flow width and total energy at locations above and below the erosion domain is assessed through hydraulic analysis. Where a spillway channel has a uniform slope, width and roughness, the analysis of uniform slope is simple, as $dE/dx =$ the slope of the channel bed (i.e. uniform flow). However, this is seldom the case for unlined spillways. Analytical closed-form solutions of the total energy for various specific geometries, such as drop-structures and knick points exist, and are recommended in Annandale (2005), although it was found during this study that these specific geometric conditions seldom apply to real world cases (note: values of dx are incorrectly represented in Annandale (1995)). Estimation of the energy gradient is the greatest source of uncertainty in equation (1), and it is recommended the energy

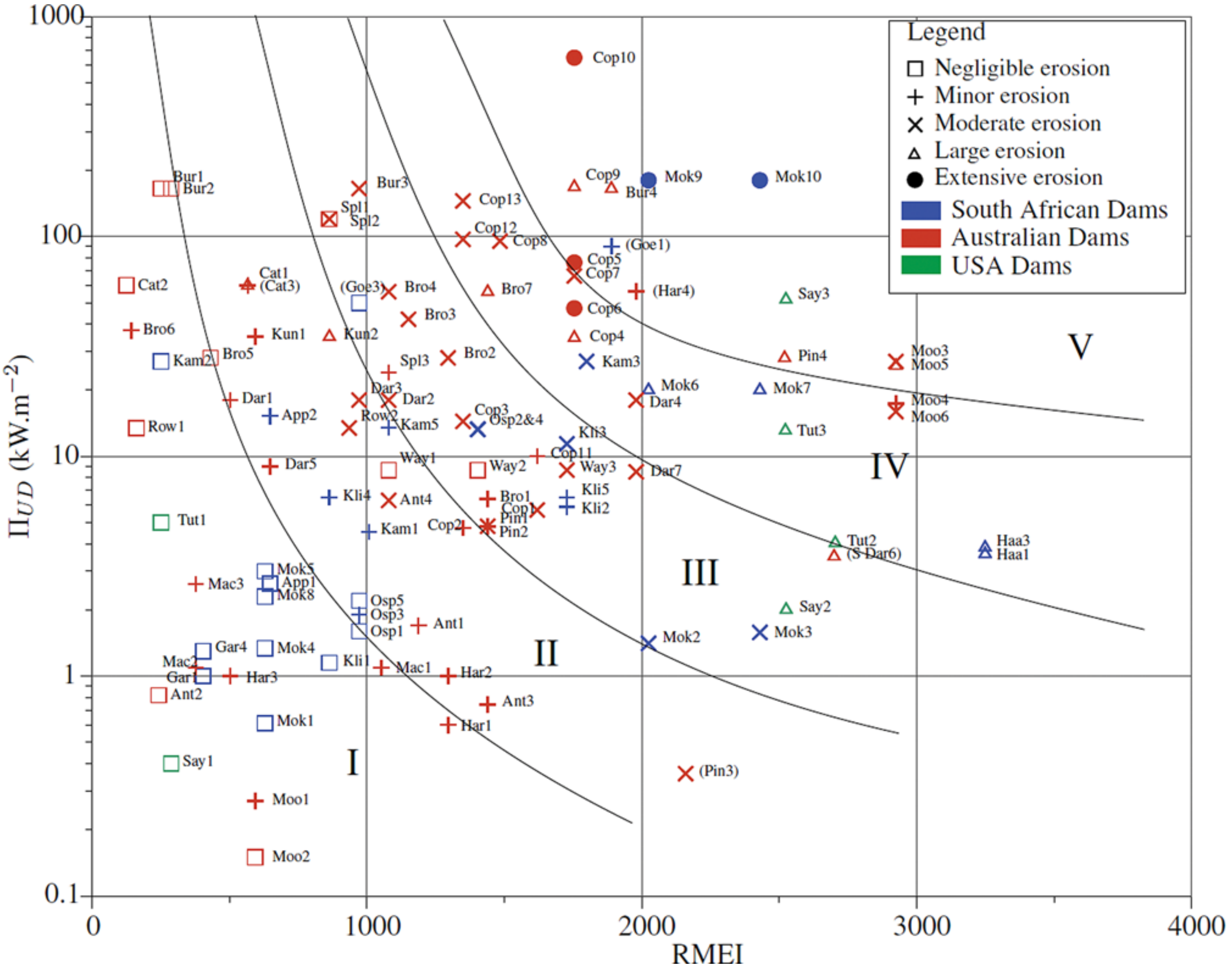

Fig. 13. Observed erosion as a function of RMEI and Π_{UD} showing erosion classes as defined in Table 2.

slope is, in most cases, most reliably estimated though hydraulic analysis of the entire spillway, with assistance from 1D or 2D models, such as HEC-RAS (USACE 2010). For hydraulic jumps, classical energy solutions are available to estimate dE over the jump, with $dx \sim 6y_2$ where y_2 is the water depth downstream of the jump (Henderson 1966).

Categorization of erosion vulnerability

RMEI and Π_{UD} parameters estimated for each spillway erosion domain can be applied to obtain an estimate of erosion vulnerability by application of Figure 13.

Conclusion

Examination of 33 unlined spillways in rock subjected to a range of flows has shown that erosion in the spillway chute and at the downstream end of the chute is controlled by geological factors and the flows in the spillway.

Within the spillway chute the main geological factors are the orientation, persistence, spacing and nature of rock defects, including bedding partings, joints, foliation and shears. The presence of kinematically viable blocks, which can be displaced, and the persistence of the basal defect for these blocks are the most important.

Where spillways discharge on to a natural slope the presence of valley stress relief features, such as sheet joints parallel to the slope, or kinematically viable blocks, often with open sub-vertical defects due to stress relief, can lead to large amounts of erosion even with small spillway discharges. For the sheet joint-controlled erosion the mechanism can be one of slope instability rather than erosion as water pressure destabilizes the slope above the persistent joints.

A rock mass characterization index that considers spillway flow conditions has been developed based on observed mechanisms of erosion at 23 of the spillways visited. This index, the 'Rock Mass Erodibility Index' (RMEI) provides guidance on the erodibility of jointed rock masses. It is shown that this index alone can be used as a guide to spillway erosion and, when coupled with stream power for spillway flows, gives a useful method for preliminary assessments of likely amounts of erosion in unlined spillways.

These methods are applicable to the conditions for which they have been developed and are not suited to assessing erosion for plunging flows, such as occur for spillways on arch dams.

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References

Annandale, G.W. 1995. Erodibility. *Journal of Hydraulic Research*, **33**, 471–494, https://doi.org/10.1080/00221689509498656

Annandale, G.W. 2005. *Scour Technology: Mechanics and Engineering Practice*. 1st edn. McGraw-Hill Professional, New York.

Barton, N. & Choubey, V. 1977. The shear strength of rock joints in theory and practice. *Rock Mechanics*, **10**, 1–54.

Barton, N., Lien, R. &Lunde, J. 1974. Engineering classification of rock masses for the design of tunnel support. *Rock Mechanics*, **6**, 189–236, https://doi.org/10.1007/BF01239496

Bieniawski, Z.T. 1976. Rock mass classification in rock engineering. *In:* Bieniawski, Z.T. (ed.) *Exploration for Rock Engineering, Proceedings of the Symposium*, 1–5 November, Balkema, Cape Town, 97–106.

Bull, W.B. 1979. Threshold of critical power in streams. *Geological Society of America Bulletin*, **90**, 453, http://doi.org/10.1130/0016-7606(1979)90<453:TOCPIS>2.0.CO;2

Dooge, N. 1993. *Die hidrouliese erodeerbaarheid van rotmassas in onbelynde oorlope met spesiale verwysing na die rol van naatvulmateriaal*. MSc thesis, University of Pretoria, South Africa.

Fell, R., Foster, M., Cyganiewicz, J., Sills, G., Vroman, N. & Davidson, R. 2009. *A Unified Method for Estimating Probabilities of Failure of Embankment Dams by Internal Erosion and Piping* (No. UNICIV Report No. R 446). School of Civil and Environmental Engineering, UNSW Australia, Sydney, https://www.engineering.unsw.edu.au/civil-engineering/research/uniciv-reports

Fell, R., MacGregor, P., Stapledon, D., Bell, G. & Foster, M. 2015. *Geotechnical Engineering of Dams*. 2nd edn. CRC Press, Taylor & Francis Group, London.

Henderson, F.M. 1966. *Open Channel Flow*. 1st edn. Prentice Hall, Harlow.

Hoek, E. & Bray, J. 1981. *Rock Slope Engineering*. Institution of Mining and Metallurgy, London.

Kirsten, H.A.D. 1982. Classification system for excavation in natural materials. *Civil Engineer in South Africa*, **24**, 293–308, http://hdl.handle.net/10520/EJC24886

Kirsten, H. 1995. *Erodibility Criterion for Jet Cutting of Intact Materials* (Report No. 197083/3). Steffen Robertson and Kirsten Incorporated, Johannesburg.

Kirsten, H.A.D., Moore, J.S., Kirsten, L.H. & Temple, D.M. 2000. Erodibility criterion for auxiliary spillways of dams. *International Journal of Sediment Research*, **15**, 93–107.

Marinos, P. & Hoek, E. 2000. GSI – A geologically friendly tool for rock mass strength estimation. *In:* GeoEng2000: an International Conference on Geotechnical & Geological Engineering, 19–24 November, Melbourne, Australia. Technomic Publishing Co., 1422–1442.

Moore, J.S. & Kirsten, H. 1988. Discussion – Critique of the rock material classification procedure. *In:* Kirkaldie, L. (ed.) *Rock Classification Systems for Engineering Purposes*, June 25, ASTM, Cincinnati, Ohio, 55–88.

Moore, J.S., Temple, D. & Kirsten, H. 1994. Headcut advance threshold in earth spillways. *Bulletin of the Association of Engineering Geologists*, **31**, 277–280.

Pells, P.J.N., Pells, S.E. & van Schalkwyk, A. 2016. A tale of two spillways. *In:* Proceedings of the International Symposium on "Appropriate Technology to Ensure Proper Development, Operation and Maintenance of Dams in Developing Countries", SANCOLD, 18 May, Johannesburg, South Africa, 2a-279–2a-288.

Pells, S.E. 2016. *Erosion of Rock in Spillways*. PhD thesis, UNSW Sydney, http://handle.unsw.edu.au/1959.4/56008

Pells, S.E., Pells, P.J.N., Peirson, W.L., Douglas, K. & Fell, R. 2015. Erosion of unlined spillways in rock – does a "scour threshold" exist? *In:* Contemporary Challenges for Dams. Proceedings of the Annual Australian National Committee on Large Dams Conference, ANCOLD, 4–8 November, Brisbane.

Pells, S.E., Douglas, K., Pells, P.J.N., Fell, R. & Peirson, W.L. 2017. Rock Mass Erodibility. *Journal of Hydraulic Engineering*, **143**, 06016031, https://doi.org/10.1061/(ASCE)HY.1943-7900.0001243

USACE 1989*a*. *Geotechnical Aspects of Rock Erosion in Emergency Spillway Channels*. USACE Technical Report REMR-GT-3, Report 1. Cameron, C.P., Cato, K.D., McAney, C.C. & May, J.H., http://wri.usace.army.mil/remr/technical_reports/

USACE 1989*b*. *Geotechnical Aspects of Rock Erosion in Emergency Spillway Channels*. USACE Technical Report REMR-GT-3, Report 2, Analysis of field and laboratory data. Cameron, C.P. & Patrick, D.M., http://wri.usace.army.mil/remr/technical_reports/

USACE 1989*c*. *Geotechnical Aspects of Rock Erosion in Emergency Spillway Channels*. USACE Technical Report REMR-GT-3, Report 4, Geologic and hydrodynamic controls on the mechanics of knickpoint migration. May, J.H., http://wri.usace.army.mil/remr/technical_reports/

USACE 1989*d*. *Geotechnical Aspects of Rock Erosion in Emergency Spillway Channels*. USACE Technical Report REMR-GT-3, Report 5, Summary of results, conclusions and recommendations. Cameron, C.P., Patrick, D.M. et al., http://wri.usace.army.mil/remr/technical_reports/

USACE 2010. *HEC-RAS River Analysis System Hydraulic Reference Manual* (computer program documentation No. Version 4.1). USACE, Hydrologic Engineering Center.

USSD 2006. *Erosion of Unlined Spillways*. United States Society on Dams, Denver.

van Schalkwyk, A., Jordaan, J.M. & Dooge, N. 1994*a*. *Die erodeerbaarheid van verskillende rotsformasies onder varierende vloeitoestande* (No. WNK Verslag No. 302/1/95). verslag aan die waternavorsingskommissie deur die Departement of Geologie, Universiteit van Pretoria, South Africa, http://www.wrc.org.za/Pages/DisplayItem.aspx?ItemID=8165&FromURL=%2FPages%2FAllKH.aspx%3F

van Schalkwyk, A., Jordaan, J.M. & Dooge, N. 1994*b*. *Erosion of Rock in Unlined Spillways. 18th ICOLD Congres*. Durban, Q.71 E.37, 555–571, and Minutes: van Schalkwyk, A. 1994. *Minutes – Erosion of Rock in Unlined Spillways*. ICOLD q.71 r.37, 1056–1062.

Woodward, R.C. 1981. *The geology of dam spillways*. PhD thesis, University of New South Wales, Australia.