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## Collation and interpretation of structural data at various scales to inform 3D structural models

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**ABSTRACT:** The structural model for Bendora Dam collated georeferenced historic field mapping, remote sensing point clouds and newly collected gap-fill mapping. The bedding orientations spoke to the folding history of the site – with the dam founded on a monoclinic limb of a syncline, medial drag folding by the Cotter Fault and lateral, rotational drag folding by the intrusion of the Cow Flat Granite. Three sets of persistent joints were present. Mapping data captured the inputs required for basic friction angle assessment (equating to the core-scale understanding). Persistence and waviness data supported detailed analysis of dilation angle which ultimately allowed the abutment scale adopted friction angle to be derived. Orientation measurements also allowed for bedding and joint waviness interpolation to be understood using the 3D modelling software Leapfrog. This modelling provided clarity on the scale of fold development across the site and demonstrated that the three joint sets observed developed at different times relative to the fold history (two pre-folding, one post-folding). This critical observation allowed different defect shear strength considerations to be adopted depending on the applicable joint set and its age relative to the fold history. It also provided an explanation as to why the Cotter River orientation downstream of the dam deviated from the Cotter Fault parallel alignment observed upstream and highlighted the critical stability issues that may present due to the planarity of the last-formed joint set.

**Keywords:** structural geological model, 3D modelling, remote sensing.

### 1 INTRODUCTION

Bendora Dam is located on the Cotter River, the middle of three dams in the Cotter River catchment which supplies water to the Australian Capital Territory (ACT), Fig. 1. It forms a critical infrastructure within the water supply network straddling two states. The dam is a 47 m high, double curvature variable arch dam with a centrally located spillway. It is located in a narrow V-shaped gorge (some 25 m wide) comprising quartzite rock outcrops of the Tidbinbilla Quartzite (TQ), Fig. 2.

As part of the 20-year Dam Safety Review, a comprehensive geotechnical study was completed. This work collated and georeferenced over 60 years of historic mapping and drilling, completed further mapping, both traditional and remotely in poorly or inaccessible locations and formulated a 3D geological and geotechnical model for the site.

This paper discusses how the individual joints sets contribute to the structural stability of the dam and how that fits with the wider geological understanding for the site. It demonstrates that ubiquitous assignment of the same parameters for all sub-vertical joints may not be appropriate when the timing of regional deformation, intrusive events and changes in principal stress directions are considered.

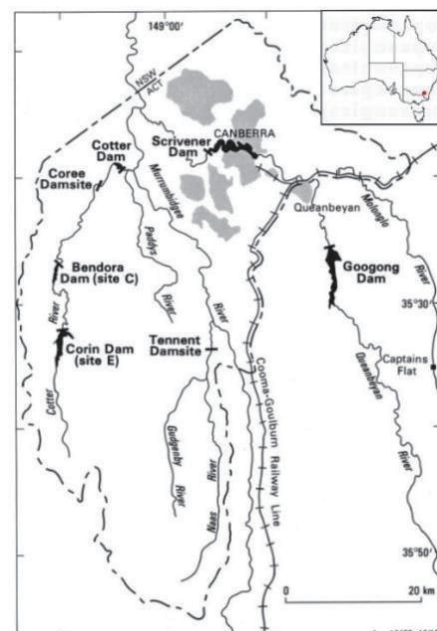


Fig. 1. Cotter River Dam system (Best, 1981).



Fig. 2. Bendora Dam configuration with close-up of right abutment

## 2 DATA

### 2.1 Digitised and georeferenced historic work

Over 60 years of mostly hand-drawn geological maps were available for the site, which were georeferenced and digitised for the structural model using ArcGIS.

### 2.2 New mapping

Traditional mapping was undertaken to fill data gaps and collect surface condition information for joints and bedding. This data provided the necessary information used to assign a basic friction angle to bedding and joints in TQ as laboratory testing was limited. The orientation data was acquired using the FieldMove CLINO digital application, oriented relative to grid north using an Oppo R11S. This allowed world grid co-ordinates to be captured, as well as descriptive information and photographs to be directly associated with each mapping point. The application measurements were regularly cross-checked with a standard geologist field compass to ensure the methodology produced results consistent with established field techniques.

### 2.3 Remote Sensing

Remote Sensing (comprising photogrammetry and LiDAR) was used to assess the structural orientation, spacing and shape character of the abutment outcrops that were no longer safely accessible. Three areas were assessed, two on the right abutment, one on the left. The process of collecting and interpreting remote sensing

data to characterise the defect sets are detailed in companion paper Stariha and Baxter-Crawford (2022).

The open-source program *CloudCompare* (V2.12α) was used to display, process and render point clouds, as the program includes several purpose-built plugins and algorithms which allow for specialist measurements and data processing applications.

## 3 GEOLOGY

The Tidbinbilla Quartzite comprises thinly to thickly bedded quartzite, silicified quartz sandstone and siltstone, with thin interbeds of friable sandstone, siltstone, claystone, and sedimentary breccia. It is fine to medium grained and highly silicified. Eleven distinct bedding planes are observed at the dam. Certain beds were more prone to sliding behaviour due to the presence of the sedimentary breccia. Observations of strength and texture comparing quartzite upstream during the reservoir inspection with the dam outcrops suggest the intact rock adjacent to the dam is slightly stronger and less porous than upstream, due to contact metamorphism associated with intrusion of the Cow Flat Granite (CFG).

The TQ outcrops as a west to north-west dipping limb of a monoclinically kinked synclinal fold. The right abutment, immediately downstream of the dam, comprises a dip slope with beds dipping approximately  $17^\circ$  to  $25^\circ$  towards the river and pronounced sub-vertical jointing. Bedding shallows to  $5^\circ$  to  $15^\circ$  in the left abutment, before steepening again. Bed spacing is typically 0.5 to  $>2$  m thick and beds form large exposure planes in the dip slope. Undulations are observed in both dip parallel and dip normal orientations at the outcrop scale, and overall gentle undulations are recognised over scales of several metres.

At the reservoir scale, the long axis of the reservoir approximately aligns with the north-south oriented Cotter Fault, separating the TQ from more altered and deformed phyllite of the Abercrombie Formation. Approximately 200 m downstream of the dam, the TQ is intruded by the CFG, Fig. 3. Mapping and modelling suggest that fault movement along the Cotter Fault caused the medial dragging of bedding to create the syncline axis. Further, bedding appears to have been rotated laterally by the intrusion of the CFG. As such the dip direction of TQ bedding within the synclinal limb varies from west dipping within the reservoir to north-west dipping at the dam location, to north-north-west dipping downstream.

Three joint sets are apparent from the mapping data collected for this study, Fig. 4. Table 1 summarises the typical joint set orientation. The joint spacing is variable with a weak zonation of strongly jointed areas and sparsely jointed areas. More persistent, continuous joints are associated with wider, more massive beds, whereas the thinner bedded zones exhibit more closely spaced,

less persistent joints.

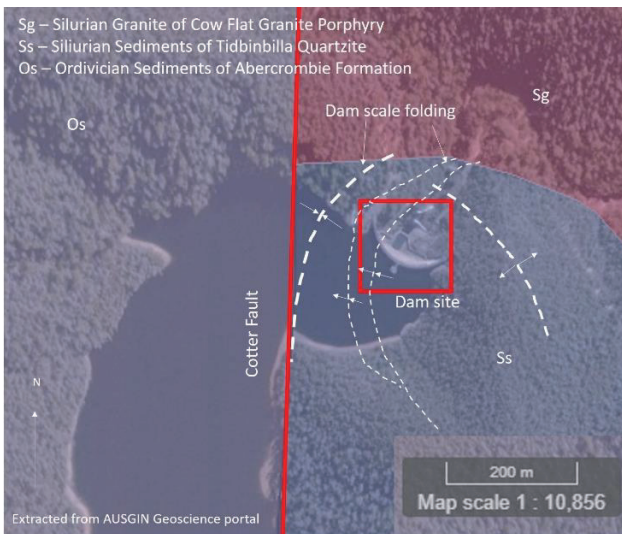


Fig. 3. Reservoir scale structures and stratigraphy (NTS).

Table 1. Summary of Jointing (relative to true north).

Joint Set	Dip (°)	Trend/Strike	Other Characteristics
1 (red)	70-90	NW-SE	Spacing 0.5-10m; persistence laterally >2m, vertically penetrates multiple beds
2 (purple)	80-90	NE-SW	Spacing mostly 0.2-0.5m; persistence laterally >2m, vertically penetrates multiple beds
3 (orange)	80-90	NNE-SSW	Spacing 0.4->2m, persistence laterally >10m, vertically penetrates multiple beds

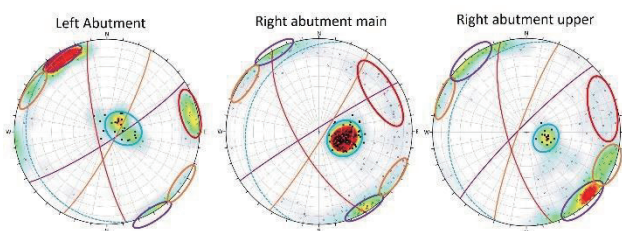


Fig. 4. Stereoplots of joint sets from photogrammetry. Set colours as per Table 1. Light blue set is bedding

#### 4 INTERPRETATION AND RESULTS

The primary stability concern for the site was the risk of planar sliding of daylighting bedding in the right abutment. However, more detail was needed to understand stability at the block scale, and whether failure of one or more jointed blocks during overtopping of the dam could lead to unravelling of either abutment.

The structural data (comprising over 500 bedding and 1000 joint measurements) provided a comprehensive understanding of how faulting and intrusions had altered

the orientation of the sedimentary bedded sequences of the TQ at the project scale.

Limited direct shear laboratory testing and field testing existed, so a forensic assessment of the infill and surface character of each major bed boundary was completed. This provided a basis for base friction angle selection for each major bed. Surface waviness at the block to abutment scale was assessed using the point cloud of the right abutment where large bed surfaces were exposed. Dilation angle was calculated using the method proposed by Dong et al. (2020) and was observed to be anisotropic. To derive inputs for stability analyses, consideration of both traditional planar slide (down-dip) mechanisms as well as the situation where applied force of water may force a block to travel across the surface (along strike) was required. The resulting assessment indicated dilation angle along strike was observed to typically be 2° to 4° higher than along the dip direction. Additionally, specific beds were assigned different dilation angle ranges, and consequently adopted friction angles, based on the results.

Further, bed waviness characterisation at the site scale was assessed using the *Form Interpolant* function within *Leapfrog*. This function uses structural data to identify broad orientation trends in 3D. Results are presented as a fabric model, comprising multiple sub-parallel planes which represent the shift in orientation of a defect set in space, without representing any one defect surface. This characterisation supports the interpretation of the drag folding of bedding by the CFG intrusion and the main syncline axis is reflected, Fig 5.

As part of the *Form Interpolant* assessment, the waviness character of the three observed joint sets was assessed. The waveform analysis indicated that Joint Sets 1 and 2 (red and purple) have been deformed by the external influences that caused folding and rotation to bedding, while Joint Set 3 is mostly planar (at the dam scale) and undeformed, Fig. 6. Set 3 approximately parallels the Cotter River immediately downstream of the dam and sub-parallel the Cotter Fault to the north of Bendora where the fault trends more NNE. This suggests the final set of joints present at Bendora are late forming, subject to the same stress regime as the northern Cotter Fault and may explain why the Cotter River locally deviated from the Cotter Fault’s plane of weakness west of the dam.

The potential for unravelling of the abutments during an overtopping event is controlled by three things:

1. Frictional component (inclusive of waviness, surface roughness and infill condition) of the bedding plane in the along-strike direction,
2. Frictional component of the joints that define the block size and
3. Spacing of joints and beds which define the block size.

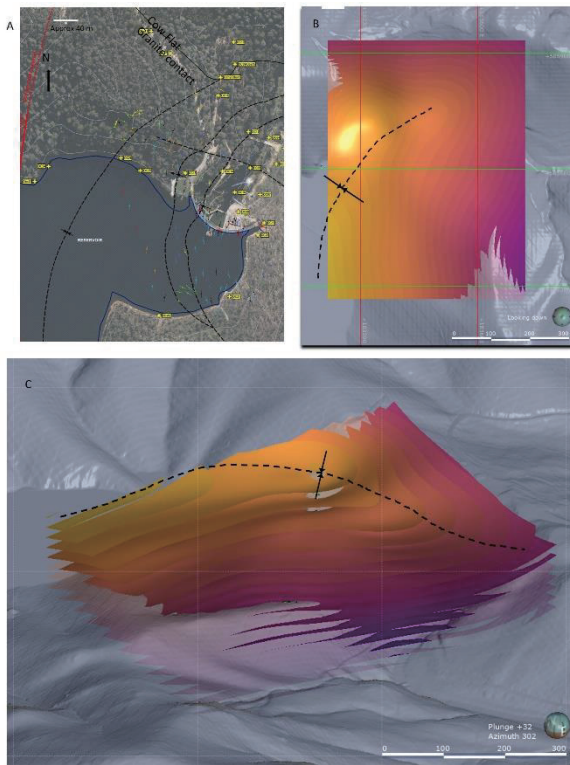


Fig. 5. Waviness Character of Bedding from Leapfrog Form Interpolation. a) Structural data, in plan b) Bedding form interpolant, in plan with synclinal axis; c) Bedding form interpolant, viewed facing north-west, with trace of synclinal axis.

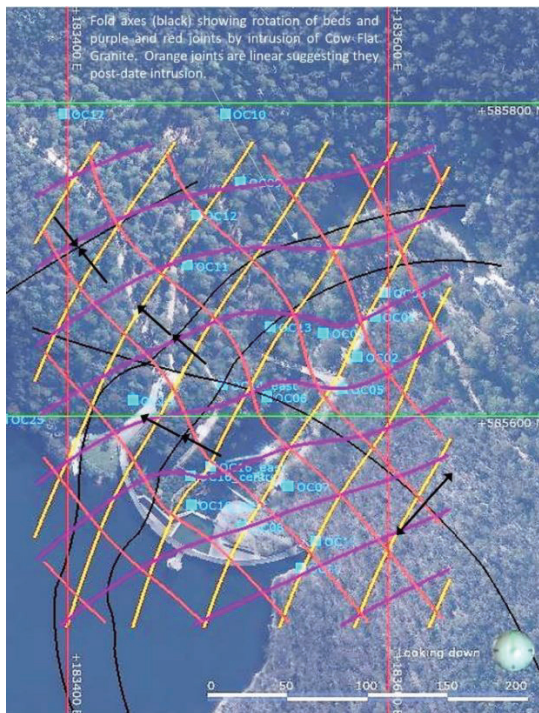


Fig. 6. Trace of joint form interpolants intersecting with a horizontal plane at the reservoir level. Colours as per Table 1. Bedding fold hinges shown in black.

Considering the apparent temporal-structural relationship with the joint sets, it is reasonable to recommend the adoption of a lower limit dilation angle for Set 3 and mean to upper limits for Sets 1 and 2 in stability analyses. Observations of the river downstream of the dam support this, indicating block failure from natural flood events was dominated by blocks where Set 3 was present. The narrow spacing and therefore smaller block size attribute to Set 2 often resulted in it acting as a release plane. Blocks with Set 1 as the bounding joint set tended to remain unscathed in outcrop. As such, blocks bounded by Set 3 and to a lesser extent Set 2 are considered most likely to be eroded by in an overtopping event. At this time, the specific water force required to remove such blocks has not been assessed.

## 5 CONCLUSIONS

Remote assessments were used to enhance the understanding of spacing, persistence, dilation and waviness of geological structures at Bendora Dam, on top of the roughness characteristics captured by traditional mapping. This allowed specific adopted friction angles to be assigned for each bed and joint set for stability analysis. This assisted in highlighting which specific beds and joints would be most likely to fail in an overtopping event and allow targeted consideration of whether additional support may be required for dam safety.

## ACKNOWLEDGEMENTS

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