Foundation Preparation and Seepage Barrier Installation at Wyaralong Dam Construction Project

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The Wyaralong Dam Alliance (WDA), a consortium of seven engineering and contracting companies, was contracted to design and construct the Wyaralong Dam, which impounds the Teviot Brook 14 km from Beaudesert in Queensland, Australia. The dam is an approximately 500 metre long, 48 metre high Roller Compacted Concrete (RCC) structure built on a foundation generally consisting of massive sandstone with intermittent conglomerate zones consisting of cemented gravels, mudclasts and sands. Geologic features of note with regard to dam stability and long term seepage at the site are dominated by downstream sloping bedding features and conglomerate zones. In addition to the bedding-related features, two predominant vertical to subvertical fracture sets exist. The condition of the vertical fractures ranges from tight and fresh at depth to highly weathered and filled with dispersive clay and gravels near the foundation surface. To provide a durable and effective long term seepage barrier for the dam, an extensive foundation cleaning and treatment operation was undertaken. This comprised drilling, blasting, and excavation of the majority of the highly weathered rock and dispersive materials supplemented by localized installation of small cut-offs and dental concrete and the construction of a double-line grout curtain installed using real time computer monitoring, the GIN methodology, and balanced, stable grout mixes.

Keywords: RCC dam, foundation preparation, grouting, GIN method, real time monitoring, grout mix designs

Introduction

Wyaralong Dam is located near the township of Beaudesert in south-east Queensland. The dam is a 48m high Roller Compact Concrete (RCC) dam, and has a capacity of 103,000ML.

The dam is founded on sandstone, with intermittent conglomerate zones consisting of cemented gravels, mudclasts and sands.

The design of Wyaralong Dam assumed that an effective water seepage barrier would be constructed beneath the upstream face of the dam. In particular, it was assumed that water pressure beneath the dam would reduce by two-thirds at the line of the foundation drains. In order to achieve this design objective, a grout curtain, along with extensive foundation cleaning and treatment operation, was required.

This paper summarises:

- The foundation and cleaning methods used at Wyaralong dam
- The drilling and grouting program, including mix design trials, methods, and verification testing
- The performance of the dam during the first filling phase

Foundation Excavation and Cleaning

The bedrock at the Wyaralong Dam site is Gatton Sandstone overlain by alluvium. The Gatton Sandstone predominantly consists of feldspathic to lithic-feldspathic sandstone with a clay matrix, with subordinate conglomerate, mudrock, minor coal, and fossil wood fragments. In the design phase of the project, the degree of weathering of the sandstone and the strength characteristics and dip direction of the site bedding features were identified as major contributors to the quality of the foundation. The bedding at the site generally dips downstream and into the right abutment of the dam. There are two predominant vertical to subvertical fracture sets, one of which was found to be highly weathered and generally oblique to the dam axis on the steep right abutment (refer Figure 1) and another generally parallel to the dam axis and relatively unweathered on the left abutment.

**Figure 1: Orientation of Vertical Joints on Right Abutment**

The first step in providing a quality foundation for the dam was bulk excavation of the material identified by site investigations as unsuitable due to its degree of weathering and the presence of deleterious materials such as dispersive clays, gravels, and organics. Because the depth of this highly weathered zone was in the order of several metres in the abutments, a drilling and blasting
Program was employed to efficiently perform bulk excavation. A significant portion of the shallow weathered rock was deemed competent to serve as a foundation, however, it was decided to drill, blast, and excavate past this material to expedite foundation cleaning operations. The decision to remove nearly all of the weathered sandstone significantly reduced grouting quantities below initial design estimates.

Following the drilling, blasting, and excavation, cleaning of the rock surface was performed using high pressure air and water jets, excavators and hand tools to remove any additional debris. Of particular concern were dispersive clays encountered in the near surface vertical fractures, which were jetted from fractures and surfaces or over-excavated where encountered near the upstream heel of the dam and treated with a series of small, localized concrete cut-off trenches. After foundation cleaning was completed, foundation levels were normalized with dental concrete to provide a working platform for drilling and grouting and RCC placement (refer Figure 2).

Drilling and grouting program

General

The drilling and grouting program for the Wyaralong Dam construction project consisted of the installation of a double-line grout curtain intended to provide an effective and durable seepage barrier for the dam.

The grouting was undertaken using Grouting Intensity Number (GIN) methods (Lombardi, 2002). The GIN method provides an estimate of effective grout penetration distance for radial, planar discontinuities and to provide a means of safely and effectively controlling the performance of grouting operations. By controlling the grout intensity (the product of the applied grouting pressure and the cumulative grout take) using real time monitoring tools, the concept allows for high pressure grouting in low take situations and low pressure grouting in high take situations, thereby maximizing treatment opportunity while reducing the risk of hydro-jacking or hydro fracture.

Water pressure testing when using the GIN method is typically limited to a pre- and post-grouting operation that provides comparative data to determine the effect of the grouting operation on the formation being grouted. At Wyaralong Dam, this data was provided by testing performed in cored holes, Exploratory (pre-grout) and Verification (post-grout) borings, along the grout alignment.

To accomplish the goals of the project, the drilling and grouting program included:

1. Drilling a double line 1.5 metres apart and parallel to the dam axis of inclined borings for the purpose of characterizing and treating the subsurface formation. Primary bores along each line were spaced at 6m centres, and secondary bores were drilled in between the primary holes;
2. Pressure testing with water and pressure grouting the holes with a balanced, stable, High Mobility Grout (HMG);
3. Real time electronic collection, analysis, and display of all water tests on pressure-flow curves and grout injections on GIN curves;
4. Daily updated data presentation of geology encountered, injected grout volumes and pressures during grouting and GIN curves for all stages completed;
5. Presentation of a daily updated subsurface profile depicting the subsurface conditions encountered and the results of water pressure testing and grouting for all borings; and
6. Drilling, water pressure testing, and grouting of Verification holes, with a target residual permeability value for all verification stages of less than or equal to 5 Lugeons.

Grout Mix Design Trials

A grout mix design program was undertaken to develop a balanced, stable mix design for grouting of the sandstone foundation of Wyaralong Dam. In the course of the trial, three types of Portland cement, both potable and site water, and numerous admixtures were evaluated to determine their effects on the rheology and workability of the grout.

The grout was originally required to conform to the following rheological properties:

- Bleed < 3 percent;
- Pressure Filtration Coefficient ($K_{pf}$)<0.040min$^{-1/2}$;
- Marsh Funnel Viscosity: 30 - 37 seconds (for 1.0L sample)
- Stiffening Time (Initial Set) > 3 hours.

Approximately 50 test mixes were batched and tested in the course of the grout mix design program. Water cement ratios were evaluated in the range of 0.6:1 to 0.9:1 by weight with various concentrations of admixtures from batch to batch. In the course of the mix design program, grouts meeting all of the rheological properties except the pressure filtration coefficient were produced.

In practice, a low pressure filtration coefficient corresponds to a high resistance to loss of mix water when
the grout is pumped under pressure, which in turn results in longer penetration distances and better overall grout quality at the leading edges of grout penetrations. A class of additives called Viscosity Modifying Admixtures (VMAs) are typically used to improve grout mix stability under pressure. Several locally available VMAs were tested at various concentrations, however, none were found to provide more than nominal benefit to the mix. Admixtures typically used for this purpose in other markets, such as welan or diutan gums, were not commercially available in the Australian market at the time. Based on the inability of commercially available products to provide pressure filtration resistance meeting the specification, the decision was made to proceed with the test program using the ‘best mix’ available and evaluate its performance directly.

Table 1 summarizes the materials and admixtures tested as a part of this program.

Table 1: Mix Constituents Used in Grout Mix Design Program

<table>
<thead>
<tr>
<th>Mix Constituent (Source)</th>
<th>Description</th>
<th>Purpose in Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blended Slag Cement 75% GP/25% GBFS (Wagners)</td>
<td>Blended slag cement - Addition of slag improves workability, penetration in fractures</td>
<td>Binder</td>
</tr>
<tr>
<td>GP Cement (Wagners)</td>
<td>Typical cement, fineness near to HE</td>
<td>Binder</td>
</tr>
<tr>
<td>HE Cement (Cement Australia)</td>
<td>High Early strength cement, (similar to Type III)</td>
<td>Binder</td>
</tr>
<tr>
<td>Potable Water (Site Supply Tanks)</td>
<td>Potable, delivered to site via tanker.</td>
<td>Cement hydration &amp; Fluidity</td>
</tr>
<tr>
<td>Site Water (from Bromelton Storage)</td>
<td>Non potable, delivered to site via pipeline</td>
<td>Cement hydration &amp; Fluidity</td>
</tr>
<tr>
<td>Rheobuild 1000 – (BASF)</td>
<td>Superplasticiser</td>
<td>Fluidifier/Water Reducer</td>
</tr>
<tr>
<td>Delvocrete Stabiliser - (BASF)</td>
<td>Retarder</td>
<td>Improve workability and pumping life</td>
</tr>
<tr>
<td>Rheomac VMA 362 (BASF)</td>
<td>Polymer type viscosity modifier</td>
<td>Increase pressure filtration resistance</td>
</tr>
<tr>
<td>Rheomac VMA 352 (BASF)</td>
<td>Polymer type viscosity modifier</td>
<td>Increase pressure filtration resistance</td>
</tr>
<tr>
<td>Welocel (Swift Co)</td>
<td>Methyl cellulose type viscosity modifier</td>
<td>Increase pressure filtration resistance</td>
</tr>
</tbody>
</table>

The mix selected for evaluation in the Grout Test Program had a W:C ratio of 0.6:1 using Wagner’s GBFS (Blast Furnace Slag) cement and included the additives Rheobuild 1000 and Delvocrete Stabiliser at dosages of 1.8% and 0.3% by weight of cement, respectively. The measured rheological properties of the test program grout mix were:

- Specific Gravity = 1.68 – 1.72
- Marsh Funnel Viscosity = 33 - 37 seconds (for 1.0 L sample);
- Bleed = 0 to 3 %;
- Pressure Filtration Coefficient (Kpf) = 0.11 to 0.15 min -1/2;
- Stiffening Time (Initial Set) = 12 – 15 hrs;
- Final Set = 20 hrs.

During the grout test program, a series of monitoring holes was drilled at various distances from the borings being actively injected to intercept the travelling grout and allow for evaluation of the mix after having flowed through the foundation. Travel distances in the order of 30 metres were noted, with grout of acceptable mix stability issuing from the holes. Based on the successful performance of the grout mix used in the test program, the 0.6:1 W:C ratio grout using blended slag cement, superplasticiser, and retarder was approved for use as the production grout mix. During production the grout mix was tested for specific gravity, Marsh Funnel viscosity, and bleed percentage three times daily with additional temperature and Marsh Funnel viscosity measurements taken at intervals to evaluate the condition of the grout in the agitator tank. If the grout temperature increased sharply or the Marsh Funnel viscosity of grout taken from the agitator exceeded 40 seconds, the grout was discarded and replaced with a fresh batch. Grout cubes taken of the production mix indicate the final 28 day strengths of the cured grout are on the order of 40 MPa, which approaches or exceeds that of the surrounding foundation material.

Overall, the selected grout mix delivered excellent performance during the course of the grouting program. The production mix proved to be very pumpable, with very little cake or scale forming in the grout lines at pumping distances up to 400m in temperature ranges from around 5 to 30 degrees C. While a mix with a better resistance to pressure filtration may have promoted greater travel than the production mix used and perhaps reduced overall grout quantities, the overall tight condition of the foundation rock combined with the maximum final hole spacing of 3.0 m provided adequate opportunity to effectively seal the foundation. As can be seen in Figure 3 and Figure 4, which show cured grout recovered in verification borehole cores through the conglomerate zone and a vertical fracture respectively, the injected grout has formed a homogenous, strong, and very tightly bonded product that should be highly resistant to seepage flow and washout over time.

![Figure 3. Grout Recovered in Verification Core through Conglomerate Zone](image-url)
Drilling

Drilling for the project was performed using rotary and rotary percussive drilling with water flush (Refer Figure 5). The percussive drill rig was fitted with a Drilling Parameter Recorder (DPR), which was set to record penetration rate, torque, thrust pressure, and water pressure in real time, allowing a drill log to be produced for each borehole drilled. These DPR logs were a useful tool for determining ground conditions and resolving final drill quantities. Initial Exploratory borings and final Verification borings were cored using either HQ or NQ sized triple tube core barrels. In addition to core recovery, optical televiewer logging was performed on select holes and multipressure water pressure (packer) tests were performed on all cored boreholes.

Primary borings were spaced at 6 m intervals, with Secondary holes split spaced to 3m intervals. Single pressure water pressure tests were performed on all Primary borings (drilled percussively) and drilling and grouting with Secondary borings was required as a minimum, resulting in a maximum treatment spacing of 3.0m. Tertiary holes (resulting in 1.5 metre spacing) were drilled and grouted where indicated by the results of adjacent primary and secondary holes. Borings were drilled to maximize interceptions with the primary fracture sets, bedding planes, and known areas of high hydraulic conductivity based on surface mapping and previously performed exploratory borings. On the left abutment, the dominant fracture set was near vertical and approximately parallel to the dam axis while on the right abutment, the dominant fracture set was near vertical and generally crossed the foundation from upstream to downstream. The bedding surfaces across the site dip around 8°. The final foundation surface on the left abutment around a 5H:1V slope and the final right abutment slope around 2.5H:1V with several intermediate benches. On the left abutment, borings were drilled with an inclination of 30° from vertical while on the right abutment borings were inclined 15° from vertical. In the upper reaches of the left abutment, borings were additionally rotated 15° toward the upstream to better intercept the vertical fractures. Figure 6 shows the inclinations of borings on the right abutment.

Grouting and Water Pressure Testing

Water testing and grouting equipment used for the program included a high shear colloidal mixer paired with a cement silo capable of automatic dosing of cement and water for mixing fresh grout; a holding tank equipped with an agitator; a control module consisting of two or four electric double acting piston pumps; pressure and flow gauges and a control computer; and packers and hoses used to control the injection location and depth. Water pressure testing was performed by manual operation of a valve to throttle pressure from a feed line independent of the piston pumps, while grout pressure was created and controlled by the piston pumps and computer control system.

In general, the sandstone comprising the foundation after foundation preparation was complete was found to be massive, unweathered, and impermeable. Initial water pressure test results ranged from less than 1 Lugeon to greater than 50 Lugeons, with the higher values occurring at intersections of vertical fractures and bedding planes at depth in the right abutment. Prior to the drilling and blasting program, very high permeabilities in excess of 100 Lugeons were encountered in the more weathered sandstone near the surface that was later removed. The results of multipressure water pressure tests performed in the Verification borings ranged from 0 to 4 Lugeons, with the majority of test results at or below 1 Lugeon.

The grouting of individual stages was controlled using a Jean Lutz computer controller in conjunction with a double acting piston pump system. The grout plants provided were equipped with two or four pumps, however the controller was capable of running up to 16 pumps.
simultaneously and autonomously based on user input control parameters.

When grouting using the GIN method, the control parameters are the maximum pressure, the maximum injected grout volume, and the GIN number. The GIN number is the product of the injected volume and pressure at any point of a grout treatment, and is selected to prevent excessive energy from pressure and volume from jacking or splitting the foundation rock material. Maximum pressures, maximum volumes, and the GIN limit were initially set based on experience, literature, an understanding of the site geology, and input from the project’s Board of Consultants and then adjusted based on conditions encountered during grouting to maximize the effectiveness of the grouting operation.

The initial and final GIN curves used at the project are shown in Figure 7 for the three depth ranges. Based on previously performed drilling, water testing, mapping of the foundation rock and the relatively massive and unfractured nature of the sandstone, it was expected the conglomerate layers and weak bedding features, (the weakest elements of the formation), would be the main areas of grout take, followed by the relatively less prevalent vertical fracture sets. Due to the relative weakness and generally horizontal orientation of these materials, less aggressive grouting parameters than used on projects of similar scope were initially selected and used successfully in the grout test program. This test program was performed outside the footprint of the dam to verify the contractor’s grout mix and the overall performance of the production system.

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In the initial production grouting on the left abutment, several observations during the grouting indicated that revisions to the GIN curves would reduce the risk of unnecessary grout injection and potential displacement of the foundation. At depths greater than 12 metres where stages intercepted known bedding features, a drop in pressure as the grout treatment approached the pressure limit and the upper third of the GIN number controlled portion of the plot (the hatched zone shown in GIN Curve 3 of Figure 7) indicated that a reduction in the maximum pressure was warranted. Figure 8 is a GIN plot depicting the pressure drops that predicated the changes to GIN Curve 3.

In stages between 6m and 12m deep, pressure drops were noted as the path of the grout treatment passed approximately 40 l/m of injected volume at a range of pressures (the zone indicated by the hatched zone on GIN Curve 2 of Figure 7). To reduce the grouting intensity in this depth range, the GIN number was reduced. These changes resulted in more efficient and less risky grout treatments, while still providing sufficient grout travel to provide interaction between grout holes and lines, and effectively treat groutable features.

**Performance of the Seepage Barrier**

The Wyaralong Dam began impounding water with the closure of the diversion pipe on December 17, 2010. Due to the extreme rainfall events that flooded much of Queensland shortly after, the reservoir filled in 25 days, much more quickly than would have been expected based on typical weather patterns in the area in the last few years. Figure 9 is a photo of the dam during its first spillway operation.

The rapid filling of the storage has meant that the performance of the seepage barrier can be assessed.
Figure 10 shows the design basis pressures (refer dashed line), which assumed a 67% reduction of pressure at the line of the foundation drains. Current piezometric levels measured at the maximum section of the dam indicate a head drop in the order of 30 metres across the grout curtain (refer Figure 10), which is a significant improvement on the design basis. Flows collected from the foundation drains drilled just downstream of the grout curtain are also significantly lower than the design thresholds, indicating that the grout curtain and foundation preparation works have created an effective seepage barrier.

![Figure 10: Pressures at Dam-Foundation Interface at Deepest Section](image)

**Figure 10: Pressures at Dam-Foundation Interface at Deepest Section**

**Conclusions**

The key findings of the foundation preparation and grouting works included:

- The foundation was cleaned and prepared by drilling, blasting and bulk excavation of the majority of highly weathered sandstone. Final foundation preparation was undertaken using water jets mounted on excavators, excavators with rock hammers, and hand tools. Small concrete cut-offs and grouting of seams were required in some locations. The foundation preparation methods used appear to have produced a watertight dam-foundation interface.

- An extensive trial program was undertaken to develop the mix design for the grout to be used in the curtain. Of the mixes trialled, all met the Specification except the limits for Pressure Filtration Coefficients. Viscosity Modifying Agents used by the WDA team members on other projects to improve Pressure Filtration, such as welan or diutan gums, were not commercially available in Australia, and as such, the Specification limits needed to be relaxed slightly.

- The grout mix selected for the project had a W:C ratio of 0.6:1 using Wagner’s GBFS cement and included the additives Rheobuild 1000 and Delvocrete Stabiliser.

- Grouting was undertaken using the GIN method, allowing real-time monitoring of the grouting.

- A trial grouting program was undertaken outside the dam footprint using the selected mix. Grout travels in access of 30m were recorded with excellent results.

- The initial GIN limits used for the trial program and the first holes on the left abutment were modified for the project to reduce the risk of hydro-jacking the foundation, and unnecessary injection of grout. Limits for the 6-12m stage, and stages deeper than 12m were modified, resulting in a more efficient and less risky grout treatment.

- Verification holes drilled to test the effectiveness of the curtain indicated that the injected grout has formed a homogenous, strong, and very tightly bonded product that should be highly resistant to seepage flow and washout over time.

Due to the diligence on the part of the Wyaralong Dam Alliance, and the state of the practice methods used to install a seepage barrier in the foundation, the dam has performed well during the first filling of the reservoir. Current uplift pressures measured along the dam footprint are generally significantly lower than the design basis used in the dam stability analysis. Seepage rates from the foundation drains immediately downstream of the grout curtain are also significantly lower than expected, indicating that an effective seepage barrier has been achieved.

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