Prevention of Foundation Piping at Arapuni Dam using Discrete Cut-off Walls

Michael Revis, Nigel Connell
Damwatch Services Ltd, Wellington, NZ

Adam Fletcher
Mighty River Power Ltd

Marco Lucchi
Trevi SpA, Italy

Nick Wharmby
Brian Perry Ltd

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ABSTRACT

Arapuni Dam, located on the Waikato River 55 km upstream from Hamilton New Zealand, has a history of seepage incidents, relating to its rock foundation, since first filling in 1927. The latest seepage event led to a comprehensive investigation to determine the extent of the foundation features requiring treatment to prevent further incidents from developing. A targeted cost effective solution involving drilling and concreting overlapping vertical piles from the dam crest through the dam and underlying rock formation to a total depth of 90m was selected to form four separate permanent cut-off walls at discrete locations beneath the dam. The discrete cut-off solution removes the risk of further piping incidents at Arapuni, restores the foundation seepage condition to that typical of a concrete dam and, with coverage of approximately half the crest length of the dam, is considerably cheaper than providing a cut-off over the full length of the dam crest. This solution was enabled by an extensive exploratory drilling and testing investigation before hand.

Investigation drill holes and weirs connecting to foundation underdrains were instrumented and monitored providing near real-time pressure and flow data. Safety of the dam was thus monitored during cut-off construction and cut-off effectiveness was verified subsequently.

1 INTRODUCTION

Arapuni Dam, located on the Waikato River 55 km upstream from Hamilton New Zealand, has had a history of seepage incidents, relating to its rock foundation, since first filling in 1927. Seepage changes have often involved sudden and significant increases, without any related external events, such as earthquakes. The most recent seepage incident at Arapuni was related to exploratory holes drilled into the dam foundation in 1995 that intersected high pressure seepage flow. This open void in a foundation fracture was grouted in December 2001 to control the deteriorating condition.

Following the incident in 2001 and confirmation of the continued presence of erodable clay in the foundation, the owner of the dam, Mighty River Power Ltd., required the formation of a high quality and verifiable cut-off solution under the dam to be completed with the reservoir full and the power station in service.

A comprehensive investigation was implemented to determine the extent of foundation features requiring treatment to prevent further incidents. A targeted and cost effective fix involving drilling and concreting overlapping vertical piles from the dam crest through the dam and underlying rock formation to a total depth of 90m was selected to form four separate permanent cut-off panels at selected locations beneath the dam (Figure 3). Construction of the cut-off panels commenced in December 2005 and was completed in August 2007.

2 THE DAM

The 64m high horizontal curved concrete gravity dam includes original features of the dam including concrete cut-off walls extending 65m below the crest and 20m into the left and 33m into the right abutment (Figure 1). A network of porous (no-fines) concrete drains extend under the dam/foundation interface referred to as the "underdrain" (Figure 1). The underdrains discharge seepage water to the downstream toe, where seepage is measured with v-notch weirs. In June 1930 the reservoir was dewatered for repairs which included a grout curtain along the heel and abutment cut-off walls (Figure 2). It was a single row cement curtain not physically connected to the dam.

3 THE FOUNDATION

The dam site is in an area of multiple ignimbrite flows from volcanic eruptions. The main dam footprint is founded on a 40-50m thick sheet of Ongatiti Ignimbrite, a point-welded tuff. The upper part is very weak, with unconfined compressive strength between 2 and 6 MPa. The lower half (the "Hard Zone") is stronger, with strengths up to 28 MPa. Three major sub vertical fissures were mapped during dam construction crossing in a N-S direction across the dam footprint (Figure 1).

Post grouting in 2001, an extensive investigation programme was implemented including cored drill holes targeting the fissures. These holes were instrumented with pressure measuring transducers. Instrumented flow measuring weirs were also fitted to the underdrain. These investigations identified the presence of four zones or fissures of major sub vertical joints that extend the full depth of the Ongatiti with little hydraulic inter-connectivity.

In the fissures, some joints are infilled with nontronite an iron rich smectite clay with high moisture content and very low shear strength. Other joints are open with near lake level pressures in them. Beneath the Ongatiti Ignimbrite, about 40m below the base of the concrete dam, are older ignimbrite deposits, identified as Pre-Ongatiti.

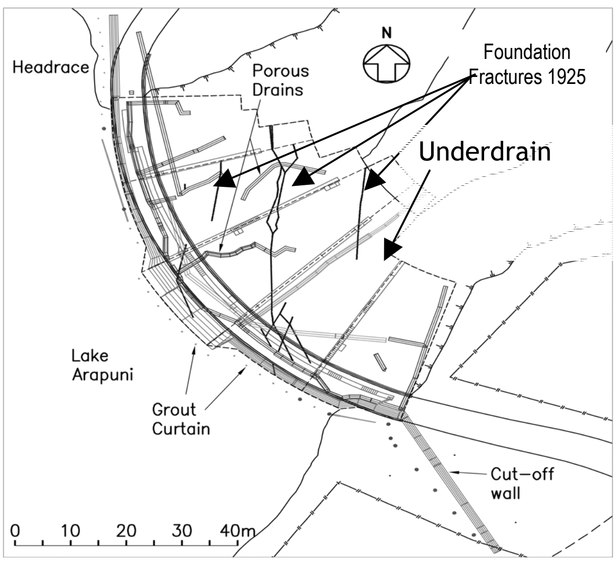

Figure 1: Plan view of Arapuni Dam. (Foundation fissures noted during construction are shown in blue)

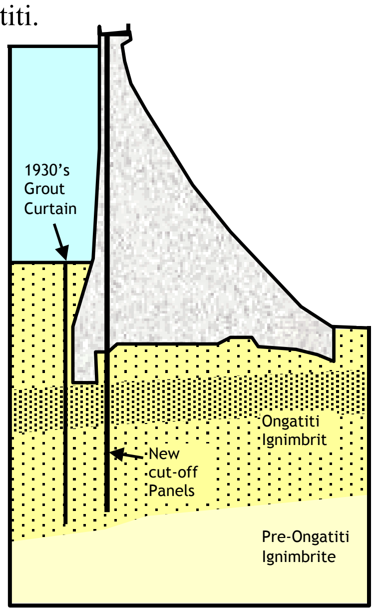

Figure 2: Typical cross section of dam showing cut-off location

4 TREATMENT PANEL SOLUTION

In 2004 the owner committed to remediating the foundation to reduce risk of further foundation seepage incidents and also continual high pressures under the dam. Identification of four discrete fissures made possible construction of four discrete cut-off walls to control seepage. The objective was to achieve this with no interruption to power station generation while avoiding environmental impacts of lake dewatering.

The joints that make up the fissures varied in width from less than 5mm up to 100mm. The nature of the joints varied with extensive areas infilled with nontronite clay, some infilled with oxides of manganese, others open with no infill and some tight rock on rock joints. Treatment panels were located as shown in Figure 4 so that:

- Panels A and B treated the Far Left and Left Fissures respectively which have open joints and near lake level pressures; and
- Panels C and D treated the Main and Right Fissures which have lower pressures with joints infilled with highly erodible nontronite clay.

During the investigation period (2000 to 2005) 122 cored investigation holes were drilled from the downstream face of the dam or from inside the dam galleries. Holes were generally angled perpendicularly across the north-south trending fracture system. Real-time monitoring of piezometers in the dam foundation during drilling indicated hydraulic connections in the foundation and these were used to support the extent of the cut-off panels.

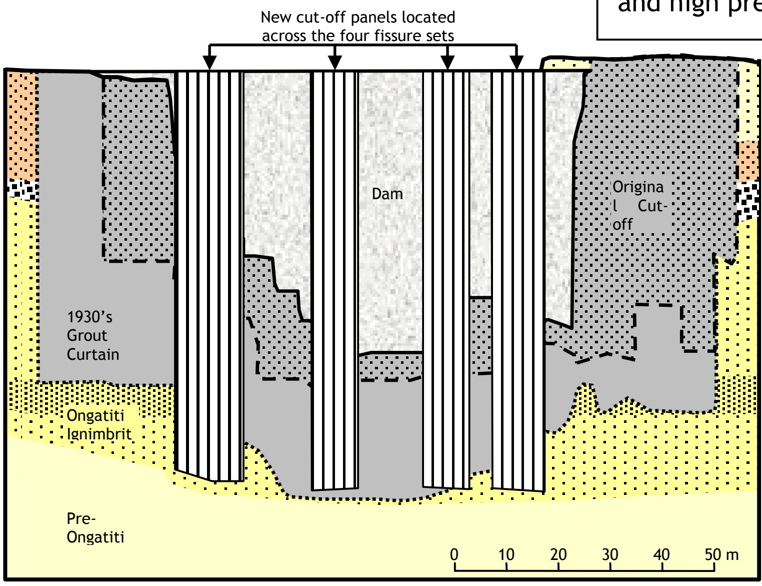

Figure 3: Elevation showing Four Cut-off Panels

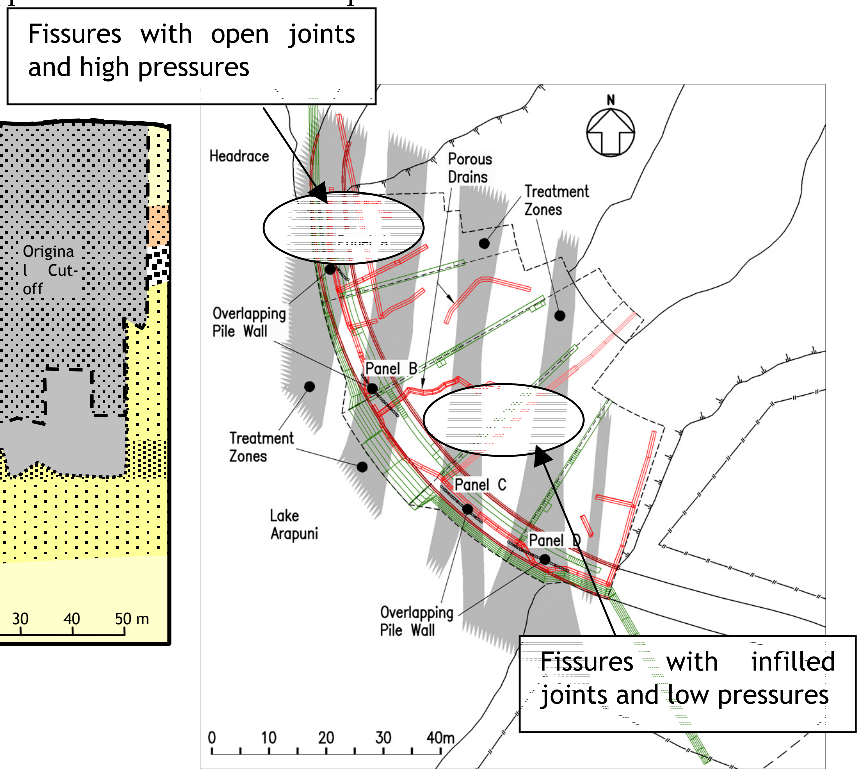

Figure 4: Plan of long-term seepage control remedial works

5 RISKS INVOLVED IN THE FOUNDATION REMEDIAL WORKS

Constructing the cut-off panels involved the introduction of drilling fluid pressures which were higher and significantly more dynamic than normal seepage conditions in the foundation. There was risk of eroding infill from joints, causing high pressures to migrate either downstream to the dam toe or upstream into the lake, in turn opening a flow path under the dam resulting in uncontrolled discharge. To mitigate this risk, relief holes were drilled into each fissure downstream of the panels, each fitted with a valve so that pressure in each fissure could be relieved if necessary.

There was also risk that the cut-off panels extended insufficiently to cut off the fissures. This was checked in the verification explained subsequently.

6 FOUNDATION REAL TIME MONITORING DURING REMEDIATION

The instrument transducers were automatically interrogated by two loggers at the dam which, in turn, delivered data to a centralised monitoring computer, checked for alarm readings and archived. During construction the interrogation frequency was usually 10 minutes although it was set as frequently as every 3 minutes during critical stages of the works.

Logged information was automatically processed by the Damwatch data management system for dam monitoring, which meant up to date data was available in near real time to both the site team and at head office. If any data logged exceeded alarm limits or for any reason data was not processed an alarm was sent to a pager and a cellphone carried by Dam Safety personnel on site. The dynamic piezometric behaviour in the dam foundation was checked by site personnel against a benchmark of pre-construction foundation behaviour. Changing trends or dynamic conditions exceeding pre-construction levels were closely observed for indications of significant deterioration in foundation conditions. Along with the observation and recording of on-site activities site personnel maintained near real time understanding of the spatial response within the dam foundation to construction activities.

The dam safety team was integrated with the construction team on site so that activities were coordinated and contingency plans could be implemented if monitored data indicated deteriorating conditions in the dam foundation.

7 OBSERVED BEHAVIOUR DURING CONSTRUCTION

The Left and Far Left Fissure showed rapid pressure fluctuations of up to 5m in response to changing water level in the open slot as drilling progressed as shown in Figure 5.

Generally pressures in the Main and Right Fissure showed damped responses to changes in the drilled slot water level. Closure of the underdrain, necessary to reduce drilling fluid loss when the underdrain was intersected, caused pressures in the underdrain and the fissure to rise above lake level on occasions. Despite this, use of the pressure relief holes was not needed as pressures did not migrate towards the dam toe sufficiently to make this necessary.

Prior to commencement of the works, safe in-fissure pressures were determined in particular which would avoid blow out at the toe of the dam. These were used to set alarm levels which were automatically checked by the computerised monitoring system on receipt of the data. The alarms alerted dam safety personnel to unsafe conditions.

The dam safety personnel maintained understanding of the construction operations and the associated impact on the foundation, particularly on in-fissure piezometric pressures. It proved possible to manage foundation conditions by adjusting underdrain outflows and on occasion the construction method and sequence. Use of the relief holes, described previously, proved not necessary.

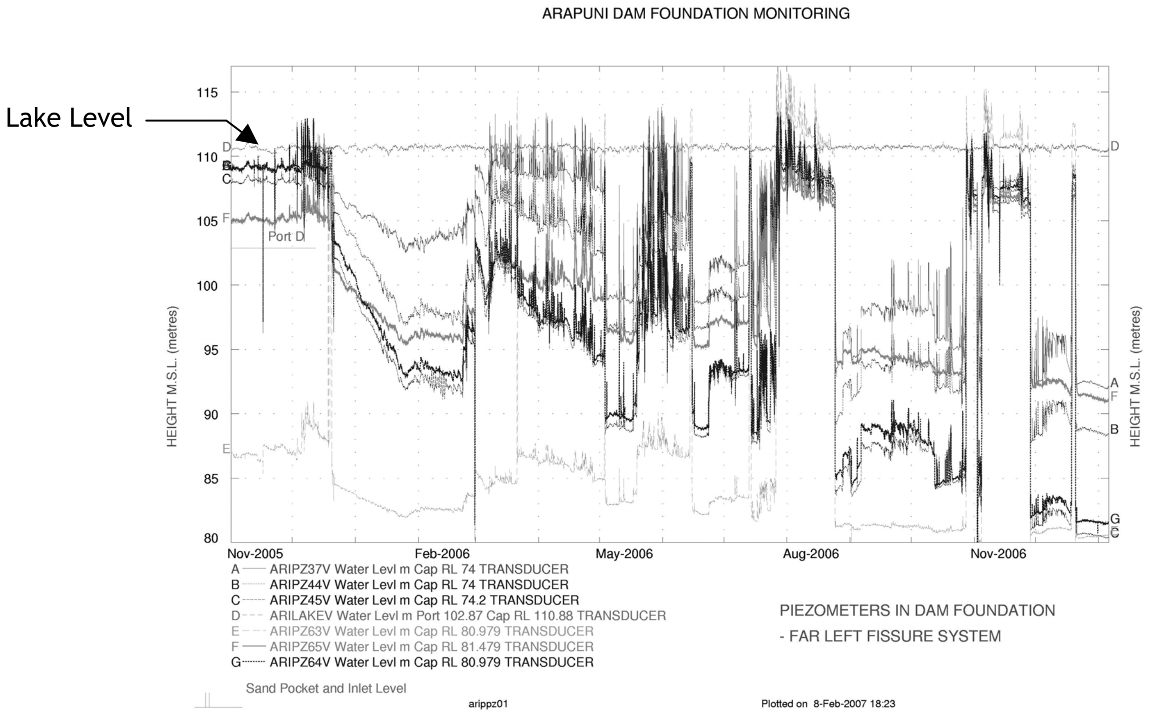

Figure 5: Pressures in the Far Left Fissure during construction.

8 VERIFICATION OF CUT-OFF EFFECTIVENESS

Physical verification checks, including inclinometer tests and down hole closed circuit television (CCTV) inspections, were used to ensure a continuous barrier had been created across each fissure (each panel was required to cover more than 99% of the designed area). Subsequently core holes in each panel and subsequent concrete core strength testing confirmed the cut-off panels achieved specified concrete strength.

As the extent of the fissures was determined from investigation drilling downstream of the cut-off panel locations, rather than direct measurement during foundation drilling, it was important to verify that the cut-off panels as constructed extended far enough laterally to cut off all the significant joints comprising each fissure.

Data logged from the instrumentation in the Left and Far Left Fissures showed a significant drop in foundation pressures in response to the construction of the cut–off panels in these areas. There was also a 90% drop in flow from pressure relief holes opened in this area during pressure relief hole testing after construction compared with prior to construction.

Foundation pressures in the Main and Right Fissures showed little change from before to after construction of the cut-off panels which was expected given the predominantly nontronite infilled nature of joints in these fissures.

Small joints were observed near the design extent of the completed cut-off walls during CCTV camera inspections. Residual pressures in the fissures and pressure relief hole testing flows indicate these small joints allow small seepage flows around the cut-off walls.

The post construction pressures, pressure relief hole testing, and down hole CCTV camera inspections of open slots prior to concreting, confirmed that the cut-off panels successfully cut-off the major joints comprising each fissure These tests and inspections also identified small joints that allow small seepage flows around the walls which are beneficial as they reduce high pressure gradients around the cut-off walls.

9 CONCLUSIONS

Four robust and verifiable concrete cut-off panels have been constructed under Arapuni Dam through the underlying ignimbrite sheet preventing future foundation erosion and leakage incidents from occurring.

The introduction of dynamic water pressures higher than lake level into the foundation during construction with a full reservoir introduced the risk of causing erosion and uncontrolled flow under the dam. Instrumented piezometers in the foundation and drains enabled near real time monitoring ensuring any deteriorating conditions in the foundation were identified and dealt with promptly. This resulted in construction proceeding without any significant dam safety issues occurring. Since the completion of the Foundation Enhancement Project instrument monitoring shows that the constructed cut-off walls successfully cut-off each fissure.

The discrete cut-off solution was only possible following extensive foundation investigations to determine the nature and location joints in the foundation. The investigations took longer than three years and cost about 20% of the final construction cost. The four discrete cut-off panels extend less than half the crest length of the dam. Investigations and resultant understanding of the foundation enabled approximately halving the extent of cut-off panel installed and reduced the project cost by a similar amount.

REFERENCES

Amos, P.D., Newson, T.G., Gillon, M.D. (2003a). *Investigation of a Deteriorating Seepage Condition in Arapuni Dam Foundation, New Zealand*, Australian National Committee on Large Dams (ANCOLD) Conference Proceedings, Hobart, Australia, November 2003.

Amos, P., Watkins, N., Lucchi, M., Wharmby, N. (2007) Extending Deep Cut-off Wall Technology - Construction of Seepage Cut-off Walls under Arapuni Dam in New Zealand with a Full Reservoir, New Zealand Society of Dams (NZSOLD) and Australian Committee of Large Dams (ANCOLD) Conference Proceedings, Queenstown, New Zealand, November 2007.

Gillon, M.D., Bruce, D.A., 2002. "High pressure seepage at Arapuni Dam, New Zealand – a case study of monitoring, exploration and remediation". US Society on Dams (USSD) Proceedings of 22nd Annual Meeting June 2002, San Diego California, USA.

Wharmby, N., Lucchi, M., Newson, T., Amos, P., (2007): Arapuni Dam Foundation Enhancement Works, 10th Australia New Zealand Conference on Geomechanics - Common Ground 2007.