Construction Flood Risk Strategies for Dam Upgrades

Colleen Baker(1), Sean Ladiges(1), Peter Buchanan(1), James Willey(1), Malcolm Barker(1)
GHD Pty Ltd

Dam Owners and Designers are often posed with the question “what is an acceptable flood risk to adopt during the construction of dam upgrade works?” Both the current ANCOLD Guidelines on Acceptable Flood Capacity (2000) and the draft Guidelines on Acceptable Flood Capacity (2016) provide guidance on the acceptability of flood risk during the construction phase. The overarching principle in both the current and draft documents is that the dam safety risk should be no greater than prior to the works, unless it can be shown that this cannot reasonably be achieved.

Typically with dam upgrade projects it is not feasible to take reservoirs off-line during upgrade works, with commercial and societal considerations taking precedent. It is therefore often necessary to operate the reservoir at normal levels or with only limited drawdown. The implementation of measures to maintain the risk at or below that of the pre-upgraded dam can have significant financial and program impacts on projects, such as through the construction of elaborate cofferdam arrangements and/or staging of works. This is particularly the case where upgrade works involve modifications to the dam’s spillway.

The use of risk assessment has provided a reasonable basis for evaluating the existing and incremental risks associated with the works, such as the requirement for implementation of critical construction works during periods where floods are less likely, in order to justify the As Low As Reasonably Practicable (ALARP) position.

This paper explores the ANCOLD guidelines addressing flood risk, and compares against international practice. The paper also presents a number of case studies of construction flood risk mitigation adopted for dam upgrades on some of Australia’s High and Extreme consequence dams, as well as international examples. The case studies demonstrate a range of construction approaches which enable compliance with the ANCOLD Acceptable Flood Capacity guidelines.

Keywords: Construction, Spillway, Upgrade, Flood, Risk, Dams, Cofferdams.

Introduction

In Australia, the vast proportion of dam construction works involve upgrading existing dams as opposed to constructing new dams. Water control strategies during construction are typically required in both circumstances, however the approach in these scenarios can be quite different. Firstly, retrofitting cofferdams or water control facilities to an existing dam during an upgrade project is often substantially more complex than at a greenfield site due to aspects such as restricted space and operational constraints, and in turn these aspects can result in substantial costs to manage construction floods. Furthermore, in the case of upgrade works on new dams, the risks associated with inadequate water control strategies are often far greater due to the potential to lead to dam breach of an entire storage as opposed to a partially completed one.

For such a complex, high risk and potentially expensive problem, there is very little guidance available worldwide on the appropriate flood risks to be adopted for a temporary water control feature on a new dam, let alone for a dam upgrade project where the consequences of failure can be far greater.

The key objective of this paper is to provide dam Owners, Designers and Contractors with insight to construction flood risk mitigation strategies on dam upgrade projects. The first part of this paper explores the practices recommended both in Australia and around the world by leading dam authorities. This paper then presents case studies that cover a range of water control strategies, along with a description of how the risk profile was found to be acceptable in each case.

The review of these case studies has led to the development of a number of guiding principles regarding how to comply with the ANCOLD guidelines during construction upgrades, and key questions to be asked in relation to the ALARP principle.
Australian Guidelines

ANCOLD (1986) Guidelines on Design Floods for Dams (Superseded Guidelines)

In Australia, recommendations regarding construction flood risk are provided in the ANCOLD Guidelines on Acceptable Flood Capacity for Dams.

The superseded version of these guidelines, ‘ANCOLD Guidelines on Design Floods for Dams (ANCOLD 1986)’, included relatively prescriptive recommendations on acceptable flood risks during construction, although it is noted it concentrated on risks associated with the construction of new dams, and not upgrade projects. An extract from these superseded guidelines is provided in Table 22 below. These guidelines take into consideration the likely duration of the construction period, and compare the probabilities against the equivalent probabilities assuming that dam has a 100 year design life (ie for a High Hazard Category this equates to approximately a 1% probability of the flood occurring at some point in the duration of the construction works, which is equivalent to the likelihood of the spillway design flood occurring during the 100 year design life of the dam for the High Hazard Category dams). This approach has now been superseded by the use of assessing risk on an annual basis. These recommended probabilities in the guideline significantly exceed the acceptable societal risk in current industry practice.

<table>
<thead>
<tr>
<th>Incremental Flood Hazard Category</th>
<th>Recommended Design Flood A.E.P. for a risk period of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 year</td>
</tr>
<tr>
<td>High</td>
<td>1 in 100</td>
</tr>
<tr>
<td>Significant</td>
<td>1 in 100</td>
</tr>
<tr>
<td></td>
<td>to</td>
</tr>
<tr>
<td>Low</td>
<td>1 in 10</td>
</tr>
<tr>
<td></td>
<td>to</td>
</tr>
</tbody>
</table>


With the advances in the use of risk procedures in dam engineering, the current ANCOLD Guidelines on Acceptable Flood Capacity for Dams (ANCOLD 2000) took a less descriptive approach to recommendations, and acknowledged that there is no consistent standard for risks associated with handling floods during construction. Various recommendations are made in the guidelines, however no universal approach is provided. Instead, the guidelines state that for construction works on existing dams “in general, the aim, as far as practicable is to not increase the existing risk”.


The ANCOLD Guidelines on Acceptable Flood Capacity for Dams is currently being revised, and a draft version of the document has been circulated for comment. Similar to previous revisions, this Guideline provides recommendations on construction floods.

The guiding principle in the draft document follows a very similar approach to that described in ANCOLD (2000), namely that “the dam safety risk to communities downstream of a dam should be no greater during the construction of a remedial works project than the risk prior to the work” (ANCOLD, draft 2016). This guidelines also states that in some cases, this approach may not be feasible, and therefore the dam owner should demonstrate that the proposed management of floods during construction has taken an ALARP approach. The Guideline also introduces the concept of ‘duration weighted average’ in terms of allowing short periods (e.g. a few weeks) of higher risk exposure to construction floods if the average risk in the year achieves the annual life safety risk profile prior to construction.
In summary, it can be said that the draft ANCOLD Guidelines provide greater scope to explore options to manage construction floods, however quantifying various aspects of the guidelines, such as how ALARP and ‘duration-weighted average’ risk are applied is not detailed.

Other ANCOLD Guidelines
The ANCOLD guidelines on Risk Assessment of Dams (2003) provide guidance on whether duration of exposure can be applied in deciding whether risks can be considered ALARP. For situations where persons are exposed to risk for a “once-off” short period, or intermittently on a regular basis, the application of exposure factors are appropriate. The guidelines suggest that for short durations, a higher individual risk is acceptable, on the basis that this higher risk is offset by periods of zero risk, and that there is an averaging process, which ensures that, over any significant period of months or years the average risk to the person complies with the guidelines.

However, the guidelines recommend that once the duration becomes sufficiently lengthy (undefined, but taken as a number of months or a year or so) of continuous exposure, that it does not seem reasonable to speak of “risk averaging”. The risk guidelines state:

“It could be argued that it is not acceptable to have a higher risk imposed on the population over the lengthy period of exposure – in particular to exceed the limits of tolerability ... than would be tolerable for an indefinite period. In such a case, it is reasonable to recall that the life safety criteria ... are not qualified as to period of exposure.

Consequently, for dams under construction or being modified, the life safety risks should be estimated, and the risks reduced ALARP within the tolerability zone, by such measurements as:

- All reasonably practicable measures at the site, such as provisions for safely passing floods, that will reduce the life safety risks;
- Construction phase Dam Safety Emergency Plans, including flood warning and evacuation planning.”

In DSC (2010) the Dam Safety Committee of NSW sets out a number of requirements for the management of flood risk during construction. In summary, the guideline provides the following description of flood risk during construction:

- The provision for passage of floods during construction (new dams or modifications to existing dams) should be based on risk assessment that considers the potential economic loss from a flood failure, as well as risks to the safety of workers and any community at risk.
- Arrangements for flood risk would normally include flood warning and evacuation plans
- The management of flood risk during construction will be site specific, noting that consideration may be given to phasing of critical construction during seasonal low flow periods to minimise risks.
- It is noted that there could be practical difficulties in meeting normal risk to life criteria, but the ALARP process, with consideration of what is practicable, may provide a basis for decision.

In summary, the DSC (2010) recommend a similar approach to that which is discussed in the ANCOLD guidelines, albeit it does not specifically state that risks during construction are to be the same as the pre-existing risks.

Australian practice on non-flood based failure modes during dam upgrade construction
It is important to note that upgrade projects often require the dam structure to be modified in a way whereby the factor of safety for stability may be less than in its existing case. For example the downstream face of an embankment dam may be temporarily excavated to a steeper slope in order to retrofit filters and place a stabilising berm. In these sorts of scenarios, it is common place to assume a greater risk for the shorter period of time. Common practice is to accept a factor of safety for slope stability of >1.3 for the construction case, compared >1.5 for the normal case. Silva et al (2008) propose a correlation between Factor of Safety for slope stability against annual probability of failure. They suggest that for facilities designed, built and operated with standard or state-of-the-art engineering, a slope with a factor of safety of...
1.3 has approximately 2 orders or magnitude greater probability of failure compared to a factor of safety of 1.5. While it is not easy to quantify, the probability of piping failure may also increase during an upgrade project, particularly if the existing embankment cross-section is being temporarily reduced. It is noted that it is rare to reduce the cross section of the embankment without requiring the reservoir level to be drawn down, therefore, for example, in the case of slope stability, the reduction in Factor of Safety may not necessarily mean an increase in societal risk.

It has not been standard practice to show that the dam risk due to earthquake loading is not temporarily increased during upgrade works. If earthquake loading is assessed during a construction phase, it is generally only in terms of a standards-based approach as opposed to a risk-based approach.

When reviewing appropriate flood risks to adopt during a construction period, it is considered important to assess whether the probability of failure for other potential failures modes of the dam are also being temporarily elevated by the construction works. It is considered that these potential failure modes need to be addressed commensurate to the degree of influence they have on the overall risk profile of the dam.

International Guidelines
ICOLD Guidelines
ICOLD (1986) Bulletin 48 – River Control during Dam Construction, provides extensive discussion on flood risks during construction. Like many guidance documents, this Bulletin is focused on flood control strategies during the construction of new dams. Irrespective, the guideline provides advice in terms of flood capacity, but takes a similar approach to the superseded ANCOLD guideline by taking into account the likely construction duration, using the following relationship:

\[ Pr = 1 - \left(1 - \frac{1}{T}\right)^L \]

Where \( Pr \) = Probability of a return flood of ‘T’ years being exceeded at least once in the ‘L’ years of construction.

The guideline recommends that the acceptance criteria for ‘Pr’ is based on an assessment of annual costs of damage (taking into account upstream and downstream damage) compared with the expected annualised cost of diversion, to provide a total cost which is then assessed against flood risk.

The ICOLD recommendations are an appropriate means to select appropriate construction flood risk during upgrade projects in terms of financial risk, but not to societal risk.
Canada (Canadian Dam Association)
The Canadian Dam Association (CDA) does not appear to provide any strict guidance on construction flood risk for dam upgrades and with the selection of reasonable flood risk during construction resting on the engineer and owner.

New Zealand (NZSOLD)
The NZSOLD Dam Safety Guidelines (2015) provide a chapter on construction floods and temporary works. The guidelines states that for new dams, the risks during construction in terms of loss of life should be no greater than over the life of the dam. The guideline also provides advice in terms of possible acceptable flood protection during the construction of new dams for different dam types. The guidelines suggests that a 10 year flood may be appropriate for a concrete dam, a 50 year flood appropriate for an embankment dam with no life safety risk, and a 250 year floor for an embankment dam where there is a likelihood for the loss of one or more lives downstream of the dam. For upgrade works, the guideline states that ‘the consequences of dam failure should not be increased during the completion of any rehabilitation works’. It is noted that it is unclear whether the guideline intended to state ‘consequences’ or in fact meant ‘risks’.

USA (FEMA)
A number of dam industry guidelines exist in the USA. The Federal Emergency Management Agency (FEMA) has a regulatory role in terms of setting out dam safety practices for Federal agencies dam owners and dam owners regulated by the Federal Agencies. FEMA’s key reference document is ‘Federal Guidelines for Dam Safety’, published in 2004. This guideline briefly covers the requirements for flood risk during construction, and states “The capacity of these appurtenances should be sufficient to satisfy the discharge requirements of the regulation plan for water control during construction”. The guidelines also states that the temporary flood control works should also generally comply with the requirements of permanent flood control works. In terms of permanent flood control works, the guideline states, “When flooding could cause significant hazards to life or major property damage, the flood selected for design should have virtually no chance of being exceeded. If lesser hazards are involved, a smaller flood may be selected for design. However, all dams should be designed to withstand a relatively large flood without failure even when there is apparently no downstream hazard involved under present conditions of development.”

UK (Institute of Civil Engineers ICE)
ICE (2015) Floods and Reservoir Safety provides guidance on acceptable flood capacities for dams, and includes a chapter on floods control during dam construction and dam improvement works. The document notes that earlier editions recommended a 1% Annual Exceedance Probability during critical construction periods for upgrade and dam removal works, however this is now regarded as too simplistic and possibly implying too great a downstream risk. The document recommends that the choice of flood during improvement works be subject to a failure mode analysis and risk assessment, with the risk of dam failure during critical construction periods shown to lie within the range of tolerability and reduced to ALARP. The document recommends that during critical periods, both weather and upstream catchment conditions should be monitored and a contingency plan put in place with appropriate warning levels and emergency actions.

Case Studies
Introduction
The following presents a number of case studies of spillway dam safety upgrades in Australia, to demonstrate different approaches taken to address construction risk.

Kangaroo Creek Dam Upgrade Project
Kangaroo Creek Dam is a 65 m high Concrete Faced Rockfill Dam located on the River Torrens in the Adelaide Hills, South Australia The dam is owned and operated by SA Water and has been classified as Extreme Consequence Category.
The dam was first completed in 1967, with subsequent upgrade works carried out in the early 1980s. The upgrade works improved the flood attenuation of the spillway, by raising the ogee crest level, constructing two low-flow ducts through the ogee and raising the dam crest by installing a “U beam” on the existing crest.

A quantitative risk assessment showed the risk position of the dam was above the ANCOLD Tolerable Risk limit. While flood overtopping was not the primary failure mode, the spillway capacity was found to be inadequate. Dam safety upgrade works are currently under construction, including:

- Upgrading the spillway to pass the Probable Maximum Flood (PMF), comprising widening the spillway by approximately 40 m and raising the dam by 3.8 m.
- Removing the “U beam”, and replacing with a conventional CFRD raise
- Construction of a downstream berm, to facilitate the raise and improve post-earthquake stability

The spillway comprises a side-channel ogee crest leading to an approximately 200 m long shallow sloping spillway chute terminating in a flip bucket and plunge pool. The upstream portion of the right side training wall forms a buttress, termed the Left Abutment Block, which supports the upper left end of the embankment. A failure of the Left Abutment Block would result in opening of the parametric joint and likely result in dam breach.

The following requirements were imposed on the project during the construction upgrade works:

- The flood-retention characteristics of the storage had to be retained
- The existing flood capacity of the dam prior to upgrade, estimated to be the 1 in 60,000 AEP flood (1800 m3/s) had to be maintained throughout the construction works
- The dam had to remain in operation throughout the construction period

In order to retain the dam crest level during the removal of the “U beam”, a staged removal approach was adopted in order to retain the existing crest level throughout construction (refer Figure 2). This involved retaining the upstream stem of the U beam as a cofferdam until the embankment has been raised. An alternative approach which was considered was to first widen the spillway prior to removing the U beam, thereby retaining the existing spillway capacity with a lower crest, however due to construction staging this approach was not adopted.

![Figure 96 Staging of embankment raise to retain existing dam crest level](image)
In order to widen the spillway, while retaining the existing flood retention function, the low flow ducts must remain open, while the ogee crest level, approximately equivalent to the 1 in 200 AEP flood level, must be maintained elsewhere. An upstream cofferdam is to be installed that is designed to overtop. Designed failure of the cofferdam to increase the flow capacity was not permitted, due to the assessed incremental consequences of the increased flood-wave which would be formed at the collapse of the cofferdam. The cofferdam is therefore designed to pass the 1 in 60,000 AEP flood without failure, therefore matching the existing flood risk. Construction of the upstream cofferdam to withstand significant overtopping has been extremely costly, with an extremely small probability of experiencing any overtopping during its service life, which is expected to be less than one year.

For the main duration of the upgrade works, the flood risk will be equivalent to the dam in its pre-upgrade state. However, to facilitate the dam raise, the Left Abutment Block must be enlarged. There is a period in which the rock at the toe of the existing Left Abutment Block must be exposed, in order to prepare the foundations for the enlarged buttress. A major spillway flow at this period may result in a temporary increased risk of undercutting and failure of the Left Abutment Block. To mitigate this risk, the area of foundation exposed at any one time is limited to an extent which can rapidly covered and weather forecasting will be monitored to select appropriate times for carrying out the excavations.

**Eildon Dam Upgrade Project**

Eildon Dam is an 80 m high zoned earth and rockfill dam located on the Goulburn River in North East Victoria. Owned by Goulburn Murray Water (GMW) it supplies water for irrigation to the northern part of the state. In the early to mid-2000s GMW undertook a major risk reduction program on the dam including:

- Raising the crest by 5.25 m;
- Constructing filters to the upper part of the embankment
- Strengthening of the spillway.

A requirement of the project was that the risk imposed to the downstream population during the works could not be increased over that imposed by the dam before the upgrade.

The works required as part of the embankment raising included removal of the upper 2 m of the embankment and the removal of the downstream shoulder of the dam for the next 5 m exposing the clay core. The total crest length of the embankment is approximately 1 km. Two construction methodologies were considered:-

1) Moving face, where the embankment was lowered and the rockfill removed in a panels of 100 to 300 m lengths, and thereby limiting the extent of the core exposed
2) Full face, where the full length of the crest was lowered and the rockfill removed, exposing the full length of the core for the upper 5 m.

When the downstream rockfill material is removed, there is no effective control mechanism for seepage through the core zone above and a significant likelihood of failure should piping be initiated through cracks in the core. Furthermore the removal of 2 m from the crest of the dam increases the vulnerability to overtopping failure.

The approach adopted to assess the construction options and to monitor the ongoing risk, was to develop a risk assessment that included:

- Actual reservoir level at the time of assessment;
- Forecast reservoir levels, based on GMW modelling;
- The extent to which the works were complete;
- The construction program for the outstanding works;
- The likelihood of intervention based on the Emergency Action Plan developed for the works.

The outcomes of the risk assessment demonstrated that the full face construction methodology could be adopted without imposing additional risk to the downstream (albeit greatly assisted by the low reservoir level due to the drought conditions). This was tested by with a sensitivity analysis of the construction program, assuming various delays in the work, which demonstrated that there was adequate contingency that the works could be delayed by 1 to 2 months. The model was developed to allow a real time assessment of the risk, by updating the reservoir level, the forecast reservoir levels and the construction progress, such that the risk at any time could be reviewed. The construction methodology included decision points where the risks were reviewed given the actual conditions and should the risks exceed the pre-construction levels the construction methodology was to be modified.

**Googong Dam Upgrade Project**

Googong Dam is a 66 m high earth and rockfill dam which is owned by Icon Water (formerly ACTEW Corporation) and assessed as having a Consequence Category of Extreme. The spillway was capable of passing the PMF. Remedial works were constructed in the spillway chute at Googong Dam to repair significant erosion which had occurred in the unlined section of the spillway as a result of previous spill events. The construction works were undertaken in a live spillway at a dam where there was negligible ability to draw down the reservoir. As part of the planning and design for the project, an assessment was made of the flood risk during construction to inform the selection of risk mitigation measures, such as provision of a temporary flood diversion.

The process used to assess the flood risk and potential impacts on the construction activities was based on simulation of the reservoir operation using 136 years of historical meteorological data. The available data included streamflow at the dam site, daily rainfall and evaporation. The historical data record was split into blocks representing the duration of construction and these were then run through a reservoir routing spreadsheet model to give the reservoir level over time. Based on this modelling and an adopted construction programme, it was possible to identify the number of spill events as well as the duration of each spill event for each block of the record. This data was then also converted into a risk cost. This was completed for each block of data and a distribution was developed for each parameter.

The process was repeated for a range of diversion strategies which allowed a comparison of the alternatives. It was found that constructing the works with no diversion in place presented an unacceptable risk of delays and associated costs and a temporary diversion structure was required.

The adopted diversion arrangement included a 1.5 m steel coffer dam bolted to the crest of the spillway over half of the width of the spillway. This allowed flow to pass down the half of the spillway left open should an event occur. Another key feature was that the coffer dam was designed to collapse once the reservoir level exceeded the crest of the coffer dam by greater than 0.5 m. This would then left the whole spillway available to pass larger floods. The intention was that the works would continue on the half of the spillway protected by the coffer dam and then the coffer dam would be relocated to the other half of the spillway.

It was acknowledged that an increase in the peak reservoir level for floods would result from partially blocking the spillway with the coffer dam. The effect of this was checked for the PMF which was the required design event for the dam and spillway. This routing allowed for modification of the rating curve to simulate failure of the diversion structure as the flood rose to greater than 0.5 m over the crest of the coffer dam. It was found that the inclusion of the coffer dam resulted in only a minor increase in the PMF peak reservoir level which was still below the crest level of the dam. It is noted that the risk to life was marginally increased
as a result of the incorporation of a coffer dam but the dam could still pass the required Acceptable Flood Capacity.

During construction of the works, the coffer dam was installed as planned. The reservoir level was low at this time and a decision was made as the works progressed that relocation of the coffer dam was not required. The area behind the coffer dam was however used as a laydown area in the knowledge that it was generally protected for smaller floods.

The completion of the works in the spillway was timely as the region experienced heavy rainfall in December 2010 and the spillway passed the flood of record for the site about 3 weeks after the final concrete pour.

Maroon Dam Upgrade Project

Maroon Dam, which is owned by South East Queensland Water (Seqwater), was constructed between 1969 and 1974. The dam is a multi-purpose reservoir, constructed to provide potable water supply, irrigation, flood mitigation and recreation. The embankment comprises a 47 m high earth and rockfill section with a central earth core, outer gravel drains and rockfill, (Fig 1). The foundation comprises rhyolite in the upper abutments with interlayered shale, siltstone and sandstone with weak clay seams, which required the construction of the upstream and downstream weighting berms for stability.

![Figure 1: Maroon Dam Embankment section](image)

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Core</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>Downstream fine filter</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>Upstream fine filter</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Coarse filter</td>
<td>11</td>
</tr>
<tr>
<td>5</td>
<td>Rockfill</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>Upstream rip rap</td>
<td>13</td>
</tr>
<tr>
<td>7</td>
<td>General fill</td>
<td></td>
</tr>
</tbody>
</table>

The dam has a High A consequence category for which the fallback Acceptable Flood Capacity (AFC) is the PMP-DF. The spillway comprises an unlined 137 m wide channel excavated through rock on the right bank with the spillway crest level at 217.51 m. The air space between the operational FSL of RL 207.14 m and the spillway level is used for flood attenuation using the outlet works and the peak recorded level was RL 210.0 m, which occurred during the 2011 floods. The PMP-DF of 3180 m³/s would have resulted in overtopping of the main embankment by 1.5 m and a staged upgrade design was carried out using a risk analysis approach. The Stage 1 comprised the following:

- Excavation of the upper level abutments, grouting drainage and filter construction for the reinstated embankment to reduce the piping risk where stress relief in the rock was evident;
- Additional weighting berm for stability; and
- Spillway channel excavation required to direct the spillway flows away from the embankment toe area

As part of the detailed study for the upgrade options, a probabilistic reservoir level frequency curve was developed for the annual peak flood events (generally occurring during the summer season) and the winter season from April to November, as shown on Figure 2
The risk assessment profile identified slope stability (29%) and piping through the foundation (68%) as the key risks for the dam with overtopping representing a small fraction (1.5%) of the overall risk of dam failure. During construction, however, the excavation of the abutments necessitated excavation of the core zone down to RL 216 m on the left abutment and RL 218 m on the right abutment, as shown on Figure 3.

It was assumed that when doing the excavation, the abutment piping probability would be reduced by a factor of 0.1 to account for the excavation of potential open jointed rock formation in the upper abutments but the slope instability probability was left unchanged. The resulting societal risks were evaluated with varying levels of coffer dam used to prevent overtopping of the abutments during the period from April to November. It was assessed that a coffer dam level at 217 m would be adequate for the construction works (Fig 4), where the societal risk was below the existing risk and was ALARP. The societal risk is also shown for
the Coffer dam at this level for the summer (Annual flood) period, which clearly showed that the risk was unacceptable with the 217 m crest level of the coffer dam.

**Figure 4  Risk Analysis results for Construction floods**

The use of the risk analysis showed that the flood risk was significantly reduced for works completed in the winter season and the use of a coffer dam constructed to 0.5 m below the dam spillway level at 217 m resulted in the societal risk being lower than the existing risk for the construction period.

**Summary of key points in Case Studies**

Based on the flood management approaches adopted during the aforementioned case studies, common themes appear to be occurring. These include:

- With the exception of the Googong Dam spillway upgrade, the proportionality between cost and risk reduction was not considered in the case studies.
- In the case of Googong spillway upgrade project, which was already capable of passing the PMF, the water control strategy during construction focused on an extensive review of historic storage data to develop appropriate cofferdam arrangements.
- In most cases, the flood control strategy included critical periods where exposure of the structure was greater, which was managed by the construction staging and controls.
- Construction program was a key focus for some risk strategies, with emphasis on:
  - Seasonality of flood events
  - The typical duration of exposure for higher risk activities.
  - The timeframe required to protect exposed works in the case of a flood.
- Although the construction program was closely scrutinised in these projects, none of the projects attempted to convert the probability of overtopping into a construction-duration based probability, such as suggested in the ICOLD guideline.
- At the time of the projects, there was no requirement to assess duration-weighted averages in terms of relaxing the risk profile (or probabilities of overtopping) for short durations in the project. Each case study had a different means to assess and manage the short durations of greater flood exposure.
- Earthquake loading had not been quantified in the assessment of risk during construction.

**Selecting the appropriate risk mitigation strategies**

There is no set formula to decide whether the risk mitigation strategies achieve ALARP. This paper presents a number of flood risk mitigation strategies which have been adopted for construction of dam safety.
upgrades. During the selection of a dam and spillway upgrade which is best suited to the site, the dam owners, designer and contractor should consider the potential dam safety risks which will be encountered during the construction works. This may drive the selection of an upgrade arrangement which is not at first inspection the most obvious. A series of questions which the owners and designers could consider are presented below:

- **Is it practical to construct an emergency spillway that is remote to the existing spillway(s), which result in no change to the risk position?**
- **What are the potential risk reductions available by temporary reservoir drawdown?**
  - Is drawdown of the reservoir practical from an operations standpoint?
  - Will the additional routing due to drawdown of the reservoir be significant?
  - What is the likelihood of flooding occurring shortly prior to the design flood?
- **What are the works that would need to be undertaken within the spillway structure?**
  - Will the construction works result in periods that the spillway structure is more vulnerable to floods? (e.g. removal of concrete lining)
  - Could flow in the spillway channel lead to a dam breach? (e.g. progressive erosion of the spillway channel leading to erosion of the dam structure)
  - Are there rapid actions which could be carried out prior to a flood to protect the spillway (e.g. rapid backfilling of exposed rock with concrete to improve erosion resistance)
- **How would the dam upgrade works be staged?**
  - Identify the key periods when heightened risks are unavoidable
  - Assess whether there are staging options which could either mitigate the likelihood of failure, or exposure period
  - Identify risk mitigation measures that can be undertaken during these key periods
  - Identify emergency planning in the event of flooding during these key periods.
- **What would the potential cofferdam arrangements look like?**
  - Is the cofferdam designed to fail at a critical flood level?
  - What is the reliability of the cofferdam failing at a design level
  - Could the failure of the cofferdam increase the risk of failure of the dam?
  - What are the incremental consequences that would be caused by a failure of the cofferdam?
- **Timing and staging of heightened risk works:**
  - Does the hydrology of the region provide seasonal variation for the magnitude of extreme floods?
  - What is the confidence in the planned construction period being achieved?
  - Is the heightened risk work easily reversed/protected in the event of forecast flooding

**Conclusions and Recommendations**

Based on a literature review of worldwide standards, there is not an agreed philosophy on the selection of available flood risks, however there is generally an implied agreement that in the case of existing dams, risks should not be exceeded during upgrade works. Australian guidelines appear to have the most developed discussion around risks associated with upgrades of existing dams.

The key conclusions identified in this paper are:

- It is inherent in the application of upgrade works that the risk will be increased during the construction activities without the use of similar strategies to those outlined in this paper.
- There is not a universally agreed philosophy on appropriate flood risk, but current guidelines generally adopt risk-based approaches. There is a general agreement that risk based analysis using the total life of the asset (eg ANCOLD (1986)) has now been superseded by an annual risk basis approach.
- ANCOLD guidelines on the Acceptable Flood Capacity for Dams have included significant changes on approach to construction flood risk in the last three revisions, with the draft ANCOLD guidelines introducing a duration-weight average.
- Case studies presented are typically focused on risk mitigation strategies such as staging of works, restricting construction program, early flood warning systems and emergency action plans (i.e. ALARP concepts).
• Seasonal flood risk can be an effective means to justify short-duration heightened-risk activities.
• A list of ALARP-based questions have been provided, particularly applicable to construction flood risks, to assist in developing risk mitigation strategies.
• Construction risk assessments typically considered flooding risks and do not consider the impact of earthquake risks.

The key recommendations resulting from this paper are:
• Apply seasonality of flood risk where appropriate.
• Consider increased likelihood of detection and repair where appropriate.
• ANCOLD should provide clear guidance on how to apply ALARP to construction works.
• Many of the risk mitigation strategies rely on staging, program and construction methodology constraints, and for this reason early consultation with contractors is recommended.
• Flood risk during upgrade construction works is rarely a purely commercial consideration, therefore flood risk mitigation should not be solely left to the contractor.
• The total life safety risk should be considered during upgrade construction works, not only flood risk. The application of “duration-weighted risk”, introduced in the draft AFC guidelines, requires careful consideration, to avoid contradiction with the assessment of ALARP and annual risk as described in ANCOLD (2003).

Acknowledgements
The authors wish to acknowledge Icon Water (formerly ACTEW Corporation), Goulburn-Murray Water, SAWater and Seqwater for giving permission to prepare and present the information within the paper.

References
ANCOLD 2016, Guidelines on Selection of Acceptable Flood Capacity for Dams – Draft issue, Australian National Committee on Large Dams, Australia
ANCOLD 2000, Guidelines on Selection of Acceptable Flood Capacity for Dams, Australian National Committee on Large Dams Incorporated, Australia
ANCOLD 2003, Guidelines on Risk Assessment, Australian National Committee on Large Dams Incorporated, Australia
DSC 2010, DSC3B Acceptable Flood Capacity for Dams. Dam Safety Committee of New South Wales, Paramatta, NSW
Institute of Civil Engineers 2015, Floods and Reservoir Safety - Fourth Edition, ICE Publishing, UK
International Commission on large Dams, 1986, River Control During Dam Construction Issue 48 of International Commission on Large Dm: Bulletin, ICOLD, France
NZSOLD 2015, New Zealand Dam Safety Guidelines, IPENZ, New Zealand