Negotiating the Geological Structure of the Enlarged Cotter Dam Site
During the Abutment Excavation Period

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The Enlarged Cotter Dam (ECD) is under construction on the Cotter River, 18km west of Canberra. The new dam comprises an 85m high roller compacted concrete gravity dam, located 120m downstream of an existing 31m high concrete dam. This paper describes the geological structures that prevail at the site and their significance with respect to design and construction considerations.

Geological mapping has confirmed that the abutment slopes are characterised by zones of prominent rock outcrop and thin mantles of colluvial soil that form overall slope angles of 45 degrees. The Cotter River valley in the ECD area has been eroded through a geological sequence of Early to Late Silurian age, comprised predominantly of porphyritic rhyolite and lapilli tuffs of the Walker Volcanics.

Geotechnical investigations for the ECD were extensive and comprehensive. The results obtained have enabled the compilation of a detailed geological model of the dam site. Particular attention was paid to defining, characterising and kinematically analysing prominent geological structures, including intersecting sheared or crushed seams and zones that traverse the dam footprint.

Prominent geological structures that were encountered during the abutment excavation had significant design and construction implications for:

- Abutment stripping and foundation preparations;
- Rock slope stabilisation;
- The foundation of the intake tower that comprises a 66m high concrete structure; and
- The foundations for 1 x 56m high and 2 x 78m high tower cranes that required positioning on the steep abutment slopes during construction.

This paper highlights the importance of understanding the geological origin, nature and distribution of rockmass defects within a complex rock foundation. Site specific construction requirements and engineering design solutions used to successfully negotiate adverse geological structures are described.

Keywords: Dam, Roller Compacted Concrete, Geological Structures, Abutment, Foundation.

Introduction

The Bulk Water Alliance (BWA) was formed in May 2008 to design and construct the Enlarged Cotter Dam (ECD). The Alliance partners are ACTEW Corporation (owners), GHD Pty Ltd (designers), and an Abigroup John Holland Joint Venture (constructors).

The ECD project consists of the following key components:

- An 85m high Roller Compacted Concrete (RCC) dam with a crest length of 335m and a 70m wide central uncontrolled weir spillway;
- A fully concrete lined stilling basin;
- A reinforced concrete intake tower on the upstream face of the dam;
- Two saddle dams (to 21m in height) constructed of earth and rockfill; and
- A reservoir with a capacity of approximately 78GL.

At the time of writing in 2012, the ECD is under construction.

Regional Geology

The published Canberra 1:250,000 and Brindabella 1:100,000 Geological Series Sheets indicate that the ECD is located within an area of Late Silurian Walker Volcanics. The Walker Volcanics is described as predominantly comprising green to purple dacite, ignimbrite and bedded tuff.

Structurally, the Winslade Fault is located about 800 metres to the south of the ECD site and trends approximately north east. The Pig Hill Fault trends approximately north south and is located approximately 4 kilometres north west of the ECD.

Regional faulting is thought to have occurred from the Late Silurian to Mid Devonian. Reactivation of some regional faults is attributed to Late Cenozoic regional uplift (Abell 1991). Field inspection of regional fault exposures by the BWA suggests no movement has occurred in recent geological time.

Geotechnical Investigations

Comprehensive geotechnical design investigations for the ECD were carried out between April 2008 and September 2009, and they included:
• 19 cored boreholes (principally inclined) in the main dam site, totalling 1,102 metres of rock core;
• 243 downhole permeability tests (packer tests);
• Installation of piezometers for groundwater level monitoring;
• 7 seismic refraction tomography surveys along and perpendicular to the ECD axis;
• Engineering geological mapping and statistical fracture surveying of abutments; and
• Geotechnical laboratory testing of rock cores.

Geological Model
A geological model was developed for the ECD site using data obtained from the geotechnical investigations. Particular attention was paid to defining, characterising and kinematically analysing prominent geological structures, including intersecting sheared seams and crushed seams that traverse the dam footprint.

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

The orientations of all defects measured during geological mapping were consolidated into left and right abutment data sets. Natural defect data was plotted as stereographic projections of poles to planes (Figure 1).

Figure 1: Stereographic projection of poles to planes (left abutment only)

Analyses of data enabled the delineation of seven defect sets present on the ECD abutments (Figure 2), three of which were found to comprise prominent vertically and horizontally persistent crushed or sheared seams and zones.

Table 1 presents a summary of the three most prominent natural defects sets identified at the ECD site.

<table>
<thead>
<tr>
<th>Defect Set</th>
<th>Mean Orientation (Dip° / Dip Direction°)</th>
<th>General Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>19 / 291</td>
<td>Predominantly joints and persistent crushed seams and sheared zones</td>
</tr>
<tr>
<td>Set 2</td>
<td>60 / 088</td>
<td>Predominantly joints and persistent crushed seams</td>
</tr>
<tr>
<td>Set 3</td>
<td>89 / 360</td>
<td>Predominantly joints with some persistent crushed seams and sheared zones</td>
</tr>
</tbody>
</table>

Construction Implications
Abutment Stripping and Foundation Preparation
Understanding the geological origin, nature and distribution of prominent Set 1, 2 and 3 geological structures was essential for the preparation of a foundation with suitable strength, stiffness and permeability characteristics on which to construct the 85m high RCC gravity dam.

Photograph 1 shows the left abutment slopes in March 2008 prior to the commencement of abutment excavation. The Cotter River flows from west to east (toward about 105°). Defect sets 1, 2 and 3 define the valley topography and prominent geological structure of both abutment slopes.

Vegetation lines reveal the dominant Set 1 and Set 2 geological structures on the natural ground surface. Set 3 geological structures form many of the prominent near vertical rock outcrops and cliff lines.
Defect sets 1, 2 and 3 form an orthogonal arrangement of geological structures. Photograph 2 provides an example of how the intersection of these defect sets can form kinematically unstable blocks on the abutment slopes. In this example defect set 1 provides the basal release plane and defect sets 2 and 3 form the side and back release planes respectively.

The block shown in Photograph 2, located at the crest of the left abutment, is about 12m$^3$ in size. Predicting the location of larger kinematically unstable blocks in the dam foundation was possible because particular attention was given to identifying and characterising those defects that were known or expected to be persistent over tens or hundreds of metres. This typically includes the ‘geological faults’, being sheared or crushed surfaces, seams and zones.

Photograph 3 shows a Set 1 crushed seam identified on the left abutment slopes during geological mapping.

This defect is typical of seams which vary from 50mm to 200mm in thickness and comprises angular to lenticular shaped pieces of rock contained between roughly parallel but undulating boundaries. The internal rock fragments are bound by closely spaced fractures that are typically sub-parallel to the boundary surfaces. The internal fractures are generally smooth to rough with some polished surfaces and silt/clay veneers and coatings.

The surface traces of prominent persistent defects were accurately located by survey (from the opposing abutment slope). The crushed seam pictured in Photograph 3 has a surveyed length of over 100 metres and is identified in Photograph 1.

Correlation of the data obtained from geological mapping, cored boreholes and seismic tomography surveys facilitated the inclusion of persistent geological structures in the dam foundation geological model.
Photograph 4: Intersection of Set 1 and Set 3

Photograph 4 (the location of which is shown on Figure 3) shows the intersection of Set 1 and Set 3 crushed seams at the midpoint of the left abutment foundation.

The rock mass at the intersection of these crushed seams had open and clay infilled defects, indicating a deeper zone of stress relief. Higher permeability, potentially erodible clay infill materials and lower stiffness made this portion of the rock mass unsuitable for the dam foundation. Approximately 500m$^3$ of unsuitable rock was excavated resulting in a 6m wide bench and 5m high step in the foundation, defined by the Set 1 and Set 3 crushed seams respectively.

Figure 3 shows how prominent Set 1, 2 and 3 geological structures have dominated the shape and treatment requirements of ECD excavations. The identification of these structures in the geological model enabled accurate planning for the excavation and treatment of the abutment slopes.

Photograph 5 (the location of which is also shown on Figure 3) shows the intersection of a Set 1 shear zone and Set 3 crushed seam at the toe of the right abutment. Whilst the intact rock at the intersection was fresh and very high strength, the presence of open and clay infilled defects indicated a zone of deep stress relief associated with the prominent geological structures. An additional 3000m$^3$ of unsuitable rock was excavated to expose suitable strength, stiffness and permeability characteristics in the rock mass.

The shape of the foundation, in particular the significant Set 3 defects, influenced the location of the RCC dam monolith joints. They were typically situated at the top of vertical faces to minimise the potential for cracks arising from stress concentrations in the RCC on account of the abrupt changes in the foundation profile.

Additionally, irregularities in the abutment slopes required the use of ‘dental concrete’ to backfill deep holes and protect vulnerable seams from deterioration whilst the foundation excavation was completed.

Figure 3: Section showing prominent geological structure in the dam foundation (looking downstream)
Photograph 6 shows the right abutment and valley floor when excavations and abutment treatment works were close to completion.

**Rock Slope Stabilisation**

**Small Scale Rock Slope Instability**

The geological model incorporates the seven rockmass defect sets mapped on the abutment slopes. These intersect to create fracture-bound rock masses with a range of stability conditions and magnitudes.

Kinematic instability mechanisms were identified for each of the abutment excavation batters. Valley stress relief, rockmass weathering and construction blasting were all expected to contribute to loosening and increased potential instability, particularly near the crest of excavation batters.

Using the results of kinematic analysis, batter angles and orientations were adjusted where possible to reduce the likelihood of sliding, wedge and toppling failures.

Intermediate benches were incorporated into the excavation design to provide rockfall catch capacity. Rockfall modelling was used to refine the batter height to bench width ratio and identify critical zones where higher densities of rock support would be required.

A total of 1845 rock bolts and 8974m\(^2\) of shotcrete were used to stabilise the abutment excavations. This compared well with the forecast stabilisation quantities reported by Barclay *et al.* (2012).

**Large Scale Rock Slope Instability**

The identification of prominent geological structures during the geotechnical investigation phase enabled potential large scale rock slope instability features to be delineated prior to the abutment excavations commencing.

It was anticipated that instability features of up to 3000m\(^3\) in size would require either removal or stabilisation in place. Appropriate design solutions and construction methodologies were established so that excavation and stabilisation works could be completed in a safe and efficient manner.

‘Feature 11’ constituted the most significant instability feature identified on the abutment slopes. Photograph 7 shows the location of Feature 11 on the right abutment above the future outlet works. A Set 7 crushed seam dipping at an angle of 30 degrees out of the slope formed a basal slide plane for Feature 11 (Photograph 8).
The Set 7 crushed seam was typically 100mm thick with angular to lenticular shaped pieces of highly weathered rock contained between roughly parallel but undulating boundary planes. The exposed rock surfaces were polished and slickensided with the striations indicating a down dip direction of shear movement.

The volume of the potential failure mass was estimated at 2700m$^3$. The decision was made to remove the mass rather than attempt the difficult task of stabilising in place as a consequence of its assessed likelihood of instability. The excavation and support methodology included:

1. Excavation and stabilisation of an access bench above the potential failure mass;
2. Drill and blast to form a rock bench below the basal slide plane; and
3. Excavate the blast debris and stabilise the resulting rock batter from below.

Photograph 9 shows the excavation and stabilisation work underway during September 2010. The upper bench has been excavated and supported using mesh reinforced shotcrete. The blast debris has been side cast using a 30 tonne excavator and the installation of rock support is continuing.

The excavation and stabilisation of Feature 11 enabled abutment excavation to continue safely below a previously unstable rock slope. In addition, a significant rockfall hazard was removed from above the dam outlet works.

Below the design foundation level, blast energy had disturbed the rock mass by wedging open the Set 3 structures, leaving loosened blocks of rock in the foundation.

Based on the nature and distribution of these geological structures, it was concluded that the rockmass on the down slope side of the intake tower had a high likelihood of instability thus would not provide a suitable foundation on which to construct the structure.

**Intake Tower Foundation**

The main dam intake tower was to be located on the left abutment, but construction programming benefits gave rise to a late change to the right abutment, being offset 5m from the primary spillway.

The tower has an overall height of 66m and was designed to be free-standing to its full height during the construction period. For long term stability once the reservoir has filled, the intake tower is secured to the upstream face of the dam.

The bulk excavation for the intake tower foundation was completed to the design level in December 2010. Detailed geological mapping identified several significant geological structures intersecting the intake tower foundation, including:

- A 50 to 100mm thick Set 7 crushed seam with an orientation of 62/026 (dip/dip direction), which was identified at the upslope side of the foundation;
- A 250mm thick Set 3 shear zone (Photograph 10) and a 15 to 20mm thick Set 3 crushed seam, steeply dipping toward the north, located on the down slope edge of the foundation; and
- Five 2 to 5mm thick Set 2 crushed seams, moderately dipping toward the east, on both the upstream and downstream edges of the foundation.

Diamond cored borehole investigations were undertaken to examine if other geological structures with adverse orientations were present within the intake tower foundation.

Using data obtained from geological mapping and cored boreholes the geological model was refined and an excavation and foundation stabilisation design and construction methodology was established (Figure 4).
Further bulk excavation was completed to expose a rock foundation that slopes between 10 to 20 degrees towards the river (Photograph 11).

Mass concrete was used to reinstate the foundation to the design level of RL 487.5 (mAHD).

The foundation reconstruction commenced with the construction of an anchored concrete footing at the edge of the abutment slope (Figure 4). The footing was anchored using two rows of fully cement grouted passive rock dowels (32mm galvanised steel bar), drilled 6m into rock.

The bulk of the foundation was then reinstated using mass concrete with surface reinforcement for crack control. The mass concrete was secured using two rows of passive rock dowels, inclined at 45 degrees from horizontal, drilled from the top of the mass concrete and 6m into rock.

A total of 366m³ of concrete was used to reinstate the intake tower foundation (Photograph 12).

With the intake tower foundation reinstatement complete, the right abutment excavation was progressed to the valley floor, 16 metres below.

Additional stabilisation of the foundation included:

- Three rows of 12m long rock passive rock dowels progressively installed in the slope below the intake tower; and
- Spot rock bolts installed in the rock slope below the intake tower as required.
Photograph 13 shows the intake tower at approximately 60 metres height and Photograph 14 shows the intake tower at full height, with the RCC providing considerable restraint to the structure.

The additional bulk excavation and foundation rock anchors provided a foundation with adequate stability, strength and stiffness characteristics on which to construct a free standing intake tower.

Photograph 13: Intake tower at 60m height

Photograph 14: Intake tower at full height

**Tower Crane Foundations**

The ECD project utilises three tower cranes for the construction of the dam. The location, founding level and height of each crane is summarised in Table 2.

<table>
<thead>
<tr>
<th>Tower Crane</th>
<th>Abutment</th>
<th>Foundation RL (mAHD)</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC1</td>
<td>Left</td>
<td>493.00</td>
<td>78</td>
</tr>
<tr>
<td>TC2</td>
<td>Right</td>
<td>484.70</td>
<td>78</td>
</tr>
<tr>
<td>TC3</td>
<td>Right</td>
<td>530.26</td>
<td>56</td>
</tr>
</tbody>
</table>

Each of the tower cranes is founded on the steep abutment slopes. For foundations on sloping ground it is necessary to account for the reduced lateral resistance on the downslope side of the footing when assessing bearing capacity and settlement. However, for steep slopes, the controlling factor is typically the stability of the slope.

**Geotechnical Investigations**

For each tower crane the abutment excavation was initially progressed to approximately 5m above the proposed foundation level.

Detailed geological mapping of available rock exposures was completed to identify geological structures that could form part of a kinematically admissible foundation failure mechanism. An orientated diamond cored borehole was drilled at each tower crane location to complete a structural geological model for the foundation.

Based on the kinematic failure mechanisms identified, a foundation excavation and stabilisation design was completed for each tower crane.

**Construction**

Once the tower crane locations were confirmed, the foundation excavations were completed to design level. Detailed geological mapping was undertaken to verify the geological model.

The foundations were scaled using hand tools (jack hammers, picks and shovels) and washed clean using high pressure water before the levelling concrete was placed to cover the rock.

Sixteen tensioned vertical strand anchors (12 x 15.2mm diameter strands) were installed for each tower crane. The structural concrete footing was then poured and the base section of the tower crane was installed.

The dam foundation excavation was continued in 5m lifts below the footing so that rock bolts and shotcrete support could be installed as required.
Photograph 15 shows the completed foundation for Tower Crane 1 (TC1) on the left abutment. Once the rock slope below the tower crane base had been adequately assessed and supported the tower was erected to its full height (Photograph 16).

Survey monitoring of the tower crane footings during and after erection confirmed negligible foundation movement occurred.

Photograph 15: TC1 foundation

Photograph 16: TC1 erected to full height

Conclusions

This paper describes some of the prominent geological structures that were encountered during the abutment excavations for the Enlarged Cotter Dam.

These structures had significant design and construction implications for:

- Abutment stripping and foundation preparation;
- The dam design including the overall geometry and positioning of monolith joints;
- Rock slope stabilisation;
- The foundation of the intake tower; and
- The foundations for the three tower cranes that required positioning on the steep abutment slopes.

The paper highlights the importance of understanding the geological origin, nature and distribution of rockmass defects within a complex rock foundation.

Recognising the geological origin of a rockmass defect enables an understanding of its engineering significance. At the Enlarged Cotter Dam site rockmass defects recognised as 'geological faults' were predicted to be persistent over tens or hundreds of metres.

The geological model delineated prominent geological structures, including intersecting sheared and crushed surfaces, seams and zones that were considered most likely to influence the stability, strength, stiffness and permeability of the rockmass in the dam foundation. This model informed both design considerations and construction planning aspects of the project.

A full-time engineering geological team presence during the abutment excavation period enabled the BWA to identify and successfully negotiate a range of prominent geological structures, the effects of which would have otherwise created construction difficulties with associated adverse workplace safety, programming and cost impacts.

References


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