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The Application of the RMEI Scour Assessment for a Heterogeneous Rockmass in an Unlined Spillway Channel

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Abstract: A scour assessment using the Rock Mass Erodibility Index (RMEI) was carried out for the Spillway Return Channel of the Fred Haigh Dam, Queensland. The dam spillway comprises an ogee crest with a 70 m concrete lined chute and a flipbucket, beyond which the unlined Spillway Return Channel discharges into the Kolan River 350 m downstream. Deep scouring (>30 m in places) has occurred in the Return Channel since its construction in 1974, with the most severe events, due to dam spilling, between 2009 and 2017. The complex geology of the site comprises rocks of the Good Night beds and Mount Whacogo Volcanics with several intrusive subvertical dykes and faults. Significant geological mapping, boreholes with televiewers and Sirovision discontinuity mapping was used for geomechanical assessments. This paper discusses the methodology used & the challenges faced to determine the rockmass characterization and parameters selection for a heterogeneous rockmass as inputs into the RMEI assessment, being validated by an alternative eGSI assessment. The rockmass was subdivided in 4 domains with similar geology and geomechanical characteristics. Discontinuities were sorted by domains and statistically analyzed to derive each of the required parameters of the RMEI. Stream Power values were obtained from CFD modelling for a range of flow scenarios. The obtained values were compared and back analyzed against the historic scour behavior of the channel.

Keywords: Spillway; Scour Assessment; RMEI; Heterogeneous Rockmass

1 Introduction

Fred Haigh Dam is located on the Kolan River, west of Bundaberg. The dam is a zoned earth and rock-fill embankment, 456 m in length with a maximum height of 52 m. It has a storage capacity of 562,000 ML with a full supply level (FSL) at EL 75.56 m AHD.

The dam spillway comprises an uncontrolled ogee-crest mass concrete structure, with a concrete lined chute terminating in a trajectory bucket which discharges to a predominantly unlined rock chute. The unlined channel downstream of the trajectory bucket was excavated for approximately 140 m until it intersected with the natural surface and to the first major bend in an existing natural channel, and then continued to the Kolan River confluence approximately 210 m downstream. The channel between the flip bucket and the Kolan River confluence is referred to in this paper as the Spillway Return Channel.

The Spillway Return Channel has had excessive scour since the dam commissioning in 1974 with the most significant events in the last 10 years. Spilling events have produced deep scouring of the channel floor and erosion of the right bank in excess of 30 m. A scour assessment was undertaken to ascertain risks of the impact of additional channel loss to defined dam Business Risks of a Pumping Station and associated power supply.

The scour assessment undertaken has been based on methodologies developed by Pells (2016) defined by the calculation of the eGSI and the Rock Mass Erodibility Index (RMEI). A number of factors were considered to assess both historic and potential scour including spillway dimensions & arrangement and review of spillway flow activity; various survey data files over time, as well as aerial photography relating to measurement of scour (bed and bank loss) including any observed scour patterns; review of geology and the associated assessment of geomechanical and rockmass characteristics; understanding of the hydraulics within the spillway channel and determination of stream power dissipation.

The RMEI and eGSI methodologies implies that the rockmass within the unlined spillway channel have continuous defects and to some degree that the rockmass is homogeneous. The rockmass within the Fred Haigh Dam is considerably variable in composition with multiple rock types overprinted by a complex structural history, resulting in a highly heterogeneous nature characterized by a series of volcanic dykes and a fractured host rock of the Good Night beds. The authors have applied both methodologies to assess the scour potential of the highly heterogenous rockmass throughout a comprehensive statistical analysis and selection of parameters at defined geological domains.

2 Flow and Scour History

Since the dam commissioning in 1974, the spillway has discharged on 21 occasions. The January 2013 flood (6.86 m depth) is the largest event recorded to date, and it has been identified as close to a 1 in 1,000 Annual Exceedance Probability (AEP) event with the corresponding maximum discharge in the order of 1,800 m^3/s. Other spilling events of note that also caused significant scour of the Channel include, August/September 2011 & 2015, April and October 2017 (associated with Cyclone Debbie) and 2018.

The scour and associated bank instability within the Spillway Return Channel has caused the formation of a number of deep scour holes within the Channel (see Figure 1), and associated deposition downstream.

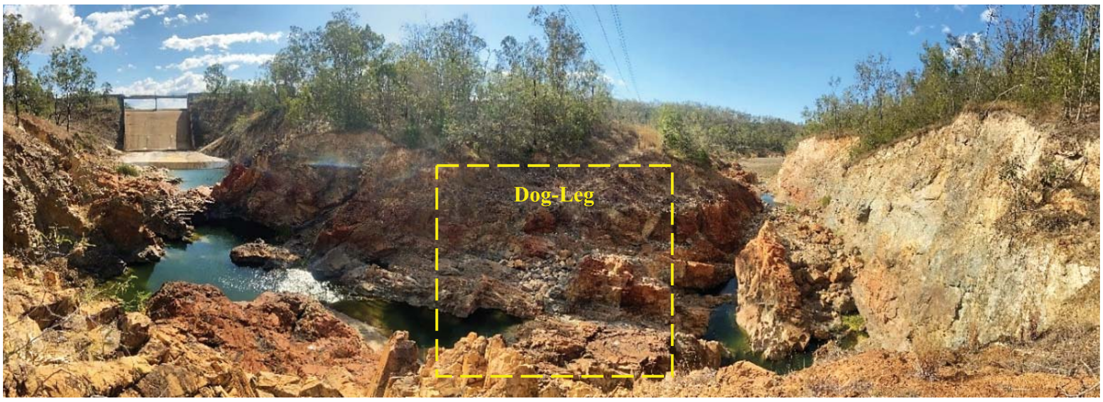

Figure 1. Spillway Return Channel general overview from the "Dog-Leg"

3 Regional Geology

Fred Haigh Dam is mostly underlain by rocks of the Good Night beds (GNB). The GNB are part of the New England Orogen and located in the Wandilla Province being within the Coastal subprovince (Jell, 2013). The Wandilla Province comprises the accretionary wedge of the Devonian – Carboniferous subduction complex located in the northern part of the New England Orogen. This complex geological history has led to a highly truncated structural setting, where the regional and site-specific stratigraphy has been overprinted by multiple faults and sheared zones, as well as intrusions with abrupt contacts between formations.

The GNB comprise deep marine deposits of Carboniferous to Early Permian (Cisuralian), typically categorized by slate, phyllite, argillite, chert, jasper, arenite, limestone, basic metavolcanics and diamictite; they generally outcrop at the upper part of the spillway channel and up to the Dog-Leg section. Below the Dog-Leg and on the right margin of the Channel the Mount Whacogo Volcanics outcrop. The Mount Whacogo volcanics are described as feldspar-phyric rhyolitic to dacitic lava with ignimbrite and porphyritic andesite to basalt lava and volcanoclastics, epiclastic sandstone and conglomerate and minor mudstone.

The findings of geological mapping undertaken do not entirely agree with the published sources suggesting that the Spillway Return Channel is dominated by rhyolitic volcanics and to a lesser extent by the GNB, with the Mount Whacogo Volcanics generally only outcropping on the right bank below the Dog-Leg.

4 Geotechnical Investigations and Mapping

Most historic geotechnical investigations for Fred Haigh Dam were undertaken in 1965 and during the initial stages of construction (1972). These investigations comprised boreholes, seismic refraction surveys and test pits. No other geological mapping of the dam site was undertaken until the early 2000's, when excessive scour and erosion of the Spillway Return Channel became sufficient from spilling events to be seen as a possible risk to appurtenant structures. From 2004 onwards a number of geological mapping and related studies associated with spilling events and further Spillway Return Channel scour/erosion were undertaken. As part of this study additional boreholes, mapping and Sirovision surveys of the Spillway Return Channel were carried out to provide discontinuity data for physically constrained areas (steep unstable slopes) which were considered potential health and safety risks to mapping teams. The scour assessment undertaken has compiled all geology mapping and borehole data from 2015 onwards, as well as defect data from the Sirovision survey. Over two thousand discontinuity data points were available for the scour assessment.

5 Geology Domain Definition

A series of Geology Domains were defined along the spillway channel in an attempt to group sections with similar geology and geomechanical properties. This was particularly challenging due to the difficulties associated with a discontinuous rockmass, which is continuously “interrupted” by dykes and faulting. These “interruptions” create “hard and soft layers” (dykes and fault zones respectively) that create jumps and turbulence to the water flow within the Spillway Return Channel. Therefore, a comprehensive review of the site geology was undertaken, in relation to the spillway geometry, structures, and areas of similar perceived erosion vulnerability, resulting in the definition of four main Geology Domains for the scour assessment as shown in Figure 2.

Domain 1 is located immediately below the flip bucket and comprised Rhyolite/GNB Metasedimentaries with large number of volcanic intrusions/dykes; Domain 2 is predominantly Mafic Intrusives & Rhyolites with minor GNB; Domain 3 comprises Rhyolites & Volcanics; minor GNB. Domain 4 is represented by rocks form the Mt Whacogo Volcanics. Additionally, Domain 3 was subdivided in Domain 3A (Highly to Moderately Weathered rock; outcropping on the upper Channel lower left bank) and Domain 3B (Slightly Weathered or better rock).

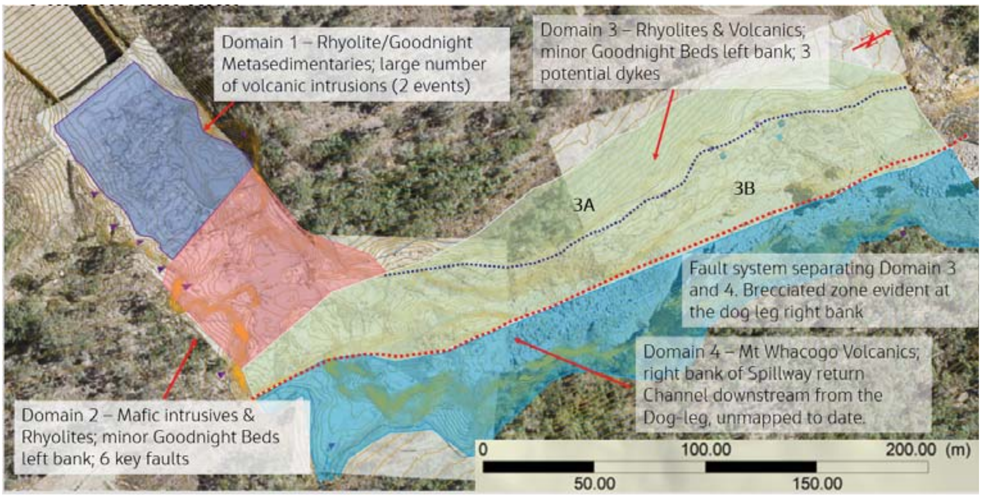

Figure 2. Fred Haigh Dam Spillway Return Channel - Geology Domains Definition and Distribution

6 Scour Assessment

Prediction of potential scour in unlined spillway channels can be difficult to assess as geological rock masses are generally complex and heterogeneous. Abrupt changes in the rockmass geomechanical properties occur within a short distance creating differential scouring and an associated complex bed and bank topographical character. Therefore, turbulent flows are generated with high degree of variability in the Stream Power Dissipation values. The general approach that has been used for this assessment combines the RMEI methodology proposed by Pells (2016) to characterize the rockmass and its vulnerability to scour together with the unit stream power dissipation (Π_{UD}) to represent the scour capacity of water. The eGSI (Pells et al, 2017) approach has also been applied to provide a sensitivity analysis & therefore confidence in the RMEI analysis. The value of Π_{UD} was estimated along the channel for a range of flood conditions with the aid of CFD modelling. This paper only provides the results of the Historic High Event (2013) and the DCF (Dam Crest Flood). The assessment undertaken for Domain 3A is indicative only since the eGSI and RMEI methods “does not reflect a condition where the rock substance is being broken down (i.e., soils, granular materials, soft rock, or hydrofracturing)” (Pells, 2016).

6.1 eGSI Estimated Values

GSI and eGSI has been determined along the Spillway Return Channel for the selected domains as a first pass to determine the Scour Classification for each domain and to provide additional confidence in the results derived from the RMEI. Pells (2016) recommends derivation of GSI values from the GSI table (Marinos & Hoek, 2000), rather than calculation from the RMR (Bieniawski, 1973). The determination of the GSI values has been carried out as per the original GSI table (Marinos & Hoek, 2000) for Domain 1 & 4, while the GSI value for Domains 2 & 3B has been derived from the GSI table modified for Flysch conditions (Marinos & Hoek, 2007) which has been interpreted to better represent the inherent rockmass conditions. The E_{doa} is a discontinuity orientation adjustment for erodibility with the value derived from Figures 3.20 and 3.21 from Pells (2016) and assessed with the aid of the kinematic analysis carried out for the Scour Vulnerability Parameter P1 of the RMEI. **Table 1** presents the derived GSI and E_{doa} parameters, as well as the eGSI.

Table 1. Resultant eGSI values for each assessed Domain

	Domain 1	Domain 2	Domain 3A	Domain 3B	Domain 4
GSI	55	40	20	50	35
E_{doa}	-17	-27	-20	-25	-13
eGSI	38	13	0	25	22

6.2 RMEI and Scour Vulnerability Parameters Calculations

The RMEI methodology defines five Scour Vulnerability Parameters namely, P1- Kinematically Viable Mechanism for Detachment, P2- Nature of the Potential Eroding Surface, P3- Nature of the Defects, P4- Spacing of the Basal Defects and P5- Block Shape. The RMEI was calculated by estimating the Likelihood Factors (LF) for each of the five Scour Vulnerability parameters (P1 to P5), as per Table 3.3 of the Pells, S (2016). Once the scour vulnerability was determined for the five parameters, the RMEI value was calculated using Eq. (1):

$$RMEI = (RF_{P1} \times LF_{P1}) \times (RF_{P2} \times LF_{P2}) \times \left[\left(RF_{P3} \times LF_{P3} \right) + \left(RF_{P4} \times LF_{P4} \right) + \left(RF_{P5} \times LF_{P5} \right) \right] \quad (1)$$

Where RF indicates the Relative Importance Factor which varies from 3 for P1 and P2 (most important factors), 2 for P3 and finally 1 for P4 and P5 (least relevant factors). The RMEI was calculated for each of the Geology Domains.

6.2.1 P1 - Kinematically Viable Mechanism for Detachment

The Scour Vulnerability Parameter P1 (Kinematically Viable Mechanism for Detachment) has been determined by kinematic analysis using DIPS with sets determined from all the relevant data for each Domain. Based on the Kinematic Failure criteria set out by Douglas, et al. (2018), the number of basal defects falling within a certain attitude of the spillway floor will contribute to the likelihood of erosion failure in the event of a spilling episode. A kinematic analysis for Planar Sliding (no lateral limits) was established for each domain at three different slope envelope intervals as follows: less than 10 degrees downstream or upstream of the channel floor, between 10 to 30 degrees and above 30 degrees from the channel floor. The kinematically viable mechanism for detachment parameter P1 factor was determined for each domain following the descriptors included in Table 3 of Douglas et al (2018) and Table 4 of Ryan & Pells (2018).

6.2.2 P2 – Nature of the Potential Eroding Surface

A series of photographic records were reviewed and analyzed for each domain along the Spillway Return Channel. In terms of spillway floor macro-roughness, it was evident from the photographs and site inspections, that the surface of the unlined section and its openness generally are described as Likely (Domain 1) to Almost Certain in Domains 2 to 4.

6.2.3 P3 – Nature of the Defects

Pells (2016) establishes 3 different methods to determine the P3 parameter, by using the UCS of the rock, the JRC roughness (Barton et al, 1977) or by using the defects aperture values. In this scour assessment JRC values have been used in favor of Aperture or Rock Strength. Aperture of the discontinuities did not provide any meaningful result based on statistical analyses, whilst no reliable data was available for UCS across all the domains (due to multiple rock types with differing weathering grades, and the fact that many of the project specific laboratory UCS tests undertaken failed along incipient fractures). Additionally, Douglas et al., (2018) and Baumaiza et al (2019) note that UCS of rockmasses is not a significant factor in characterizing rockmass erodibility. Parameter P3 for Domain 4 was estimated based on Sirovision data, photographic records, and site observations.

6.2.4 P4 – Spacing of the basal defects

Parameter P4 was primarily determined by an assessment of the discontinuity data from the geological mapping and borehole logs (Domain 3 only). The parameter was based on the basal joint spacing and only planes with a dip lower than 15 degrees were considered. The amount of data was relatively small compared with other parameters, since the number of planes that daylight at the bottom of the channel were limited.

6.2.5 P5 – Block shape

Parameter P5 is defined as the relationship between the height and the width of the block. The block shape parameter has been determined by selecting the average basal discontinuities spacing divided by the average spacing of all the subvertical planes. Parameter P5 for Domain 4 was estimated partially on Sirovision data, but mostly photographic records and observations. Table 2 presents the assessed P1 to P5 parameters and the calculated RMEI as per equation 1.

Table 2. Assigned Likelihood Factors for each Scour Vulnerability Parameter per Domain

Scour Vulnerability Parameter	Domain 1	Domain 2	Domain 3A	Domain 3B	Domain 4
P1	4	5	5	3	4
P2	4	5	5	5	5
P3	3	4	5	3	5
P4	4	4	5	3	3
P5	3	3	3	3	3
RMEI	1872	3375	4050	1620	2880

7 Stream Power Dissipation Values

The Stream Power Dissipation values were calculated using a complex CFD model, with the relevant obtained values reproduced in Table 3 showing the 90-percentile value across each Domain.

Table 3. Stream Power Dissipation (kw.m^{-2}) 90 Percentile for each Domain

Scenario	Domain 1	Domain 2	Domain 3A	Domain 3B	Domain 4
Historic High Event	47,641	38,301	9,248	9,248	18,255
DCF	98,977	75,388	14,827	14,827	25,508

8 Scour Classification

Pells, S (2016) established a qualitative classification to provide an estimate of scour vulnerability in terms of five classes where the descriptors range from 'negligible' for Class I to 'extensive' for Class V. The scour classes have been derived by plotting the eGSI vs the II_{UD} on Figure 3.23 Pells (2016), similarly the RMEI vs the II_{UD} were plotted on Figure 3.56 to obtain the scour class. This was carried out for each Domain and the Historic High Event, as well as the DCF as shown in Figure 3. The resultant scour classes are summarized in Table 4.

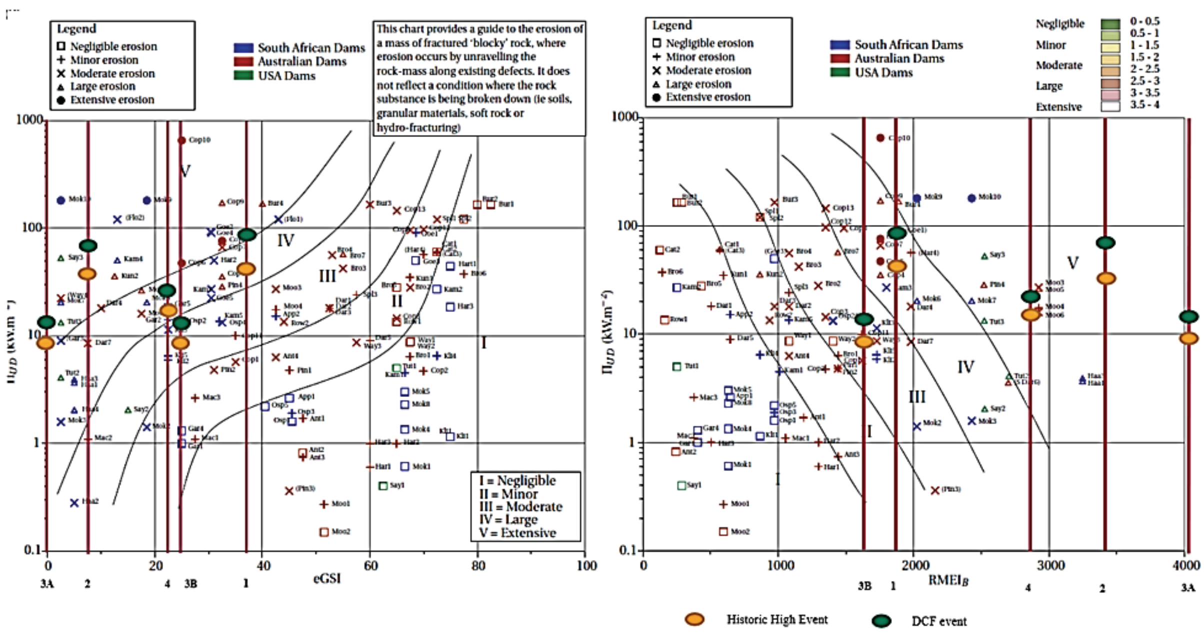

Figure 3. eGSI (Left) and RMEI (Right) vs Stream Power Dissipation (kw.m^{-2}) plots for all Domains

Table 4. Scour Classification for each Domain

Scenario		Domain 1	Domain 2	Domain 3A	Domain 3B	Domain 4
Historic High event	eGSI	IV	V	V	III	IV
	RMEI	IV	V	V	III	V
DCF	eGSI	V	V	V	III	IV
	RMEI	IV	V	V	III	V

9 Discussion of Results

The authors have assessed the RMEI as a primary method, but also have undertaken the assessment using eGSI with the results being compared against the historical scour data. Since the scour class is directly associated with the RMEI value / eGSI value, as well as the Steam Power Dissipation, it was envisaged that both classifications will show higher scour potential closer to the flip bucket where the Steam Power dissipation is higher. The scour class obtained through the RMEI and eGSI analysis showed that Domain 1 located closer to the flip bucket will have a higher potential to scour despite having the second lowest value in the RMEI (the lower the more resistant to scour) and the highest value in eGSI (the higher the more resistant to scour). Equally the opposite is true for the results showing the Domain 3B as the areas less likely to present deep scouring, since the Steam Power Dissipation is lower in this area and also due to the fact that Domain 3B presents the lowest RMEI value and the second highest eGSI value. However, the results do not correlate with the historical scour in the Domain 4 area, which includes the right bank of the lower section of the Channel. Here the actual scour has been greater than predicted by the eGSI method but matches with the RMEI. This discrepancy has been attributed to the lack of geology field mapping of this area and the likely mis-selection of the E_{doa}. Additionally, most of the erosion has occurred laterally, rather than vertical scouring of the rock.

10 Conclusions

This paper presents the results of a case study where a heterogenous rockmass has been assessed for scour potential by following the eGSI and the RMEI methodologies proposed by Pells, S. (2016) along the Fred Haigh Dam Spillway Return Channel. The scour potential assessments of heterogenous rockmasses has been challenging as abrupt changes in the rockmass geomechanical properties occur within a short distance. These abrupt changes produce turbulent flow generating a high degree of variability in the Stream Power Dissipation values. In these situations, it is recommended to assess the rockmass as a series of Geological Domains, with each domain representing a significant portion of the spillway with similar definable properties, with in this case four Domains being identified. Each domain has been assessed for the Historic High Event and the DCF flood scenarios. The scour assessment using the RMEI and eGSI revealed consistent results for each defined Geology Domain / flood scenario, as well as the actually observed scour along the Spillway Return Channel; however, the eGSI did not reflect the actual scour magnitudes observed in Domain 4 possibly since most of the scour has occurred laterally rather than vertically. The quality and quantity of the data was a defining factor in the success of the methodology application, with the appropriate selection and statistical analysis of the right data an extremely important factor in the assessment of the Scour Vulnerability Parameters (P1 to P5) for the RMEI calculations. The eGSI and the RMEI methodologies can be applied with confidence on heterogenous rockmasses, however the RMEI does require a large amount of quality data to successfully assess scour potential.

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