

Utah State University

DigitalCommons@USU

International Symposium on Hydraulic Structures

Jun 28th, 10:30 AM

Spillway Rock Scour Analysis - Composite of Physical & Numerical Modelling, Paradise Dam, Australia

E. J. Lesleighter

Lesleighter Consulting Pty Ltd, lesleighter@yahoo.com

E. F.R. Bollaert

AquaVision Engineering

B. L. McPherson

Specialist Services NSW Public Works

D. C. Scriven

SunWater Limited

Follow this and additional works at: <https://digitalcommons.usu.edu/ishs>

 Part of the [Hydraulic Engineering Commons](#)

Recommended Citation

Lesleighter, E., Bollaert, E., McPherson, B., Scriven, D. (2016). Spillway Rock Scour Analysis - Composite of Physical & Numerical Modelling, Paradise Dam, Australia. In B. Crookston & B. Tullis (Eds.), *Hydraulic Structures and Water System Management*. 6th IAHR International Symposium on Hydraulic Structures, Portland, OR, 27-30 June (pp. 343-352). doi:10.15142/T300628160716 (ISBN 978-1-884575-75-4).

This Event is brought to you for free and open access by the Conferences and Events at DigitalCommons@USU. It has been accepted for inclusion in International Symposium on Hydraulic Structures by an authorized administrator of DigitalCommons@USU. For more information, please contact digitalcommons@usu.edu.



Spillway Rock Scour Analysis - Composite of Physical & Numerical Modelling, Paradise Dam, Australia

E J Lesleighter¹, E F R Bollaert², B L McPherson³ and D C Scriven⁴

¹Director, Lesleighter Consulting Pty Ltd, NSW

²Principal, AquaVision Engineering Sàrl, Ecublens
Switzerland

³Principal Engineer, Specialist Services NSW Public Works

⁴Principal Civil Design Engineer, SunWater Limited, Queensland
Australia

E-mail: lesleighter@yahoo.com

ABSTRACT

A number of problems and solutions of rock scour downstream of spillways have been evaluated using a composite approach based on the gathering of detailed data from a physical model and utilizing those data in a sequence of calibration and application of numerical modeling of the scour. This paper will describe the application of the Computational Scour Model (CSM - Bollaert, 2002 and subsequent) as the numerical procedure that makes the composite approach a proven methodology for such problems. The paper will focus on a case study application of the procedure based on the experiences of flooding and scour at the Paradise Dam, Queensland, Australia.

Flooding in 2013 caused substantial scour downstream of the primary spillway. The occurrence led to a series of studies for the evaluation of the geology and the evident hydraulics behaviour, using a well-instrumented physical model to capture pressure and velocity transients, all as part of a process to determine the scour mechanism and to determine the response of the spillway and areas downstream to future floods of larger magnitude. Utilizing the transient data from approximately 60 pressure transducers, ADV measurements for transient velocities, and a detailed geologic assessment, the comprehensive scour modeling procedures developed by Bollaert were applied for calibration of the numerical model and its application for possible discharge scenarios.

The paper will discuss the design and construction of the physical model and instrumentation as a key part of securing adequate data for the composite procedure, and goes on to illustrate the outcomes of the CSM procedures.

Keywords: *Spillways, flood hydraulics, hydraulic modelling, numerical modelling, rock scour, transients, numerical analysis, energy dissipation.*

1. INTRODUCTION

Since 2010, a succession of floods in eastern Australia, and particularly in Queensland, brought about spillway operation with return periods in the region of Annual Exceedance Probabilities (AEP) of 1 in 2,000 or more. Rock erosion at Wivenhoe Dam (near Brisbane) has been discussed in a number of publications (Lesleighter, Andaroodi & Stratford (2012); Lesleighter, Stratford & Bollaert (2013); Bollaert & Lesleighter (2014); and Bollaert, Stratford & Lesleighter (2014)).

Paradise Dam, Queensland, is a RCC dam with a 315 m long stepped primary spillway with an ogee crest level of EL 67.6 m. A flood with a peak discharge having an AEP of 1 in 30 occurred in December 2010-January 2011. This caused a certain amount of re-adjustment of the loose rock and alluvium and some damage to the stilling basin apron due to ball milling effects from rock in motion. The focus of the present paper is an appreciably larger flood (AEP in 1 in 170) in January 2013, which caused extensive and deep scour downstream of the apron as well as removal of a 1-metre-high end sill.

Following that flood, investigations comprising the geology downstream of the spillway, detailed surveys, and concrete works to repair and enhance the stilling basin apron have been directed towards investigation of the rock scour and its possible occurrence in the future. A key thrust of the studies has been the use of a physical model to quantify the hydraulics and hydrodynamics of the primary spillway and numerical modelling to evaluate the possible rock scour for future discharge scenarios. The paper provides detail according to the following:

- A description of the scour
- The geology of the areas prone to scour
- The flood characteristics
- The design of the physical model
- The application of geologic and model data for processes of calibration and application of Comprehensive Scour Modeling, (CSM – Bollaert (2004)), and
- The modeling outcomes and preliminary investigation of types of remedies.

2. PARADISE DAM PRIMARY SPILLWAY

The primary spillway is 315 m long with an ogee crest at EL 67.6 m and maximum height of 36.1 m. The crest is constructed in conventional reinforced concrete, and the downstream stepped face is capped with reinforced concrete anchored into 620 mm tall RCC steps. At the base of the steps, spillway flows meet a horizontal apron approximately 20 m in length with a vertical end sill 1 m in height. At the left end of the spillway, the original apron was at a level of EL 37.6 m, and at the right end, the apron was at EL 30.9 m. Figure 1 is a photograph of the dam and spillway. Figure 2 shows some detail of the primary spillway.



Figure 1. Paradise Dam primary spillway (2007)

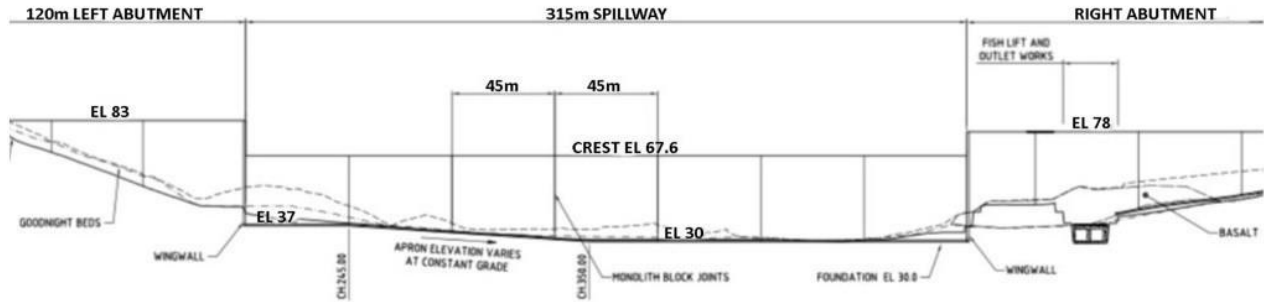


Figure 2. Transverse section of primary spillway (from upstream)

3. THE FLOOD OF 2013

The primary spillway was overtopped by 6 m on 29 December 2010. The reservoir level peaking at EL 73.6 m and remained above the crest level for more than three weeks. The peak discharge was equivalent to approximately 9,600 m³/s, or a unit discharge, q , of 30.48 m²/s. Table 1 presents the AEP discharges up to the AEP 1 in 10,000. Of much more consequence was a flood in January 2013. The peak reservoir level was EL 76.2 m, 8.6 m above the crest, and the corresponding discharge was 17,090 m³/s, a unit discharge of 54.3 m²/s. The Paradise outflow hydrograph is shown in Figure 3.

Table 1. Paradise Dam AEP Discharges

AEP (1 in year)	Discharge (m ³ /s)
50	12,840
100	15,410
200	17,490
500	20,820
700	22,330
1,000	24,440
2,000	28,180
3,000	31,950
10,000	48,740

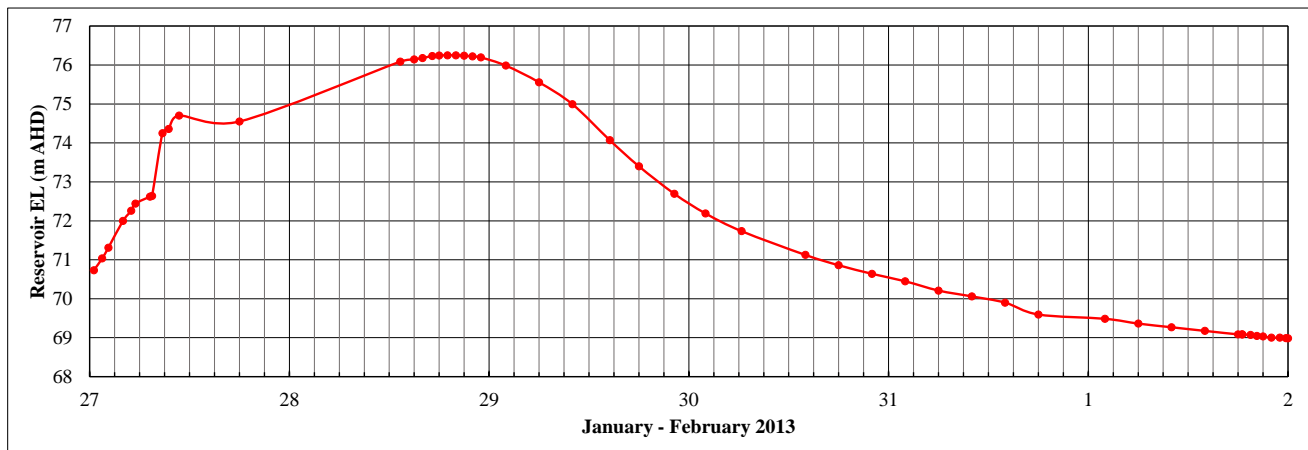


Figure 3. Paradise primary spillway stage hydrograph January 2013

The earlier flood produced some scour of material downstream of the spillway – mainly removal of alluvium and some movement of loose rock and rip rap. The 2013 flood, however, produced scour right across the length of the

primary spillway, some deep scour adjacent to the apron, and removal of the end sill. Figure 4 is a photograph of the flood behavior, and Figure 5 illustrates the scoured surface over the area downstream of the spillway.

The damage was judged sufficiently extensive to warrant a certain amount of repair concrete works in the interim and led to a series of activities to fully investigate what the event meant in relation to future floods. Those activities broadly comprised more detailed geologic investigations, and a model testing and scour modeling program – the latter being the emphasis of the present paper.

4. GEOLOGY

The scour from the 2013 flood (Figure 5) demonstrated a geologic condition that provided scant resistance to the energy dissipated during the four-to-five day 2013 flood event. The dam is generally founded on metasediments known as the “Goodnight Beds” except on the right side where it is founded on basalt. Following the flood of 2013 and subsequent scour, further geotechnical investigations were undertaken. Features of particular note are faults, termed the “Paradise Fault” and the apron faults.

The Paradise fault, located downstream of the dissipator slab, is a zone of Goodnight Beds that has been subjected to intense structural deformity. The zone is characterised by a series of closely spaced shears, dykes, and faults. These features are steeply dipping. The apron faults are a series of major thrust faults that meander between outcropping downstream of the dissipator slab or concealment under the slab. These faults dip moderately underneath the dissipator slab.



Figure 4. Flood behaviour January 2013



Figure 5. 2013 flood scour downstream of the primary spillway

The deep scour that occurred in the 2013 flood, relatively close to the apron, including the removal of the vertical end sill, led to a series of investigations and analyses related to dam stability and the part that the geologic conditions played in the dam's integrity. It was necessary to augment the geologic knowledge of the site by extensive site investigations and mapping.

The safety evaluations included not only the depth of scour that had occurred – up to 13 m below apron level in one location – and the geologic investigations, but also investigation of the integrity of the concrete in the spillway apron. At an early stage following the 2013 flood, concrete works were implemented immediately downstream of the apron and included a capping slab on the apron itself. These measures were simply a precaution while the more detailed studies were being carried out.

As it was clear that future floods might lead to more extensive scour of the apron and rock downstream of the apron, the dam owner, SunWater, defined and initiated additional studies of the geology and evaluations of the stability of the dam as well as the program of hydraulic modeling and numerical scour modeling, which are the subject of the present paper.

5. PHYSICAL MODEL

A three-dimensional hydraulic model was commissioned by SunWater. It was built and tested by the Manly Hydraulics Laboratory (MHL), Sydney NSW for detailed studies of the Paradise Dam spillways. The hydraulic modeling was one part of a two-part hybrid approach to the rock scour investigation – the other part being the application of a numerical modeling calibration and analysis procedure.

The model was built to a scale of 1:70, with the ability to test for discharges up to the AEP 1 in 10,000. It was set up to investigate the spillway's as-built condition, the post-2011 flood condition, the post-2013 flood condition including interim works mentioned above, and studies of the secondary spillway overflow of the right abutment of the dam. Figure 6 provides a general view of a portion of the model with some of the flush-diaphragm transducers. Figure 7 shows the model operating at a mid-range discharge. Model instrumentation included more than 60 pressure transducers, a large number of piezometers, and an Acoustic Doppler Velocimeter (ADV) with electromagnetic flow metering up to model discharges of 1,200 L/s. Figure 8 illustrates the pressure transducer coverage on several lines.

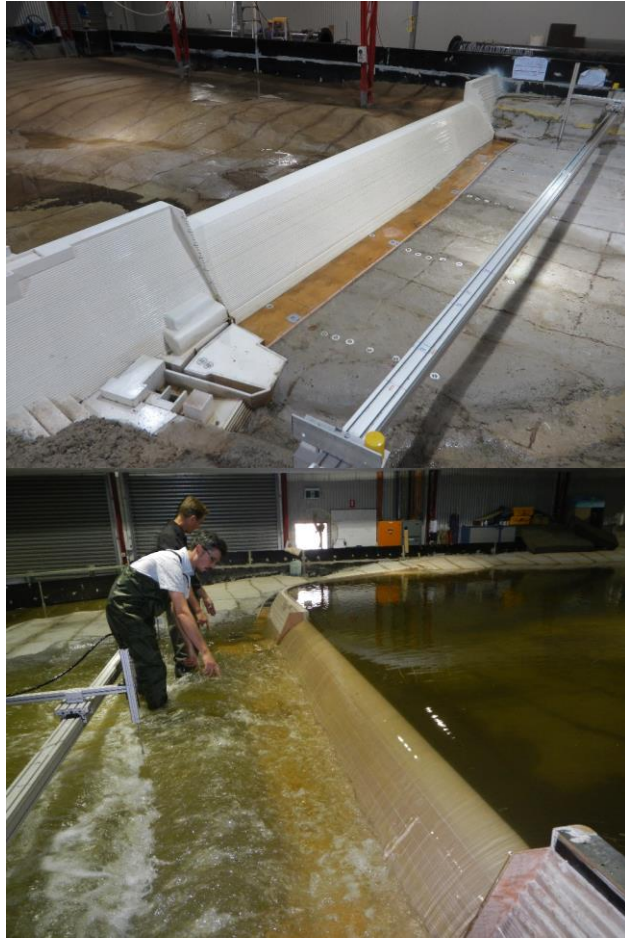


Figure 6. Model showing pressure transducer lines

Figure 7. Paradise Dam physical model

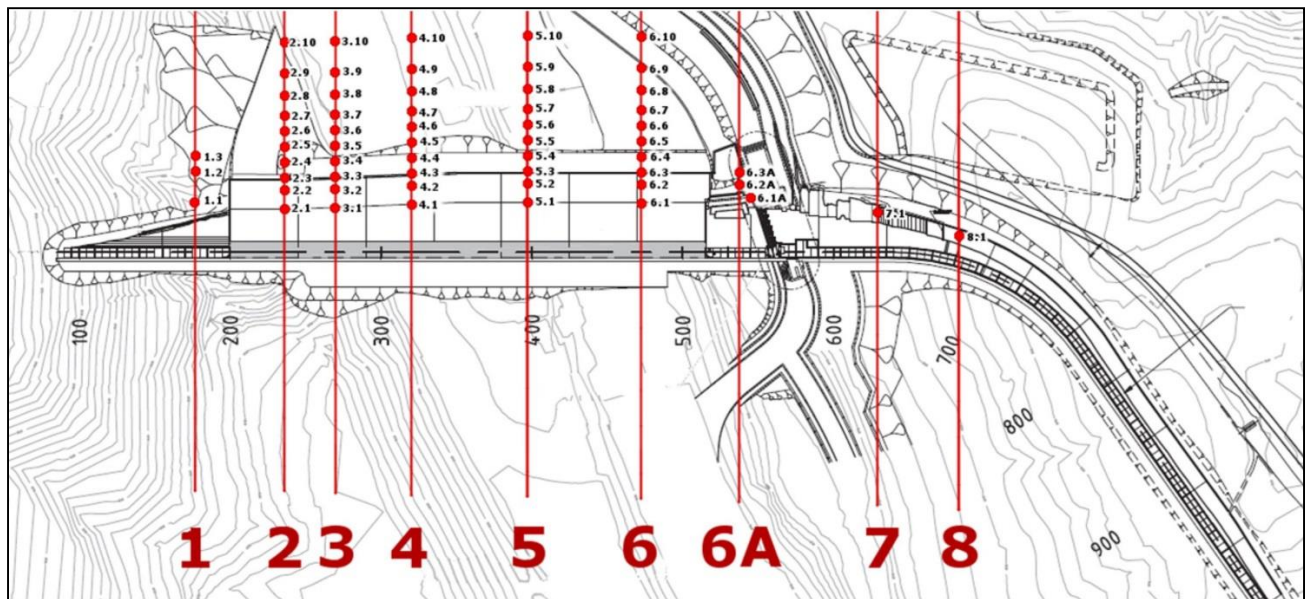


Figure 8. Paradise model pressure transducer coverage

The sensors used were Keller Series 25 flush diaphragm temperature-compensated vented-gauge transmitters, factory-adjusted to provide a single-ended high level linear output from -30 to +200 mbar. Velocity measurements were made using a SonTek 10-MHz ADV. Velocities at each measurement location (subject to the water depth) were recorded at four or five heights for each flow test in the x, y, z directions. All ADV velocity measurements were recorded at a sampling rate of 20 Hz for a 60-second period. The transient pressures at 58 locations in the spillway apron and downstream were measured at a sampling rate of 400 Hz for a period of 150 s (60,000 values).

6. FACTORS AFFECTING ROCK SCOUR

In evaluating the factors which affect rock scour, it becomes clear that it is not simply a case of velocity, however high the velocity may be, but it is the characteristics of turbulence and the intensity of turbulence in the energy dissipation process, which is going on in dissipators and plunge pools. Furthermore, the presence of entrained air is important because of the physics of what is going on in flows impacting rock bodies containing an array of fissures. Vital to the erodibility issue is the particular geology of the plunge areas. The character of the rock mass with its variability and low strength character is key to the manner in which the rock will respond to the flows impacting it. The velocities impacting the deep tailwater at Paradise would be generally less than about 25 m/s, and at the rock surfaces, the impact velocities due to a certain amount of decay would be appreciably lower. Of particular relevance to the ability of a plunging jet and hydraulic jump to fracture the rock is the way pressure transients impact the rock surface and penetrate the rock defects and bedding.

The scour that occurred at Paradise Dam primary spillway resulted from discharges that had a difference in head between the reservoir level and the tailwater level of less than 30 m – a difference that can be classed as modest when compared with many spillways operating under much greater heads.

For a long time, the design of stilling basins was based on velocities and sufficient depths to retain a hydraulic jump. Bowers and Toso, 1988, reported as follows: “*many of the large dams in the United States utilize ... structures designed before information was available on the magnitude of fluctuating pressures in the hydraulic jump ... turbulent pressure fluctuations in the hydraulic jump should be considered in the design of stilling basins...*” It is the key effect of the transient behavior that is encompassed in the numerical procedures to estimate rock scour as described below.

The hydrodynamics of situations like those at Paradise Dam show that it becomes not simply the velocities, or even the pressures impacting the rock surfaces, but also the transient behavior in the turbulent flow and in addition a mechanism of amplification of pressures within the rock defects and fissures. The transients play a vital and often neglected part.

7. BOLLAERT COMPREHENSIVE SCOUR MODEL (CSM)

The Comprehensive Scour Model comprises three methods that describe failure of jointed rock. The Comprehensive Fracture Mechanics (CFM) method determines the ultimate scour depth by expressing instantaneous or time-dependent joint propagation due to water pressures inside the joint. The Dynamic Impulsion (DI) method describes the ejection of rock blocks from their mass due to sudden uplift pressures. The Quasi-Steady Impulsion Model (QSI) describes peeling off of rock blocks from their mass by quasi-steady wall jet flows. The structure of the Comprehensive Scour Model consists of three modules: the falling jet, the plunge pool and the rock mass. The latter module implements the aforementioned failure criteria. More details on equations that describe the hydrodynamics can be found in Bollaert (2004).

The ‘falling jet’ module describes how the hydraulic and geometric characteristics of the jet are transformed from dam issuance down to the tailwater pool. The ‘plunge pool’ module describes the characteristics of the jet when traversing the pool into which the jet impinges and defines the water pressures at the water-rock interface. In the Paradise situation, the overflow jet impacts the tailwater and spreads to then be deflected by the apron into the tailwater on the way to impacting the rock, generating in this way a sort of semi-submerged hydraulic jump turbulence. Finally, the ‘rock mass’ module contains the aforementioned rock break-up methods. The main

hydrodynamic parameters used by the CSM are the bottom flow velocities and the fluctuating and maximum dynamic pressures. In this study, these were recorded firstly on a physical model for different discharge scenarios, and then used as input by the CSM. Full details of the numerical rock break-up modules are outside the scope of this paper, and a comprehensive discussion of the components of the methodology and their direct relevance to the dynamics of rock scour is described by Bollaert et al, 2014 (ICSE Perth).

The detailed analyses that have applied the CSM procedures passed through two stages of calibration using the actual flood hydrograph in histogram format and use of the calibrated model to estimate various scour flood discharge scenarios. The calibration, for the most part, used the actual hydrographs of the 2013 flood. The calibration analyses for one of the profiles downstream of the spillway, Line 2 (see Figure 8), are shown in Figure 9.

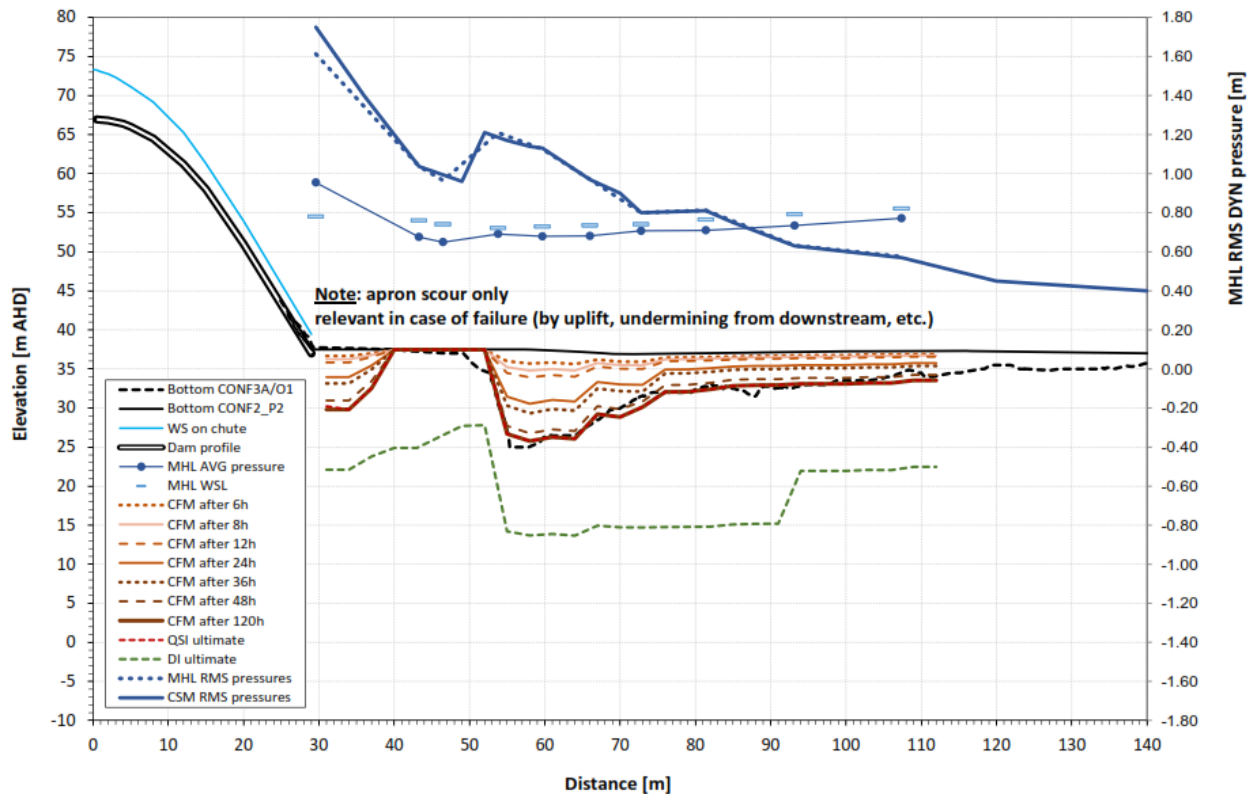


Figure 9. CSM calibration for the 2013 flood hydrograph

The profiles show the analysis of scour for the three modules described above (CFM, QSI, and DI). In this flood, the rock scour was extensive. There are some key profiles to note. In light blue, the average of the dynamic pressures elevation from the transducers is shown. In heavy blue, the standard deviation of the measured and CSM calculated fluctuations is shown (read right). Other key profiles are in brown and show the estimate of progressive scour with exposure times for 6 to 120 hours. These may be compared to the black dashed profile, which is the surveyed profile following the 2013 flood.

On the basis of a successful calibration, as adjudged from the profiles exemplified in Figure 9, the CSM procedure was in a position to proceed to analysis of future scour. For those procedures, it was necessary to determine a long-term series of flood discharges that could be applied to determine on a time or year basis the expected scour that could occur downstream of the primary spillway. Using the selected discharge scenarios and the dynamic pressures and flow velocities as measured on the physical model, the CSM was set up also to investigate possible works if they were determined to be required.

Figure 10 is an example of the estimated potential scour downstream of the existing apron for a range of discharges devised to represent a scenario of six floods with discharges ranging from an AEP of 100 to and AEP of 1 in 10,000. While each module of the CSM procedure is shown (brown, red dashed, and green dashed), the time estimate of

scour using the Comprehensive Fracture Mechanics module, shown in brown, is deemed to represent the possible scour progress for the selected hypothetical range of floods and discharges. As noted on the figure, the scour profiles “under” the apron (distance 30m to 50m) apply to the possible scour in the event that the apron was actually removed.

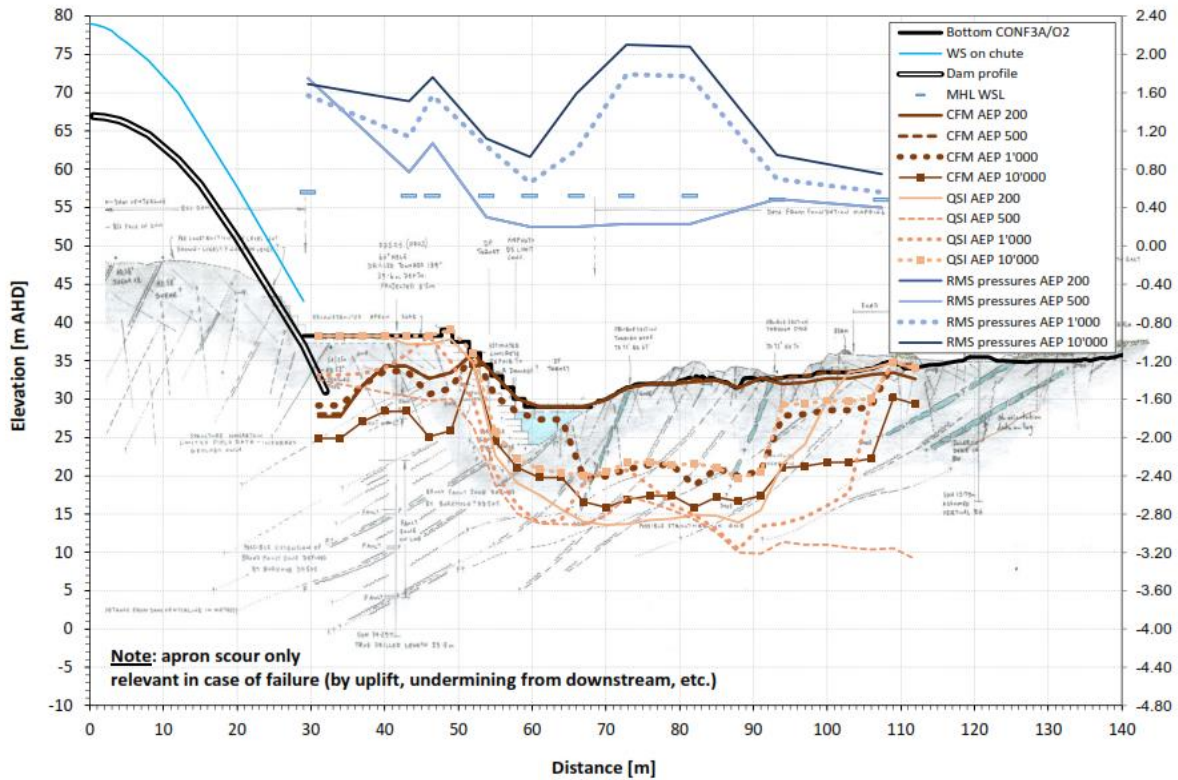


Figure 10. Estimate of future scour progress for a range of large flood discharges

8. CONCLUSIONS

The paper uses a real situation of flood-induced scour to illustrate an advanced composite methodology to evaluate the factors in hydraulics and energy dissipation that cause the scour of rock around dams and spillways. The Paradise Dam experience is a notable example, similar to many others in different types of spillways, of how high-power flows are able to scour rock – even rock that is apparently or seemingly hard and durable. The methodology described herein illustrates two key components, in addition to a proper and full understanding of the local geology, namely (1) a well-scaled and instrumented physical hydraulic model and (2) a comprehensive, physics-based application of the data to the numerical analysis of pressure and pressure amplification to the breaking up and scour of rock. Composite application of both components allowed sound calibration of the numerical model and estimates of future scour progress for different discharge scenarios.

9. ACKNOWLEDGEMENTS

The authors are indebted to SunWater Limited for permission to present the information contained in this paper and note the comprehensive manner in which the ongoing investigations have been mounted, managed, and applied according to the needs of the dam as one of its important water supply facilities.

10. REFERENCES

- Bollaert, E F R. (2004). A comprehensive model to evaluate scour formation in plunge pools, *Int. J. Hydropower & Dams*, 2004(1), pp 94-101.
- Bollaert, E F R, and Lesleighter, E J. (2014). Spillway rock scour experiences and analysis – the Australian scene over the past four decades, *Int. Symp. on Hydraulic Structures*, Brisbane, June.
- Bollaert, E F R, Stratford, C E, and Lesleighter, E J. (2014). Numerical modelling of rock scour, Case study of Wivenhoe Dam, *Int. Conf. Scour and Erosion*, Perth, December.
- Bowers, C E, and Toso, J. (1988). Karnafuli project, model studies of spillway damage, *ASCE Jl. of Hydraulic Division*, May.
- Lesleighter, E J, Andaroodi, P, and Stratford, C E. (2012). Rock erosion experiences in the Wivenhoe Dam Spillway, *ANCOLD*, October.
- Lesleighter, E J, Stratford, C E, and Bollaert, E F R. (2013). Plunge pool rock scour experiences and analysis techniques, *IAHR Congress*, Chengdu, China, September.