With the construction of a new dam, the project is assumed to be complete following the commissioning stage. However, it is not until after first filling that the behaviour and performance of the structure can be truly assessed.

During the first filling of the enlarged Cotter Dam, an 87m high RCC gravity dam located west of Canberra, excess seepage developed in the gallery, primarily from two of the monolith joints. Subsequent underwater investigations of the upstream face in these locations identified cracks offset from the monolith joints, originating close to the foundation.

The investigation and rectification program implemented at the dam provides important industry learnings with regards to how unforeseen issues can arise and how they can be rectified. This paper will include a discussion regarding the possible causes of the cracking, and the potential risk mitigation measures that could be considered to avoid similar issues occurring in future projects. The discussion includes a review of options for design and positioning of transverse joints, along with possible measures to prevent cracking in future similar applications.

The investigative methods utilised to determine the cause of the excessive seepage at the Cotter Dam are discussed. The options considered for remediating the seepage, and the final methodology adopted will also be presented. The paper will also discuss the challenges in undertaking the remedial works, and the lessons learnt for consideration on future projects.

**Keywords:** RCC dam, excess seepage, transverse joint, investigation, crack

**Introduction**

The enlarged Cotter Dam is an 87m high roller compacted concrete (RCC) gravity dam, located west of Canberra on the Cotter River. The dam was constructed between 2009 and 2013 by the Bulk Water Alliance; comprising the owner Icon Water (formerly ACTEW Water), the designer GHD, and the constructor John Holland and Lendlease (formerly Abigroup).

As the dam began to impound water, seepage through the transverse (monolith) joint drains was recorded in the dam gallery. The rate of seepage was initially within expected bounds. In the months following construction completion and dam commissioning, two instances of sudden increase in seepage flow rate occurred. The weirs monitoring seepage from the right abutment of the dam gallery recorded the increase in seepage, as shown in Figure 1.

The telemetered seepage measurements at Weirs 1 and 2 had initially been relatively low, with a gradual increase as the reservoir began to fill. At the end of June 2014 the combined seepage from these weirs was in the order of 100L/min. On the 1st July 2014 the seepage rate at Weirs 1 and 2 rose almost instantaneously; from 35L/min that morning to 130L/min by afternoon for Weir 2 alone. No significant increase in seepage rate was noted on the seepage weirs on the left abutment gallery at this time. Inspection in the dam gallery found excessive flow through the dam monolith joint at Ch. 205m. The joint had become pressurised, with water jetting through the joint where it crossed the gallery floor.

In the weeks following the seepage rates at Weirs 1 and 2 levelled off and even decreased slightly, before continuing to increase gradually as the reservoir continued to fill. A second sudden increase in seepage rate at both weirs was again noted on the 2nd August 2015. Inspection now found a similar increase of flow into the gallery through the transverse joint at Ch. 217m. Thereafter the increase in seepage rate at the two weirs was gradual and proportional to the rising reservoir level. Unsteady seepage recordings occurred from this time onward, as depicted in Figure 1, as a result of the turbulent flow conditions in the gallery drain, which affected the v-notch weir readings.

The total seepage through the dam (including the contributions from the weirs on the left abutment) at the end of June 2014 was approximately 320L/min. By October 2014 this had increased approximately six fold, to almost 1,900L/min. The reservoir was 82% full (by volume) at this time. The excessive flow into the gallery from the monolith joints at Ch. 205m and Ch. 217m was creating a safety hazard in terms of access on the inclined gallery stairs.
The drainage channel that conveyed the combined seepage collected in the gallery to the Cotter River downstream was at risk of exceeding capacity and flooding the gallery entrance floor. Remedial works were therefore required to address the increase in seepage.

This paper discusses the investigative methods utilised to determine the cause of the excessive seepage at the Cotter Dam. The options considered for remediating the seepage are also presented, as is the final approach adopted. The paper will also discuss the challenges in undertaking the remedial works, and the lessons learnt for consideration on future projects.

**Seepage Investigation**

**Diver Investigation**

Following the initial incremental increase in seepage rate in the gallery, divers were engaged to complete an inspection of the monolith joints and surrounding upstream face of the dam. As the incremental increase in flow roughly coincided with an increase in water level, it was suspected that the seepage was coming from the newly flooded areas of the dam, or in close proximity to the level of the water in the reservoir at the time. Diving operations were therefore limited to 20m below the reservoir level, which also reduced investigation costs. Water ingress to the joints was tested by spraying diluted milk along the monolith joints and the exposed concrete face of the dam 3m either side. No obvious high seepage areas were detected, and no particularly defective concrete was observed.

**Remote Operated Vehicle (ROV) Investigation**

Having failed to locate the source of the increased seepage at relatively shallow depths with divers, alternative investigation methods were considered. With increased dive depth the allowable dive time is significantly impaired, reducing the efficiency and increasing the cost of the investigation.

Considering the time, cost and quality of information required from the investigation, the option of the Remote Operated Vehicle (ROV) was adopted. This ROV unit mobilised to site was capable of descending to depths of 90m (greater than the maximum reservoir depth at Cotter Dam). The unit was fitted with four thrusters for control, had underwater lighting, real time video footage, and the capability of fitting an injection nozzle to allow dye to be inserted into the reservoir at suspected defect locations to further investigate any potential inflows.

The ROV inspection concentrated on the monolith joints at Ch. 205m and Ch. 217m, and the concrete immediately adjacent. The unit was lowered first to the foundation interface at joint Ch. 217m, where a crack was detected approximately 0.8m to the left of the joint, and extending 9m upwards subparallel to the joint.

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Upon detection of the crack, the dye nozzle was fitted to inject dye into the reservoir at the crack location, in an attempt to ascertain whether the crack was taking in water. As shown in Figure 2, flow into the crack was clearly observed.

The process described was repeated with the ROV to investigate the joint at Ch. 205m and another crack was detected. The cracks adjacent the joints at Ch. 217m and Ch. 205m were nine and four metres long respectively. Both of the cracks were on the downslope side of the joints and extend sub-vertically back towards the monolith. The cracks were within 1m of the monolith joints and extended below the level of the monolith joint/foundation interface. Both joints were estimated to be open up to 4mm wide. The location of the cracks found is shown in Figure 3.

**Cause of Cracking**

A change in the temperature of concrete leads to a change in its volume. The primary causes of temperature change in large concrete dams are the heat of hydration of cement and supplementary cementitious materials (and the subsequent dissipation of that heat) and changes in ambient temperature. Where restraint is present (either internal or external), this leads to stresses and strains being developed in the concrete. When these exceed the tensile capacity of the concrete, cracks develop.

This is a widely understood and well documented phenomenon in mass concrete structures (ACI, 2007). As a control measure transverse joints are introduced into concrete dams to control the location and width of such cracking. For Cotter Dam, the monolith joints were induced into the fresh RCC using a vibrating plate and plastic. It was intended for the joints to extend the full thickness of the RCC. The upstream end of the joint was formed with rigid plastic boards which were extended through the Grout Enriched RCC (GERCC) zone at the face of the dam and connected with the centrebulb of the waterstop. The detail is shown in Figure 4.

The cracks are understood to have come about as a result of thermal shrinkage of the dam as it has cooled, however the reason the cracks have occurred adjacent to the monolith joint rather than in the monolith joint itself is unclear. Possible causes of the cracking are listed below. Any of these, or a combination, could have contributed to the cracking:

**Joint Location**

1. The position of the joint at Ch. 217m was at the top of an abrupt change in slope. This location was deliberately selected as stress concentrations were anticipated in this location. It may be that the final joint location was slightly beyond the crest of the slope; however this is not immediately apparent from site records (survey and photographs). It also does not explain the cracking at Ch. 205m.

2. Subtle and/or localised irregularities in the foundation profile may have been present, leading to preferential cracking of the concrete rather than opening of the monolith joint.

3. Shrinkage related movement of the concrete near the centre of the monolith may have led to a form of sympathetic cracking.

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Joint Construction

4. It is possible that the joints were not fully induced through the RCC in these locations. If the joint was not effectively induced right through to the foundation, some tensile capacity would exist at the induced joint which would increase the risk of cracking off the line of the joint. With the joint inducing boards associated with the waterstop on the upstream side of the dam however, this is considered unlikely.

5. A row of formwork anchors (z-bars) were typically placed in this area. It has been seen in other areas that cracks can align with z-bars. A row of z-bars should, however, have minimal crack initiating potential compared with the fully de-bonded adjacent transverse joint.

6. The interface between the RCC and the GERCC associated with the waterstop is in this location. A deliberate effort was required to properly compact this interface. It is therefore possible that some layers may not have been fully densified in this area, thereby creating a zone of weakness where cracking would be more likely to occur.

Other

7. Localised settlement of the foundation relative to adjacent areas, giving rise to cracking of the concrete.

8. The overall spacing of the monolith joints was also considered as a possible cause for the cracking. The maximum spacing of the transverse joints on Cotter Dam was up to 18m wide. However the affected monoliths were only 15.5m and 12.3m wide.

Measures to Prevent Cracking in Future Projects

Preventative measures that could be considered to avoid similar cracking in future projects include:

Joint Location

Consideration could be given to constructing the monolith joints slightly below the crest of abrupt steps in the foundation. This does however present a risk of cracks developing from the crest of the step back to the joint.

At the base of the right abutment another large sub-vertical, joint defined face was present in the foundation. In this location (Ch. 174m in Figure 5) the transverse joint was constructed 1m offset from the rockface. Very little seepage has been detected at this joint.

Other projects have successfully adopted other alternative details against steep abutment foundations. These include casting the waterstop into the face of the abutment and treating the abutment as an extension of the transverse joint. This is achieved by first excavating a channel up the abutment to secure the waterstop into the abutment and can only be considered for very steep abutments.
Joint Spacing

In the vicinity of slope irregularities where a higher risk of unplanned cracking exists, consideration could be given to reducing the transverse joint spacing in that location, effectively creating a narrower monolith. This reduces the magnitude of any shrinkage in response to temperature change, which in turn limits the potential for unplanned cracking.

Slope Correction

Slope correction concrete can be used to eliminate abrupt foundation irregularities. This was adopted at Ch. 62m on Cotter Dam as seen in Figure 5. Very little seepage has been detected at this joint. This work was also undertaken to manage abutment seepage and as a non-critical path activity. Time and cost constraints may limit the use of this method in other circumstances. In some cases slope correction can also be achieved through additional excavation, although the orientation and extent of foundation defects may limit the potential for this form of treatment.

Reinforcement

Consideration could be given to adding reinforcement to the RCC and/or facing concrete in areas where residual risk is considered to exist. Such contingency measures could be implemented with minor time and cost implications. This technique was used successfully in other areas on Cotter Dam where the risk of cracking was identified (e.g. at conveyor pedestals and other similar temporary works structures that were left in place and encapsulated within the dam).

Construction Process

If the risk of cracking in the vicinity of a particular waterstop is considered to be higher than usual, tighter construction tolerances and increased supervision can be introduced to ensure additional care is taken in constructing the joint in that location.

Figure 4 – Transverse Joint Detail
Seepage Remedial Works
Assessment of Repair Options
The following design criteria were adopted for the seepage/crack repair:

- The repair was to reduce seepage through the dam without causing other operational issues (i.e. without blocking foundation drains);
- The repair was to be capable of withstanding potential future movement in the vicinity of the cracks; and
- The repair was to provide a durable solution.

The following options were considered for the repairs:

- Securing and sealing a flexible PVC membrane on the upstream face over the cracks, using divers to secure the membrane on to the face. The membrane would be secured to the dam upstream face with a stainless steel bracket, and protected from damage with a stainless steel plate cover that allows joint movement.
- Injecting the cracks with a polyurethane expansive grout from the upstream face of the dam using divers.
- Injecting the cracks with polyurethane expansive grout from the gallery.
- Installing new waterstops downstream of the existing dam waterstops by drilling down the line of the joint from the crest and installing a hydrophilic compound in the void.

An evaluation of the options available for the crack repair was made to select the methodology best suited to the conditions at the Cotter Dam. A summary of the assessment is presented in Table 1.

Adopted Repair Methodology
Injection of a polyurethane expansive grout into the cracks from the upstream face of the dam using divers was selected as the preferred repair methodology. The reliance on divers was considerably less for this option than the flexible membrane option. Furthermore in terms of quality and confidence in achieving a seal, injection of grout from the upstream face was preferred over grouting from the gallery. The hydrophilic waterstop was acknowledged as a solution that would provide a high quality result, however the anticipated high costs associated with this option ruled it out of further consideration. Furthermore the alignment of the cracks beyond the upstream face was unknown, so there was a risk that the hole from the crest, for insertion of the waterstop, would not intersect the crack.
<table>
<thead>
<tr>
<th>Assessment Criteria</th>
<th>Membrane</th>
<th>Upstream Grout Injection</th>
<th>Gallery Grout Injection</th>
<th>Hydrophilic Waterstop</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Suitability/ Application</strong></td>
<td>- Provided installed correctly, should provide a flexible barrier to prevent seepage through cracks. - Heavily reliant on diving time for fixing membrane to dam face. Estimated 28 hrs for Ch. 217m alone. - Membrane and fixing details fabricated off site prior to installation. Potential issue if crack dimension is different/has changed.</td>
<td>- Some reliability on divers for installation of grout injection points on upstream face of dam (parallel with cracks). - Injection of grout can be carried out at the surface without need of diver. - Some uncertainty with regards to applying grout products under 40m of reservoir head, and into seepage flow through the crack.</td>
<td>- Pressure grouting against seepage flow more favourable for sealing. - Difficulties envisaged in targeting crack locations with drill holes from the gallery. - Difficult access inside the inclined gallery to establish drilling works (platforms would need to be established). - Concerns around controlling seepage water flow when intercepted.</td>
<td>- Method would seal joint for entire length (crest to foundation). - Hole for insertion of waterstop would have to be drilled close to upstream face of gallery to ensure seal (given unknown extent of crack in downstream direction). - Drilling works would likely have to be from a platform on the dam crest. - Longer drilling depths (crest to abutment foundation).</td>
</tr>
<tr>
<td><strong>Timing</strong></td>
<td>- Ready supply of materials. - Application time considered slow due to surface preparation and underwater bolting to dam face (estimated bolts at 150mm centres minimum).</td>
<td>- Ready supply of materials and plant. - Relatively rapid application time anticipated.</td>
<td>- Ready supply of materials and plant, more work in establishing drilling operations in gallery. - Slow targeted drilling works.</td>
<td>- Expected lead time in acquiring hydrophilic waterstops from overseas. - Lengthy drill time anticipated with deep holes.</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>- No significant material costs. - Excessive dive time would have a notable cost bearing.</td>
<td>- Notable material costs, ultimately dependent on volume of grout used. - Diving time less significant so contributes less to overall cost.</td>
<td>- Notable material costs, ultimately dependent on volume of grout used. - Some cost associated with establishing drilling operations and temporary works in gallery. Drilling costs likely to be similar to diving costs.</td>
<td>- More notable drilling costs due to set up of platform on crest and longer drilling lengths. - Cost of waterstops and shipping from overseas expected to be considerable.</td>
</tr>
<tr>
<td><strong>Environmental</strong></td>
<td>- No concerns with water supply during installation or long term. - EHN fish virus preventative control measures to be put in place in the Cotter reservoir for the diving equipment.</td>
<td>- Grout approved for use in potable water storages. - Controls required to prevent grout material waste flowing downstream into the Cotter River. - EHN fish virus preventative control measures to be put in place in the Cotter reservoir for the diving equipment.</td>
<td>- No EHN fish virus preventative control measures required (no work in reservoir). - Grout approved for use in potable water storages. - Controls required to prevent grout material waste flowing downstream into the Cotter River.</td>
<td>- No EHN fish virus preventative control measures required (no work in reservoir). - Controls required to capture drilling offcuts on dam crest from flowing into Cotter River or reservoir.</td>
</tr>
</tbody>
</table>
Quality
- Some concerns with sealing membrane interface with:
  - Uneven upstream dam surface;
  - Foundation interface.

Upstream Grout Injection
- Grout would need 'calibrating' to ensure it sets prior to being washed through crack with seepage flow.

Gallery Grout Injection
- Grout would need 'calibrating' to ensure it sets prior to being washed through crack with seepage flow.
- Concerns with regards to difficulty in intercepting the crack on the upstream face when drilling from the gallery.

Hydrophilic Waterstop
- Alignment of drill holes important to ensure interception of seepage through the monolith joint for the full length of the hole.

Safety
- Management of safe diving times and work over and in water.
- Management of safe diving times and work over and in water.
- Safe measures for mixing/pumping grout.
- Management of drilling platform in gallery and safe access to.
- Safe measures for mixing/pumping grout.
- Management of drilling platform on dam crest and safe access to.

Application of Repair
Grouting of the cracks was to be undertaken in two stages. A hydrophobic polyurethane grout was to be injected first to stem the seepage flow through the cracks. This grout reacts when in contact with water, producing a rigid foam. Immediately after a hydrophilic polyurethane grout was to be injected; this reacts when in contact with water to form a resilient flexible seal that accommodates ongoing crack movement.

The grouts to be applied rely on an accelerator to initiate expansion when they come into contact with water. The volume of accelerator to be introduced into the grout depends on the environment in which the grouting works is being undertaken, in terms of the temperature and the pressure. The grouting subcontractor undertook laboratory trials off site, replicating the 9°C water temperature and 400 kPa pressure (approximate reservoir head at that time). This allowed a best estimate of the accelerator dosage to be determined prior to mobilising to site.

The procedure for grout injection of the cracks at dam monolith Ch. 205m and Ch. 217m is summarised below:

1. Diver drills a 12mm diameter hole into the crack, offset by 150mm, as shown in Figure 6.
2. Diver inserts and secures injection packer into the drill hole.
3. Injection hose connected to the packer from the surface, and the hydrophobic polyurethane grout pumped from surface.
4. Initial hydrophobic grouting discontinued when observed exiting the upstream face of the dam through the monolith joint. Hydrophilic polyurethane grout then pumped into crack, at pressures up to 2,750kPa.
5. Once material observed coming out of the crack on the upstream face, or inside the dam gallery, grouting to cease.
6. Diver to move up or down crack 0.5m and start new injection point, repeating the above process until the length of crack grouted.
7. Joint tested by spraying dye on upstream face for signs of residual seepage flow, additional injection points may be required depending on outcome.
Result and Lessons Learnt

The crack grouting operations at Cotter Dam were undertaken over a seven day period in October 2014. The success of the treatment is demonstrated by the seepage reduction achieved. Prior to commencing grouting works the seepage collected in the dam gallery totalled at approximately 1,900L/min. At demobilisation from site the total seepage had reduced to 800L/min. In the months that followed, the seepage continued to decrease, to a low of 220L/min in mid-April 2015. The reduction in seepage is shown in Figure 7.

In undertaking the grouting works, some components of the work were more time consuming than originally anticipated. With this knowledge some recommendations with regards to improvements can be made for future application of this approach to sealing leaking cracks in concrete dams.

The short drill holes for insertion of the injection packer for grouting the cracks were drilled by the divers with a hydraulic power drill. The time required to drill the holes ranged from five minutes up to fifteen minutes, depending on the diver’s ability to achieve resistance to the drilling action. A means of supporting the divers against the upstream face of the dam would have greatly improved the efficiency of the drilling works.

The primary time consuming component of the works was the grouting. During initial applications of the hydrophilic polyurethane grout, the seepage flowrate through the cracks was such that the grout did not have time to react prior to being washed through into the gallery. Increasing the accelerator dosage assisted, but ultimately a means of reducing the flow through the cracks was sought. A flexible building putty was applied along the length of the crack on the dam upstream face to reduce the inflow. This slowed the flow of the grout through the crack, thereby allowing the grout to expand and set within the crack as intended.

The advantage of grouting from the upstream face was the flexibility it offered. The crack observed at monolith joint Ch. 205m was approximately 5m longer at the time of grouting than when it was measured two months prior using the ROV. Had alternative methods (such as the upstream PVC membrane) been adopted, significant downtime would have occurred prior to installation for the dimensions of the bracket and membrane to be modified to suit the final dimensions of the crack. Worst still, depending on the timing of the works, the patch could have been installed only to find that the crack propagated beyond the extent of the repair soon thereafter.

Conclusions

Temperature change, thermal stresses and the potential for cracking is a widely understood phenomenon associated with construction of large concrete dams. The forces at play are however complex and despite attempts to predict and manage cracking by the spacing and strategic placement of transverse joints, on occasion unplanned cracking occurs. This was the case at Cotter Dam. The unplanned cracking at Cotter Dam lead to excessive seepage developing in the gallery, primarily from two of the monolith joints on the right abutment.

Several possible contributing factors have been identified as to why the cracking occurred including the exact positioning of the transverse joints, the joint construction and other reasons.
Alternative joint locations, targeted reduced joint spacing, slope correction treatment and reinforcement have been identified as possible treatment measures to limit the risk of similar cracks occurring in future projects.

The use of both ROV technology coupled with divers enabled a cost effective means of investigation and treatment to be achieved.

A range of possible treatment methodologies exist, each of which have their advantages and disadvantages. The optimum solution is likely to vary from project to project. In the case of the Cotter Dam, where significant uncertainty existed with cracking at considerable depth and with difficulties associated with access from other locations; grouting from the reservoir offered the flexibility required. One of the cracks had propagated an additional 5m in length from when it was initially inspected to when the repairs were undertaken, two months later. Had an alternative treatment methodology been adopted this could have significantly impacted on the cost, time and effectiveness of the repair.

Ultimately the cracks were grouted from the reservoir using a combination of modern hydrophilic and hydrophobic polyurethane grouts. The current technology is such that the chemistry can be adjusted to suit the intended application and modifications can be made in the field depending on performance. This coupled with other simple measures allowed for successful treatment to be achieved. The adopted methodology also allows for subsequent applications to be undertaken, in the unlikely event this is required.

Ultimately the seepage from the dam has been reduced to approximately one tenth of what it was prior to grouting, a very successful outcome. The total seepage through the dam is currently approximately 300L/min which is considered to be well within acceptable limits for an 87m high RCC dam.

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