Case studies of foundation grouting using the GIN method at the enlarged Cotter Dam

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The Enlarged Cotter Dam (ECD) Project, located in ACT, consisted of the construction of a new 87 m high roller-compacted concrete (RCC) dam and two central core zoned earth and rockfill saddle dams up to 23 m high on the low points of a ridge to the south-west of the Main Dam. The Main Dam is the highest RCC dam constructed in Australia.

A continuous single-line grout curtain with a total length of 1.2 km was constructed across the full extent of the Main Dam and the two saddle dams with the aim of reducing future seepage losses through the dam foundations. The grouting processes were similar for the main and saddle dams respectively, however the grouting of the Main Dam and saddle dams was carried out as two separate contract packages by different subcontractors. As such, the project provides a unique opportunity to undertake a comparison of the foundation conditions and control equipment and outcomes from the two packages of work. The foundation conditions were different at each of the three dams, with varying geology across the site.

The saddle dam grouting was completed in 2010, with the grouting carried out at the base of the core trench prior to construction of the embankments, while the grouting of the Main Dam was conducted in 2012-13, with most of the grouting works executed from the drainage gallery within the constructed dam.

Consistent throughout construction of the ECD grout curtain was a similar philosophy of real-time computer control, the use of Grout Intensity Number (GIN) parameters, water pressure testing, desirable grout mix properties and the avoidance of damage to the foundations. There were a number of key differences in the grouting process for the saddle dams and Main Dam; these include the ground conditions, the pumping control systems used, the GIN parameters adopted and the grout materials and mixes selected.

This paper provides a critical evaluation of the two grouting programmes, an assessment of the effectiveness of the grouting, comments on tools and methods used, and proposes a set of recommendations for curtain grouting over a range of ground conditions based on lessons learnt during the project.

Keywords: grouting, grout curtain, dam, foundations, Grouting Intensity Number, GIN

Project background

A prolonged drought during the late 1990s and early 2000s tested the security of the water supply for the Australian Capital Territory (ACT). In response to this, a study was undertaken by GHD in 2004-5 to investigate options for the augmentation of the ACT water supply which initially considered three potential dam sites and associated pipelines, pumping stations and water treatment plants, as well as an inter-basin transfer system.

The Enlarged Cotter Dam (ECD) was one of a number of options adopted as part of the Water Security Program undertaken by ACTEW Corporation.

In 2008, the owner formed the Bulk Water Alliance (BWA), involving ACTEW Corporation (the Owner Partner), GHD (the Design Partner) and Abigroup and John Holland (the Construction Partners), to implement the works.

The ECD project consisted of the design and construction of a new RCC gravity dam immediately downstream of the existing Cotter Dam that will increase the storage capacity of the existing reservoir from approximately 4,000 ML to 78,000 ML. The project included:

- an 87 m high roller-compacted concrete (RCC) gravity dam, with a crest length of 330 m and RCC volume of 380,000 m³,
- a 60 m high dry intake tower incorporated into the upstream face of the dam connected to outlet works at the toe of the dam,
- Primary and secondary spillways over the crest of dam and a reinforced concrete stilling basin at the toe of the dam,
- Two zoned earth and rockfill embankment dams, 19 m and 23 m high, on the ridge forming the right abutment of the Main Dam to retain the enlarged storage.

The completed dam was commissioned in August 2013 and handed over to the owner in early September 2013. The near-completed Main Dam and saddle dams are shown in Figure 1.

Figure 1. Overview of the near-completed ECD Main Dam and saddle dams in June 2013

Geological setting

Regional geology

The ACT is within the Lachlan Fold Belt (Lachlan Orogen), which extends across most of New South Wales, Victoria and Tasmania. The published Brindabella 1:100,000 Geological Series Sheet indicates that the Main Dam and both saddle dams are founded on a westerly dipping sequence of the Late Silurian Walker Volcanics. The bearing of the dam axis for the Main Dam is approximately 030° and for the saddle dams is approximately 060°. Downstream is to the southeast/south-southeast of the dams. The Walker Volcanics are described as predominantly comprising green to purple dacite, ignimbrite and bedded tuff, minor andesite, volcaniclastic sediment and limestone. According to Abell (1991) and Owen and Wyborn (1979), the characteristics of the ACT region were as follows:

- Ordovician – turbidite sediments deposited in a deep oceanic basin (Monaro Slope and Basin) east of the Molong Volcanic Arc (Abell 1991),
- Early Silurian – uplift transformed the region into a shallow marine environment (Canberra-Yass Shelf), receiving mainly terrigenous sediments,
- Late Silurian – widespread acidic volcanism (agglomerate, lava, airfall tuff and ignimbrite flows) changed the region into a mostly terrestrial environment, locally inundated by the sea. Volcanism then ceased in the area and granitic magmas moved upward through the
crust to cool as felsic intrusions (Abell 1991). A Late Silurian granite intrusion now forms Mount McDonald, immediately uphill of the Main Dam left abutment.

- Early Devonian – acidic volcanism recommenced with two large composite volcanoes centred in the Cooleman area (near Tantagara Dam) and Mount Coree (10 km west of Cotter Dam) before thick fluvial sediments were deposited across the region in the Middle Devonian. Several periods of folding and faulting gave rise to a strong north-south trend in regional geological structures. Such faults include:
  - Winslade Fault – about 800 m to the south of the site, trending approximately northeast-southwest, and
  - Pig Hill Fault – about 4 km northwest of the site, trending approximately north-south
- Late Cenozoic – reactivation of some regional faults attributed to regional uplift

Field inspection of regional fault exposures suggests no significant movement has occurred in recent geological time.

**Site geology**

The Main Dam and the two saddle dams are founded on a westerly dipping sequence of the Early to Late Silurian age Walker Volcanics. The geology at each of the dams is as follows:

- **Main Dam**
  - Moderately to slightly weathered, very high strength porphyritic rhyolite with persistent crushed seams and zones that provide seepage paths beneath the dam,
- **Saddle Dam 2**
  - Typically highly to moderately weathered, high strength rhyolite with thin tuff beds on the left abutment and a mudflow deposit encountered on the right abutment,
- **Saddle Dam 1**
  - Intense fracturing and hydrothermal alteration of the rhyolite encountered throughout the foundation.

**Geotechnical investigations**

Comprehensive geotechnical design investigations for the ECD were carried out between April 2008 and September 2009, including orientated diamond-cored boreholes, permeability profiling, piezometer installation, seismic refraction tomography surveys, engineering geological mapping and laboratory testing.

**Geological model**

A geological model was developed for the ECD site using data obtained from the geotechnical investigations, with a particular focus on defining, characterising and analysing prominent geological structures (crushed and sheared seams/zones) that traverse the dam footprint.

**Geological structure**

Geological mapping and a review of rock cores indicated the occurrence of three predominant rockmass fracture types in the site area—joints, sheared surfaces/seams and crushed seams/zones. For descriptive purposes the BWA adopted seam and zone thicknesses as being less than or greater than 250 mm respectively.

The orientations of all defects measured during the geotechnical investigations were consolidated into data sets for four project areas: Main Dam left abutment, Main Dam right abutment, Saddle Dam 1 and Saddle Dam 2. Natural defect data was plotted as stereographic projections of poles to planes and then used to delineate defect sets for each area, as shown in Figure 2 for the Main Dam left abutment area.

Seven defect sets were delineated on the Main Dam abutments, three of which were found to include persistent crushed or sheared seams and zones that were likely to provide continuous seepage paths through the foundation (Table 1).
Table 1. Main Dam – description of persistent defect sets

<table>
<thead>
<tr>
<th>Defect set</th>
<th>Dip/Dip Direction</th>
<th>Description of orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>19 / 291</td>
<td>Shallow dip upstream</td>
</tr>
<tr>
<td>Set 2</td>
<td>60 / 088</td>
<td>Steep dip downstream</td>
</tr>
<tr>
<td>Set 3</td>
<td>89 / 360</td>
<td>Near vertical, striking upstream-downstream</td>
</tr>
</tbody>
</table>

**Permeability**

Water Pressure Tests (WPT) were carried out over selected depth intervals in each of the geotechnical investigation cored boreholes.

Of the 361 permeability tests undertaken, only 20% of the Main Dam tests and 5% of the Saddle Dam tests yielded a permeability value of greater than 5 uL (Figure 3). Based the geological model, the design team correlated high permeability test results with rockmass that had experienced near surface stress relief, or with prominent defects that intersected the borehole at greater depth.
Foundation excavations

The foundation excavation was designed to remove rock mass with open and clay infilled defects due to near-surface stress relief, to provide a kinematically stable foundation with suitable rock mass strength, stiffness and permeability characteristics on which to construct an 87m high concrete gravity dam and the two saddle dams.

The excavation depths for the Main Dam and Saddle Dam core trenches were selected to expose a rock mass with a typical permeability of less than 5 uL. However, it was expected that persistent crushed or sheared seams and zones that yield a higher permeability would require grout treatment to reduce seepage losses through the foundation.

The variable lithology and fracturing conditions encountered in the Walker Volcanics ensured that the ground conditions were uniquely different for each of the three dam sites. Foundation properties were as follows:

- **Main Dam** – excavation depth typically 5 to 16 m in depth, exposing moderately to slightly weathered, very high strength porphyritic rhyolite with persistent crushed seams and zones that traverse the dam footprint (Figure 4).
- **Saddle Dam 2** – core trench was excavated to a mean depth of 4 m to expose a highly to moderately weathered, high strength porphyritic rhyolite with thin tuff beds on the left abutment and a highly oxidised mudflow deposit (interpreted as a caldera collapse mudflow) encountered on the right abutment (Figure 5).
- **Saddle Dam 1** – core trench was excavated to a mean depth of 6.5 m due to intense fracturing and hydrothermal alteration of the rhyolite (Figure 6)
Geological model refinement

Detailed engineering geological maps of the excavated dam foundations were prepared by the ECD geotechnical team. Geological structures with the necessary orientations and persistence to provide continuous upstream-downstream seepage paths were overlain on the grout curtain design. The spacing, depth and orientation of grout holes was adjusted to best intersect the inferred location of these features.

General grouting design philosophy

Purpose of the grout curtain

The construction of a grout curtain in the foundations for the Main Dam and saddle dams was required to reduce the permeability of the foundations below the dam, in order to reduce the seepage losses, to reduce the likelihood of piping through open joints in the Saddle Dam foundations and to improve the efficiency of the foundation drains. It was considered that the primary grout holes would form the final stage of the foundation investigation and to this end every fourth primary hole was cored, with full core recovery.

Grout curtain geometry

A single line grout curtain was adopted, given the competence and low general permeability of the foundation.

Maximum grout curtain depths of 40 m and 30 m were adopted for the Main Dam and saddle dams, respectively. The grout hole depths were primarily based on the permeability results of the investigation.

A primary hole spacing of 12 m was adopted, with higher order holes at split spacing. Primary and Secondary holes were mandatory. The hole alignment was selected to provide optimum intersection with the main geological features. The design was refined as more geological information became available.

The final grout curtain layout for the Main Dam is shown in Figure 7.

![Figure 7. Main Dam grout curtain layout after final investigations](image)

Water pressure test data available before the start of grouting programme

Investigation and grouting phase comprehensive WPTs were classified in accordance with the approach presented by Ewert (2005), as this provided a better understanding of the permeability of the rock mass.
A summary of the classification of the investigation phase WPTs from the saddle dams and the Main Dam is included in Table 2.

**Table 2. Summary of investigation phase WPT classifications**

<table>
<thead>
<tr>
<th>Type</th>
<th>Type description</th>
<th>Saddle Dams</th>
<th>Main Dam</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – Tight</td>
<td>Tight rock, no absorption during highest pressure stages</td>
<td>27%</td>
<td>22%</td>
</tr>
<tr>
<td>2 – Saturation</td>
<td>Tight rock, insignificant absorption during higher pressure stages due to saturation of isolated voids</td>
<td>9%</td>
<td>6%</td>
</tr>
<tr>
<td>3 – Fracturing</td>
<td>Tight rock, over-proportionate increase of take during higher pressure stages due to &quot;fracturing&quot; of latent discontinuities</td>
<td>12%</td>
<td>8%</td>
</tr>
<tr>
<td>4 – Permeable</td>
<td>Permeable rock, typically linear pressure-flow (P/Q) relationship</td>
<td>26%</td>
<td>33%</td>
</tr>
<tr>
<td>5 – Dilation</td>
<td>Permeable rock, over-proportionate increase of water take during higher pressure stages due to temporary &quot;dilation&quot;</td>
<td>13%</td>
<td>13%</td>
</tr>
<tr>
<td>6A – Erosion</td>
<td>Tight or permeable rock, large increase in water take after reaching a critical pressure without returning to original water take on pressure reduction</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>6B – Clogging</td>
<td>Significant under-proportionate increase due to transport of erodible material which clogs defect</td>
<td>12%</td>
<td>17%</td>
</tr>
</tbody>
</table>

Based on this assessment, it was anticipated that about a third of the primary holes would intersect permeable features and accept grout.

The WPT results from the investigations phase and from the saddle dam grouting were reviewed to provide an indication of the water test pressure at which fracturing of the rock occurred. This critical pressure (P_{crit}) was then used to establish test water pressures and grout pressures for the curtain grouting. The P_{crit} boundary established from the investigation WPT data and the saddle dam grouting phase is presented in Figure 8.

![Figure 8. Interpreted P_{crit} data from investigation phase and saddle dam grouting phase](image-url)
**Adopted approach**

**Grouting method and parameters**

**Grouting method**

The GIN or Grouting Intensity Number method as described in Lombardi (2003) was adopted as the primary method for the curtain grouting and includes grouting within an envelope defined by $P_{\text{max}}$ (maximum pressure in bar), $V_{\text{max}}$ (maximum volume of grout take in L/m) and GIN (product of pressure in bar and injected grout volume in L/m). The advantages of the approach that resulted in the selection of this method were:

- A single stable grout mix, generally consisting of cement, water and superplasticiser, which meant one less variable to control, noting that similar grout mixes had been employed on previous dam, tunnel and anchor grouting operations with good outcomes.
- The adoption of the single grout mix allowed for a central grout plant to be used to feed multiple grouting pumps.
- Computer-controlled grouting with real time recording reducing the reliance on manual observation and allowing continual adjustment of the process by the grouting engineer.
- Limitations on combination of high pressure and high grout take, which are most prone to causing hydrofracture.
- Detailed real-time records of grouting pressures, flows and volumes for assessment of grouting results.

A key part of the grouting approach was to use the Apparent Grout Lugeon ($uL_{gr}$) as a parameter for real-time monitoring and management of the grouting process. As outlined in Naudts et al. (2003), this is a measure of the permeability of the rock with grout as the testing fluid, and is given by the following relationship:

$$uL_{gr} = \frac{Q_{gr}}{L} \times \frac{10 \text{bar}}{P_{\text{eff}}} \times \frac{V_{\text{marsh,gr}}}{V_{\text{marsh,water}}}$$

where $uL_{gr}$ is the Apparent Grout Lugeon, $Q_{gr}$ is the grout flow rate (L/min), $L$ is the length of the stage (m), $P_{\text{eff}}$ is the effective grouting pressure (bar), $V_{\text{marsh,gr}}$ is the Marsh Cone flow time of the grout (s), which was assumed to be consistent at 35 seconds for 1000 mL for ease of calculation, and $V_{\text{marsh,water}}$ is the Marsh Cone flow time of water, which is 28 s.

A progressive reduction in $uL_{gr}$ indicates progressive sealing while an increase in $uL_{gr}$ during injection (i.e., drop in pressure or increase in flow) indicates a possible event such as heave or plastic fracturing during grouting. The reconciliation of $uL_{wr}$ and the $uL_{gr}$ also provide a valuable indicator of the suitability of the grout mix to the features being grouted.

**GIN parameters**

Adopted grouting pressures were based on the assessed $P_{\text{crit}}$ of the dam foundation. The grouting phase WPT pressures were based on 120% of the future hydrostatic pressure, as long as it did not exceed the $P_{\text{crit}}$. The initial maximum grout pressures were twice the WPT pressures.

The grouting criteria set before commencing the first trial panel on the Saddle dams were modified during the grouting process. The refined GIN curves used for the grouting are given in Figure 9.

Changes made to the GIN parameters during the grouting process were:

- $V_{\text{max}}$ increased from 125 L/m to 175 L/m and then to 250 L/m based on assessment of ground response to grouting.
- $P_{\text{max}}$ reduced for Stages 1, 2 and 3, reduced to 2 bar, 4 bar and 7.5 bar respectively
- GIN changed from 750 all stages to 500 (Stages 1 to 3), 750, 1000, 1250 and 1500 (Stage 4 to 7 respectively)

**Stop criteria**

Stop criteria determine when grouting of a stage may stop. Stringent stop criteria were adopted on this project for the completion of a grout stage, as there was great benefit in achieving the best possible injection and closure from each grout stage to ensure that the stage had reached its full grouting potential to reduce, where possible, the need for higher order holes.

![GIN adopted for Saddle and Main Dams](image)

The final stop criteria for the Main Dam grouting, outlined in Table 3, utilised the apparent lugeon value to define the stop criteria. The stop criteria for the saddle dam were similar, but a different approach was adopted on reaching $V_{\text{max}}$. As a result of the differing geology and more open joints in shallower stages, the hole was flushed on reaching $V_{\text{max}}$ and injection was recommenced rather than discontinuing grouting and moving directly to higher order holes. It was considered that this would be beneficial in reducing the number of higher order holes required for closure of the larger aperture features encountered in at least part of the saddle dam foundation.

**Table 3. Grouting stop criteria for Main Dam**

<table>
<thead>
<tr>
<th>At limit on GIN curve</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>On reaching $P_{\text{max}}$</td>
<td>Hold pressure and stop when take is less than 1 apparent lugeon for 5 minutes</td>
</tr>
<tr>
<td>On intersecting the GIN curve</td>
<td>Follow GIN curve and stop when take is less than 1 apparent lugeon for 10 minutes or on reaching $V_{\text{max}}$</td>
</tr>
</tbody>
</table>
| On reaching $V_{\text{max}}$ | - If stage is within 10% of GIN, continue grouting for up to an additional 50 L/m  
- If stage is not approaching GIN, grouting is discontinued |
Closure criteria

Final adopted closure criteria for the grouting of the Main Dam were as follows:

- < 30 L/m of grout take (~32 kg cement/m with a 0.6:1 W/C grout);
- < 3 uL on the grouting phase water test.

In addition to these closure criteria, higher order holes were also required where major geological features were identified in the geological model.

Developing a clear understanding among the site personnel and grouting contractor was important and resulted in programme benefits. This allowed for greater forward planning for higher order holes.

Once closure was achieved, then no further holes were required for the grout panel. Where there were concerns about successful closure, a check hole was drilled across the panel to confirm that grouting had been successful.

Multiple-stage grouting

For the saddle dams, grouting of multiple-stage grouting was undertaken when the WPT indicated the hole was tight. Multiple-stage grouting here refers to grouting more than one stage in the same grout hole at once. That is, instead of the grouting packer being raised in 6 m intervals, it may be raised in 12 m or greater intervals. This was found to be successful and provided economy in reducing the number of hook-ups. This was typically only done with deeper stages. The grouting parameters for the higher of the combined stages were adopted, noting that the lower part of the combined stage experienced a higher pressure due to the greater grout column height.

For the Main Dam, multiple-stage grouting was trialled, but generally not carried out due to the potential for time delay between analysis of the WPT results and commencement of grouting. The scheduling of the grouting at the main dam did not provide a delay between the water testing and grouting of a stage, which would allow interpretation of the water test. This was partly due to the scheduling of the process within the tight confines of the gallery.

Grouting subcontracts

The grouting for the project was undertaken as two separate subcontracts, as follows:

- The grouting of the saddle dams and 10 holes on the upper right abutment of the Main Dam was undertaken by Subcontractor A from May to August 2010
- The grouting of the remainder of the Main Dam was undertaken by Subcontractor B from September 2012 to June 2013

Grouting equipment

Both the saddle dams and Main Dam were grouted using a computer-controlled pump, with the computer programmed to track the grout pressure along the GIN envelope. A comparison of the grouting equipment used is presented in Table 4.

Grout mix design and quality control

A grout testing programme was carried out. The same grout testing was carried out during the grout trials to establish the optimum mix constituents.

The grout comprised Boral GP cement, water and Rheobuild 1000NT superplasticiser. The purpose of the superplasticiser was to decrease the apparent viscosity without increasing the bleed. Rheobuild 1000 also acts as a retarder, increasing the thixotropic set time.

The grout trial aims to produce a stable grout that will not sediment in grout lines or injected features, of sufficiently low viscosity that it will be able to penetrate into narrow features that need grouting.
### Table 4. Comparison of grouting equipment

<table>
<thead>
<tr>
<th>Item</th>
<th>Contractor A</th>
<th>Contractor B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer System</td>
<td>Proprietary system</td>
<td>Jean Lutz Cinaut 15</td>
</tr>
<tr>
<td>Grout Pump(s)</td>
<td>3 sets of double piston pumps</td>
<td>Hany ZMP725 double acting piston pump</td>
</tr>
<tr>
<td>Min Flow Rate</td>
<td>3 L/min per set of pumps</td>
<td>1 L/min</td>
</tr>
<tr>
<td>Max Flow Rate</td>
<td>20 L/min per set of pumps</td>
<td>11 m³/hour (183 L/min)</td>
</tr>
<tr>
<td>Pressure Range</td>
<td>1 bar – 90 bar</td>
<td>1 bar – 50 bar</td>
</tr>
<tr>
<td>Multiple simultaneous grouting</td>
<td>Good. Ability to run 6 grout lines simultaneously.</td>
<td>Good. Can grout up to 12 simultaneous lines, grouting multiple lines not trialled.</td>
</tr>
<tr>
<td>Pressure Control</td>
<td>Very good. Pressure controlled by regulating the flow.</td>
<td>Pressure was controlled by regulating the flow (not a standard setup for this pump system). Achieved excellent pressure with correct control settings, but would significantly overshoot $P_{\text{max}}$ in low permeability holes if default settings used. Pressure spikes in low permeability holes during piston switch over were fixed by installing a damping cylinder.</td>
</tr>
<tr>
<td>Ability to track down GIN</td>
<td>Very good.</td>
<td>Very good.</td>
</tr>
<tr>
<td>Ability to conduct WPT</td>
<td>No</td>
<td>Yes, can conduct WPT if detailed time/flow/pressure records required.</td>
</tr>
<tr>
<td>Presentation of results</td>
<td>Very good.</td>
<td>Presentation layout was limited. Opted to import data into Excel spread-sheet to prepare final charts.</td>
</tr>
<tr>
<td>Main Advantages</td>
<td>Good system for grouting low permeability foundations.</td>
<td>Very flexible system that can deal with large range of conditions (high/low flow with high/low pressure).</td>
</tr>
<tr>
<td>Main Disadvantages</td>
<td>Low maximum pump flow rate, had larger features been encountered would have extended the time spent grouting stages and may have warranted shortening stage to suit. Ability to restart a hole difficult.</td>
<td>Complicated computer system, so selection of most appropriate settings time consuming. Systems support located in France, so time zone differences make technical assistance slow.</td>
</tr>
</tbody>
</table>

The frequency and specified limits of the grouting are provided in Table 5, along with the intended purpose of each test.

The grout mix selected for the saddle dams grouting was W/C 0.7:1 with Rheobuild dosage 1 L/100 kg cement. This grout was generally very consistent, with occasional bleeds approaching 5% when grouting was conducted in cold weather.

The grout mix finally selected for the Main Dam grouting was W/C 0.6:1 with Rheobuild 1000 dosage 1 L/100 kg cement. Between the two grouting programmes, the cement constituents had changed, with an increase in the mineral addition of the cement. This is believed to have affected the grout properties, as the Main Dam mix was found to be less stable than the grout used at the saddle dams. It is important that the cement source and product is kept constant throughout the grouting to ensure consistency of the final product. It may be beneficial to use more than one cement source in the mix trial to determine whether an alternative source may result in better grout performance.
During the grout trials for the Main Dam it was observed that doses of superplasticiser greater than 1.5 L/100 kg cement for the W/C ranges used would cause the grout to become unstable and cause flocculation of the grout.

The grout testing indicated high bleed when the grout was near the maximum specified limit. In general, grout bleed is higher at low temperatures. The high bleed is believed to have been caused by a change in how the superplasticiser reacts at higher temperatures. When the water temperature was cooled to below 25°C and the high shear mix time increased to a minimum of 2.5 minutes, the grout bleed returned to within specified limits.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Acceptance Criteria</th>
<th>Frequency</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Temperature</td>
<td>≥5°C; ≤35°C</td>
<td>1 per mix</td>
<td>Half-hourly Controlling the temperature of the water and grout provides consistency in how the grout behaves.</td>
</tr>
<tr>
<td>Grout temperature at injection</td>
<td>≥10°C; ≤30°C</td>
<td>1 per mix</td>
<td>Half-hourly</td>
</tr>
<tr>
<td>Density</td>
<td>Within a tolerance of ±0.01 of the S.G. determined in the mix trial.</td>
<td>1 per mix</td>
<td>Half-hourly Main QA tool during production. Provides a measure of the specific gravity of the grout and confirms the correct proportioning of the batched grout.</td>
</tr>
<tr>
<td>Apparent Viscosity (flow time)</td>
<td>35 s ± 2 s</td>
<td>1 per mix</td>
<td>Half-hourly QA during production. Second confirmation of the mix constituents and ensures the viscosity of the grout is sufficiently low to penetrate narrow features</td>
</tr>
<tr>
<td>Bleed</td>
<td>&lt; 5%</td>
<td>1 per mix</td>
<td>2 per day (am and pm) QA during production. Measure of the stability of the grout. However, a limitation is that the test takes two hours to complete, and during production the grout has been injected before the result is obtained.</td>
</tr>
<tr>
<td>Strength</td>
<td>Characteristic strength at 7 days of 7 MPa</td>
<td>1 set of 6 cubes per mix</td>
<td>1 set of 6 cubes per 50 m³ of grout mixed with a minimum of 1 set of 6 cubes per day QA during production but also a measure of resistance to washout</td>
</tr>
<tr>
<td></td>
<td>Characteristic strength at 28 days of 10 MPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean of 4 consecutive sets of cubes greater than 12 MPa at 28 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No value less than 7 MPa at 28 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thixotropic Mix Time</td>
<td>Determined during the mix trial, but was to be no less than 60 minutes.</td>
<td>1 per mix</td>
<td>Not required unless directed by the Designer Time required for the grout to stop behaving as a liquid, noting that this test was only undertaken during the mix trials. Are holes closing because grout is setting early?</td>
</tr>
</tbody>
</table>
Discussion of results

Grouting data

A sample of the results from the grouting process is included in Figure 10. Data from Saddle Dam 2 is included, as this area included the greatest variability in geological conditions and response to grouting. This data shows the reducing permeability of the rock with depth. Most results on Stage 1 reached $V_{\text{max}}$, Stage 2 and 3 reached either the GIN curve or $P_{\text{max}}$ and Stage 4 and below typically terminated on $P_{\text{max}}$.

![Figure 10. Sample grouting output from Saddle Dam 2](image)

Samples of the final output including the grout lugeon plot are included in Figure 11, as these plots are not easily accessible outside of actual grouting programmes. These samples are provided to demonstrate the standard of output/record that is available from successful computer controlled grouting operations. Figure 11(a) is an example of a stage terminating on $P_{\text{max}}$, while Figure 11(b) tracks down the GIN curve and terminates on $V_{\text{max}}$.

Groutability of the rock mass

All stages were subject to a WPT (comprehensive or abbreviated) ahead of grouting, which allows comparison of the ability of grout to enter the same features that water is able to enter. By comparing the $uL_{\text{wt}}$ to the $uL_{\text{gr}}$ (taken at the time that the theoretical volume of grout to fill the hole has been injected) it is possible to assess the suitability of the grout to the features that accept water. This comparison is provided in Figure 12 for the Main Dam grouting stages. The volume of grout injected into each stage is indicated on the chart in terms of the size of the bubble. This plot indicates that the bulk of the stages that accepted reasonable volumes of grout (30 L/m or more of grout, which is approximately 30 kg/m of cement) showed consistent water and grout injection characteristics.

Importantly, there are very few instances where small WPT values are linked to larger grout takes, but there are some high initial $uL_{\text{gr}}$, possibly indicating some dilation due to the higher grout injection pressures. This may indicate that the grouting pressures were too high in some instances, however, a review of the records indicates that this was limited. Based on results of the 1381 stages which had a permeability of 1 uL or less on the water test,
13 stages (~1% of stages) exceeded the 30 L/m closure criteria, indicating very good control of damage from excess grouting pressures.

Figure 11. Sample presentation of data – a) Contractor A (left) and b) Contractor B (right)

A small number of results have small \( uL_{gr} \) initial values and very low grout take, but larger WPT values greater than 3 \( uL \). These are assumed to be narrow features accessible to water but not to grout. This assumption is reinforced by the core recovered from the cored

Figure 12. Grout lugeon vs water lugeon with grout take for Main Dam

LEGEND - Grout Take (L/m)
- 100
- 30
- 10

Water take, but very low grout take/lugeon

Possible dilation where significant grout taken but very low water take
primary holes. As most grout curtains in Australia traditionally have had more relaxed permeability closure criteria, holes with lower water test results (between 3 uL and 10 uL) and grout takes within the closure criteria were considered individually and assessed to determine whether higher order holes were required. This assessment of the need for higher order holes was based on the geometry of the permeable geological feature, the depth of the stage and the amount of grout that had been injected.

A graphical representation of the extent of higher order holes which were required is presented in Figure 13. Significant proportions of the Main Dam upper abutments (MD Ch 0-70 and MD Ch 210-350) required at least tertiary holes, as did the upper left abutment of Saddle Dam 2 (SD2 Ch 40-125). On the upper left abutments of the main dam and Saddle Dam 2, it was interpreted that the grout curtain encountered multiple shallow dipping Set 1 crushed seams. The upper right abutment of the Main Dam (>MD Ch 300) encountered a Set 3 fault while the mid-upper abutment (MD Ch 210-300) was affected by stress relief. Conversely, the Saddle Dam 1 foundation proved to be tight, despite the intense fracturing encountered. As a result, very few holes other than the mandatory primaries and secondaries were required through this section of the curtain.

![Figure 13. Summary of requirement for higher order holes across the grout curtain](image)

**Summary of grouting programme**

A summary of the grouting programme is presented in Table 6, including metres grouted and volume injected for each order of hole.

**Recovery of grout**

**Saddle Dams**

Following completion of the Saddle Dam grouting, additional foundation excavation was undertaken, revealing in-situ grout in seams and defects. The grout had a good consistency and strength. Figure 14 shows an example of a grouted feature which was exposed.

**Main Dam**

Grout recovered in check holes for the Main Dam was generally of good quality, with a bond on both surfaces of the grouted feature and high intact strength, with most grout recovered in
thin seams less than 5 mm in width. Grout with a very soft consistency was recovered from a check hole on the upper right abutment. The grout was associated with the grout that had exhibited high bleed during testing. As the WPT indicated a tight foundation with no signs of washout, it was decided to leave the grout in place and to document its presence.

Table 6. Summary of grouting programme

<table>
<thead>
<tr>
<th>Hole order</th>
<th>No of holes</th>
<th>Total hole length (m)</th>
<th>Grout volume injected (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main Dam</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary</td>
<td>43</td>
<td>1,502</td>
<td>19,009</td>
</tr>
<tr>
<td>Secondary</td>
<td>38</td>
<td>1,320</td>
<td>12,233</td>
</tr>
<tr>
<td>Tertiary</td>
<td>44</td>
<td>1,161</td>
<td>6,608</td>
</tr>
<tr>
<td>Quaternary</td>
<td>13</td>
<td>318</td>
<td>1,460</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>138</strong></td>
<td><strong>4,301</strong></td>
<td><strong>39,310</strong></td>
</tr>
<tr>
<td><strong>Saddle Dam</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary</td>
<td>70</td>
<td>2,280</td>
<td>21,042</td>
</tr>
<tr>
<td>Secondary</td>
<td>70</td>
<td>2,190</td>
<td>21,298</td>
</tr>
<tr>
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<td>14,937</td>
</tr>
<tr>
<td>Quaternary</td>
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<td>512</td>
<td>7,460</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>222</strong></td>
<td><strong>6,270</strong></td>
<td><strong>64,737</strong></td>
</tr>
</tbody>
</table>

Figure 14. Grout exposed during final foundation excavation of Saddle Dam 2

Check holes

Following completion of grouting, a total of 9 check holes were cored. Comprehensive WPT of the check holes indicated all stages were within the closure criteria, with over 90% of the stages tight, and all stages below 3 uL.
Conclusions

Continuous reviews throughout the construction of the grout curtain for the main dam and saddle dams led to the following:

- Efficient GIN grouting design parameters tailored to suit specific site conditions.
- Low pressures based on assessment of $P_{\text{crit}}$ sufficient for grout penetration of open joints.
- A pumping control system which was effective in tracking the GIN envelope and could control the full range of pressure/flow combinations encountered.
- Detailed geological model based on surface mapping and orientated cored holes allowed significant grout takes to be correlated with geological features and allowed higher order holes to specifically target significant defects, providing greater assurance of closure.
- All zones within the grout curtain met closure which was acceptable to the designers.
- Both contractors and their equipment performed as required, noting that customisation was required in both cases resulting in a learning curve.
- The adopted approach was suitable across the variable geological conditions encountered at the site with minimal modification of the adopted parameters.

Recommendations

The following recommendations are provided as guidance for future foundation grouting programmes:

- Starting with a well-developed geological model and undertaking continual development and refinement of the model as the grouting progresses is essential.
- Use more than one source of cement in grout mix trial to identify the best product for the circumstances.
- Grout mixing times should be increased for low ambient temperature as indicated by increased bleed during cooler periods.
- The GIN curve could be replaced by PV steps to allow computer control system to be pressure controlled in pressure steps rather than the complexity of tracking down the GIN curve.
- A clear understanding by all parties of the closure criteria from the outset simplifies the process for calling up higher order holes.
- Multiple-stage grouting can be an economic solution where WPT indicates stages are tight, particularly at depth.

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References


