SPILLWAY GATE RELIABILITY AND HANDLING OF RISK FOR RADIAL AND DRUM GATES

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ABSTRACT
This paper discusses reliability issues of the fourteen 3.85m high by 7.89m wide radial gates at Glenmaggie Dam in Victoria and the twin 3.6m high by 16.5m wide drum gates at Little Nerang Dam in Queensland. The Glenmaggie dam radial gates are manually controlled using electrically driven (mains and diesel generator power supply) hoist motors with a petrol driven hydraulic pack for use in the event of complete electrical power supply failure. A detailed fault tree analysis was developed for the spillway gate reliability of the Glenmaggie Dam gates as part of the risk assessment for the dam, which was being completed at the time of publishing the paper. Each of the identified components of the spillway gates, including human error in operation was used to evaluate the probability of failure of a single gate or multiple gates for inclusion in the event tree to estimate the risk and assist the evaluation of the requirement for remedial works. The Little Nerang drum gates are fully automatic hydraulically operated gates with independent operating mechanics and a common override system in the event of automatic system failure. Drum gates are uncommon on dams and the system operation is discussed together with an assessment of the reliability and measures taken for handling operating risks during floods for the dam, which has some stability concerns.

Key Words: Spillway, Gates, Fault Tree, Failure, Sensitivity, Human Response

1. INTRODUCTION

1.1 Glenmaggie Dam

The Glenmaggie Dam is a concrete gravity dam with a maximum height of 37m. The dam is owned and operated by Southern Rural Water Authority of Victoria and is used primarily for irrigation water supply.

A Design Review of Glenmaggie Dam carried out in 1999 (SMEC 1999) indicated that Glenmaggie Dam:

- withstands the PMP design flood (Satisfies ANCOLD Criteria);
- cracks right through at the dam-foundation interface under the Maximum Design Earthquake (1:10,000 AEP) and so was judged as not passing the ANCOLD criteria for earthquake resistance.

Subsequently, Southern Rural Water (SRW) commissioned Gutteridge Haskins & Davey Pty Ltd (GHD) to carry out a staged review of Glenmaggie Dam, which included the following:

Part 1 A Seismic Capacity Evaluation using time history with updated seismic ground motion data for the Seismology Research Centre. This part of the study found that despite sustaining damage, the dam withstood the MDE.

Part 2 A limited scope risk assessment to review the overall risk profile of the dam under earthquake and flood loading to confirm the level of risk.

A structural analysis was carried out for flood and seismic loading of the spillway gates for inclusion in the Part 2 risk analysis and fault trees were developed for the spillway gate operation to determine the system reliability as input to the risk analysis.

The spillway operation and maintenance procedures and test intervals were used to derive failure probabilities for components and the response procedures to flood events were reviewed and incorporated in the fault trees.

1.2 Little Nerang Dam

The Little Nerang Dam is a concrete gravity
dam of 44 m maximum height located in the Gold Coast area of Queensland. The dam is 16 kms upstream of Hinze Dam and provides the Gold Coast City Council with the most economical means of supplying additional water using the gravity supply to Hinze Dam and/or the Mudgereeba Water Purification Plant.

A number of dam safety and stability studies have been completed for the dam since 1988 resulting in the following:

- Concerns over potential instability of the dam during large flood events if the spillway gates failed to operate and consequent lowering of the FSL to RL 168.0m by locking down of the two spillway gates to ensure a greater measure of dam safety;
- Improvement of the drainage system and installation of new foundation uplift monitoring piezometers;
- Review of piezometer response to changes in water level using the data obtained from the temporary Y2K raising of the gates;
- Simplified risk analysis of the combined gate failure probability and critical stability reservoir level to evaluate the required AFC.
- Preparation of detailed operation and maintenance manual and emergency action plan with particular emphasis on the operation during floods.

This paper presents a brief description of each dam followed by the analysis methods and fault tree results for the gates at Glenmaggie and the evaluation of the method of dealing risks of gate failure at Little Nerang Dam.

2. DESCRIPTION OF DAMS AND GATE OPERATING SYSTEMS

2.1 Glenmaggie Dam

Lake Glenmaggie, is located on the Macalister River some 175 km east of Melbourne and supplies the Macalister Irrigation District.

The dam is a concrete gravity structure of 293m crest length with a slight curvature in plan (414.5m radius). An inspection gallery has been provided 1.8m from the upstream toe of the section. This facility allows monitoring of seepage and drainage installations and also accommodates piezometer installations.

The dam has a central gated spillway section with 14 radial gates each 3.85m high and 7.89m wide operated by an electrically driven mechanical hoist located on the operating deck above the spillway (Photo 1). The history of the dam construction is as follows.

1919-27 Constructed – FSL Capacity 131,000 ML
1957 Addition of Spillway Gates - FSL Capacity 190,000 ML
1957-58 Foundation grouting and drainage installation
1977 New piezometers and additional foundation drains installed
1989 70 x 8200kN post tensioned anchors installed ($7M)

The dam has left (north) and right (south) bank irrigation outlets along with a 3.8 MW power station to utilise releases from the southern outlet.

Gates

Each gate consists of a curved skin plate with a structural steel bracing framework and two radial arm assemblies transmitting the hydrostatic water load to trunnion pins in the intermediate piers and side walls (Photo 2). Rollers on each side control lateral movement.

When all gates are fully opened they provide a flood discharge capacity of 3390 m$^3$/s with the reservoir level at the crest of the non-overflow
abutment sections of 79.55m AHD. The Probable Maximum Flood with an inflow of 11,700m$^3$/s results in a reservoir level of 84.8m AHD, assuming all gates are fully open. At this level, the structure will be completely overtopped but stability analyses have shown that it should withstand this loading.

**Hoist and Controls**
Each radial gate has its own electric motor centrally located above the gate, which is coupled to a worm reduction gear box and drive shaft. Further spur gear reductions drive twin rope drums from which the lifting ropes are attached to the gates (Photo 3). Thruster brakes are used to maintain the gate position for each gate operation.

The gates are operated from the structure using the relevant switch board. Should the power supplies fail, an emergency petrol driven hydraulic pump can be connected through a dog clutch to the drive shaft to open each gate (Photo 4).

**Power Supply**
The electric power can be supplied from the normal incoming grid supply or a 20kVA standby diesel generator. Only two of the gates can be operated at any one time using the diesel generator supply.

The standby generator is located in a building on the right bank near the dam crest level and a single power supply cable is taken from the diesel generator switchboard to the main switchboard, which results in a common cause failure mode for the power supply at Glenmaggie Dam (ie a fault at the main switchboard, diesel switchboard or power supply cable will disable both AC power supplies).

**O & M Procedures and Response to Inflows**
Southern Rural Water has a program of regular inspection and maintenance of all gates and their hoist equipment. This includes oiling, greasing and testing of components at prescribed intervals. Qualified electrical personnel also carry out 3 monthly inspections and testing. Any faulty mechanical or electrical components are immediately replaced or appropriately serviced. The gates are exercised monthly (if not used for flood operation). Ageing components such as limit switches are replaced before they become a problem. The gates are repainted or patch painted as is determined necessary from regular inspections.
During a flood, the gates are operated via a set procedure. Inflows and rainfall can be monitored remotely and inflows are computed before gate movement is determined. The frequency of this depends on the magnitude of the storm. In general, the gates are opened in 0.5m increments and although only one gate is operated at a time, several gates may be partially open at once. The central 8 gates are opened prior to the outer 6 gates to minimise downstream erosion.

2.2 Little Nerang Dam

The Little Nerang Dam has a capacity of 8400 ML and was constructed between 1954 to 1961. The dam is a concrete gravity structure of 175m crest length with a central ogee gated spillway section having twin 3.6m high by 16.5m wide rotating drum gates for flood control. The outlet works are located in the right bank block adjacent to the spillway and comprise a multilevel dry tower offtake leading to a single outlet conduit. A drainage gallery has been provided at 3.1m from the upstream face with drain holes at 6m centres extending into the foundation and concrete section above.

Gates

The two gates are of identical form and size, and consist of watertight steel drums, which float on the water in the gate chambers rotating about a hinge on their upstream edge, as shown on Figure 1. The gates, which lower to discharge, are ideal for passing floating debris over the spillway without delay or blockage in times of flood. The position of the gates is determined by water pressure in the drum chambers. If the automatic control gear is functioning, the gates will be controlled entirely by the height of water in the dam.

With the exception of the emergency control hydraulic system, the gates are not interconnected and work entirely independently. The interconnection of the hydraulics provides an added level of operating redundancy to each gate and the interconnecting valves are kept open at all times.

Seals are provided on the ends of the upstream and downstream skin faces of each gate to prevent water leaking between the gate and its adjacent end abutments or piers. Seals are also provided along the downstream gate seats, and bear against the downstream drum skin of each gate to prevent water in the gate chambers from escaping.

Figure 1  Little Nerang Section of Drum Gate

Controls

The gate can be operated using three methods of control:

- Automatic Control
- Manual Control
- Emergency Control

The controls, which operate each gate under normal conditions and for manual control, are located in Control Rooms formed within the concrete structure immediately adjacent to the outer ends of each gate. The controls, which operate the gates under emergency conditions, are located in a Control Room formed within the concrete structure of the centre pier between the two gates.

Access to all three Control Rooms is gained via vertical shafts and a horizontal gallery formed within the concrete structure below the level of the bottom of the drum chambers.

Automatic Control (Figure 2)

As long as the dam water level is up to the top of the spillway ogee crest (RL 168.02m) or higher, the gates will float at their maximum height with top edges at RL 171.6m.
Figure 2  Automatic Control when Water Level is Above RL171.6m

Photo 5 Little Nerang Dam - Larner Johnson
If the water level continues to rise, it will flow over the top of the gates and the floats in the float chambers will begin to rise.

Through the associated rigging, shown schematically on Figure 2, the floats will begin to open the Larner-Johnson discharge valves (Figure 3 & Photo 5). By the time the water level has reached 180mm over the top of the gates (RL 171.78m) the Larner-Johnson valves should be fully open and sufficient water will be discharged from the drum chambers to cause the gates to move downward to discharge more water over their top edges.

Figure 3  Larner-Johnson Flow-valve

The downward movement of the gates will tend to lower the dam level by increasing the discharge over their top edges, at the same time the movement will be reflected through the control rigging to slightly close the Larner-Johnson valves and reduce the rate of discharge of water from the drum chambers. If as a result of these combined effects, the dam water level is reduced to RL 171.60m or lower, the Larner-Johnson valves will re-close fully and the gates will resume their position at maximum height.

Manual Control

Manual lowering of one or both gates is achieved by closing the interconnecting valve for the emergency system and the valve on the 375mm inlet line to the drum chamber on the gate to be lowered and then opening the Larner-Johnson valve and discharging the water from the drum chamber. The gate position can be held at any position by closing the Larner Johnson valve, however, this cannot be relied upon to keep a gate indefinitely in a fixed position because leakage into and out of the drum chamber will influence the gate level over a long period.

Emergency Control (Figure 4)

If the dam level continues to rise to the emergency control intake level at RL 172.21m, water will flow into this inlet and into the emergency control bucket. The bucket contains a drain hole in the bottom, allowing water to flow into the bucket well and then drain away to the downstream face of the dam. When the water level reaches 172.25m, the inflow will exceed the outflow and the bucket eventually fills. When this occurs, the weight of the bucket and its contents will overcome the counterweight and open the pilot valve. This will discharge the water from above the 457mm float valve (Figure 5) and allow the float valve to open.

Figure 4  Emergency Control When the Water Level is above RL 172.21m
The valve on opening drains water from the drum gate chamber, which reduces the uplift pressure on the drum gate lowering the gate at a faster rate than normal by:

- Acting in addition to normal operation; and
- Creation of a powerful hydraulic suction as the water falls down through a long pipe exiting just under the lip of the ‘ski-jump’ at the bottom of the spillway. This suction evacuates the water from the gate chamber much quicker than it can enter, thus lowering the gate regardless of normal operation.

When this additional discharge causes the dam level to recede below RL 172.21m water can no longer enter the emergency control intake, hence the bucket will empty and the counterweight will close the pilot valve. This in turn will cause the float valve to close and cut off the discharge of the drum chamber water, following which the gates will then return to their highest level.

### 3. SPILLWAY GATE FAULT TREE ANALYSIS

The spillway gate reliability for the Glenmaggie Dam gates was evaluated using fault trees required to capture the various paths to failure of a single gate or multiple gates.

A fault tree is defined as “a systems engineering method for representing the logical combinations of various system states and possible causes which can contribute to a specified event (called the top event)”.

#### Methodology

For the purpose of the Glenmaggie Dam gate study, the “top event” for the fault trees was defined as failure of a single gate or multiple gates when considering failures of components common to all gates e.g. AC Power supply.

The fault trees were structured to examine both the independent component failures and the failures of components common to all gates. The independence of gate operation for multiple gates will provide increasing redundancy, which greatly reduces the estimated probability of a failure and subsequent loss of discharge capacity. For common cause failures, a larger number of gates will generally offer a limited advantage.

In order to comply with the basic requirements of the fault tree process, as defined above, the fault trees were developed using the following steps:

(a) Definition of the spillway gate system into components and sub-components as shown on Table 1, abstracted for the electrical system;

(b) Site visit to examine and confirm the definition of the system and discuss the operation and maintenance procedures with the site personnel as well as determine the human response to gate operation failure;

(c) Perform a Failure Modes and Effects Analysis (FMEA) for the components of the gate system as defined after steps (a) and (b);
Table 1 Abstract of Component Definition for Glenmaggie Gate Electrical System

(d) Development of the single gate fault tree using immediate cause concept for the electrical and mechanical components, and structural failure of the gates or supports (Figure 6).

(e) Each of these areas was then broken down systematically into basic events, which could either be a single component e.g. wire rope failure or an event for which failure rate data is available e.g. diesel generator. Figures 7 and 8 show part of the breakdown for motive power failure.

A critical issue in the fault tree development is the inclusion of common cause failures for components where two or more systems are dependent on a common component, failure of which could lead to failure of both systems e.g. a common power supply cable for the mains and diesel generator to the dam (see Figure 7).

![Figure 6 Fault Tree Basis for Top Event](image1)

![Figure 7 Fault Tree Details Abstract 1](image2)

![Figure 8 Fault Tree Details Abstract 2](image3)
(f) Evaluation of available failure rate and human error data and use of established mathematical methods of analysis to estimate the failure likelihood of equipment on the basis of the type of the event in the Fault Tree and the operating experience at Glenmaggie dam for the following:

- Dormant components e.g. hydraulic hose;
- Continuous running components;
- Running failure probability of a dormant component, given a successful start;
- Probability of occurrence of an event;
- Combined Dormant Failure and Running Failure.

Human error was included in the following areas of the gate operation for which typical estimates of human error are shown on the table below.

- Individual controls at the gates;
- Back-up diesel generator switching;
- Operation of the hydraulic backup system.

<table>
<thead>
<tr>
<th>Human Error Factor</th>
<th>Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual Operate Valve/switch, left in wrong position Maintenance. Shutdown, or calibration</td>
<td>0.085</td>
</tr>
<tr>
<td></td>
<td>Routine operation</td>
</tr>
<tr>
<td></td>
<td>Routine Testing</td>
</tr>
<tr>
<td>Normal Operation (Includes operation of hydraulic backup)</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 2 Glenmaggie Dam Human Error Probability Estimates (Draft Results)

(g) Quantification of the fault trees;

(h) The analysis of multiple gate failures was achieved by developing the fault tree with gates using common cause components to obtain the probability of 1, 2 3 gates failing etc, as shown on Figure 9.

Analysis Results
The results from the fault tree analysis included:

- Overall likelihood of system failure;
- Cut sets for failure combinations of events, which is the minimal number of events that could lead to system failure. These showed that there are several sets with only two events leading to system failure;
- Fault tree gate failure probabilities;
- Importance rating for events.

The results obtained for single and multiple gate failure, which were provisional at the time of publication, are shown on Tables 3 and 4.

![Figure 9 Fault Tree for Multiple Gates](image)

<table>
<thead>
<tr>
<th>No of Gates Failing</th>
<th>Probability of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.125</td>
</tr>
<tr>
<td>2</td>
<td>0.037</td>
</tr>
<tr>
<td>3</td>
<td>0.0193</td>
</tr>
<tr>
<td>4</td>
<td>0.00686</td>
</tr>
<tr>
<td>5</td>
<td>0.00681</td>
</tr>
<tr>
<td>6 or more</td>
<td>0.00681</td>
</tr>
</tbody>
</table>

Table 3 Abstract of Combined Failure Probabilities for Glenmaggie Dam Gates (Draft Results)

<table>
<thead>
<tr>
<th>6 or More Gates fail</th>
<th>1 to 6 Gates Fail</th>
<th>No Gates Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00681</td>
<td>0.20178</td>
<td>0.79141</td>
</tr>
</tbody>
</table>

Table 4 Glenmaggie Dam Gate Failure Probabilities (Draft Results)
Discussion of Fault Tree Analysis Results

A breakdown of the main system contributions to the overall failure likelihood is shown in Table 5, which indicates that the electrical and hydraulic motive power and the mechanical hoisting equipment are the major contributors to failure of a gate to operate.

<table>
<thead>
<tr>
<th>System and Subsystem</th>
<th>P (Failure)</th>
<th>% Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Motive Power</td>
<td>4.31E-02</td>
<td>34%</td>
</tr>
<tr>
<td>Hoisting Mechanism</td>
<td>7.12E-02</td>
<td>57%</td>
</tr>
<tr>
<td>Support Structures</td>
<td>1.10E-02</td>
<td>9%</td>
</tr>
<tr>
<td>Gate Structure</td>
<td>4.99E-03</td>
<td>4%</td>
</tr>
</tbody>
</table>

Table 5 Glenmaggie Dam Risk Analysis
Analysis of Sub System Failures for Spillway Gates (Draft Results)

Hydrological Risk Analysis

The spillway gate reliability results were used in a risk analysis, which included seismic and flood events. The following failure pathways were developed for the flood events based on the results of the structural and hydrological analysis and a FMECA for the dam system and subsystems as follows:

- Flood event;
- Debris present;
- Spillway blockage due to debris;
- Spillway gates fail to operate;
- Spillway gates structural failure;
- Resulting reservoir level

- Non-overflow crest section failure mode:-
  - Overtopping
    - Downstream erosion - section instability
      ṹ breach or no breach
    - No downstream erosion - section instability
      ṹ breach or no breach
  - No Overtopping
    ṹ Section instability, breach or no breach

The risk analysis included an evaluation of the erosion on the abutments due to overtopping as well as @Risk simulations using friction and cohesion distributions to evaluate the stability of the concrete spillway and non overflow sections. The results of the risk analysis are summarised in Table 6 for one Flood Range (F2) and shown on Figures 10 and 11.

Figure 10 Percentage Failure Contributions for Flood Ranges and Failure Pathways

It can be seen that cases involving spillway gate failure make a 10 to 20% contribution to the probability of failure due to hydrological events.

Figure 11 Glenmaggie Dam Societal Risk
The results of the risk analysis show that spillway gate failure has a small contribution to the overall risk of dam failure which is below the ANCOLD tolerable limit for societal risk. The results of the study have helped to identify the critical components of the system and will also assist in any future decisions regarding remedial works for the spillway gates. At present Southern Rural Water has no plans for undertaking remedial works to the spillway gate system, apart from routine upgrading of equipment to current standards.

The study also showed the importance of the gate operator in the correct functioning of any spillway gate system. Redundancy in gate operating systems was also shown to be important.

### 4. LITTLE NERANG DAM SPILLWAY DRUM GATE RISK ANALYSIS

The methodology used to evaluate the risk to life for the drum gate operation and comparison with the ANCOLD acceptance criteria was carried out using the following tasks:

- Evaluation of uplift data for foundation piezometers and Critical Stability Levels for estimation of failure probabilities;
- Development of spillway gate discharge rating data;
- Floodrouting of floods from 1 in 2 AEP to the PMF and estimation of Critical Stability Flood exceedence probabilities;
- Estimation of Population at Risk and Loss of Life;
- Evaluation of Hazard Rating and Deterministic Fall Back Position Acceptable Flood Capacity;
- Risk to Life Estimation, including gate failure estimation;
- Comparison of Risk with ANCOLD Criteria

#### Uplift Data

Analysis of the available uplift data for the foundation piezometers has shown that the uplift is generally at or below the 33% design line for all blocks except block 11 adjacent to the spillway for which the uplift follows a modified design line of 44% residual head at the drains. This revised uplift distribution was used for analysis of block 11 at the foundation while the 33% design line was adopted for the remaining non–overflow and spillway blocks at the foundation and a 25% residual head was used for the drains within the concrete section.

The data indicates that there is no trend of increasing foundation pressures evident in the data base, however, a 50% residual uplift head...
was also used for analysis of Block 11 for a sensitivity analysis.

The resulting analyses indicated that Block 11 was the critical block. Reservoir levels at which the shear friction factor was equal to 1.0 were determined, as shown on Table 7, for various residual drain uplift factors.

<table>
<thead>
<tr>
<th>Description</th>
<th>Critical Level (m AHD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundation (RL 136.0m)</td>
<td></td>
</tr>
<tr>
<td>33% uplift</td>
<td>174.25</td>
</tr>
<tr>
<td>44% uplift</td>
<td>173.75</td>
</tr>
<tr>
<td>50% uplift</td>
<td>173.45</td>
</tr>
<tr>
<td>Dam Top - Change of Slope RL 167.2m</td>
<td></td>
</tr>
<tr>
<td>25% uplift</td>
<td>173.81</td>
</tr>
</tbody>
</table>

Table 7  Little Nerang Dam Critical Stability Levels for Block 11

Spillway Rating Curves and Floodrouting

Spillway rating curves were developed for gate operating scenarios for which flood routing was completed using floods ranging from a 1 in 2 AEP event to the PMF as follows.

- Both gates locked down (Case I)
- Both gates operating normally (Case II)
- Both gates suffer malfunction and remain in up position (Case III)
- One gate operating normally and one gate suffering malfunction (Case IV)

The reservoir level flood exceedence data is shown on Figure 12 together with the critical stability levels.

Population at Risk (PAR) and Loss of Life (LOL) Estimation

The population at risk is located within 3.5km from the dam and comprises 6 houses and a youth rehabilitation centre, which ceased to operate and was purchased by the Gold Coast City Council to reduce the PAR as a risk reduction measure.

The estimated total and incremental PAR for the gate operating Cases are shown on Table 8, together with an estimate of the total PAR that could be present after a warning is given. It was assessed that the Total PAR would be appropriate for the Sunny Day failure events i.e. seismic failure.

<table>
<thead>
<tr>
<th>Gate Operation Case</th>
<th>Total Breach PAR</th>
<th>Total Breach PAR after Warning</th>
<th>Incremental Breach to No Breach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to purchase of Rehabilitation Centre</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 &amp; II</td>
<td>56</td>
<td>22</td>
<td>46</td>
</tr>
<tr>
<td>III &amp; IV</td>
<td>56</td>
<td>22</td>
<td>46</td>
</tr>
<tr>
<td>After purchase of Rehabilitation Centre</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 &amp; II</td>
<td>18</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>III &amp; IV</td>
<td>18</td>
<td>9</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 8  Little Nerang Dam Population at Risk for Gate Operation Cases

Loss of life estimates were made using the USBR (Graham 1999) methodology assuming a high severity of flooding. The appropriate loss of life factor is 0.75 of the PAR for which the LOL estimates were made, as shown on Table 9. No loss of life was assumed for flood events with no dam failure.

<table>
<thead>
<tr>
<th>Gate Operation Case</th>
<th>Total LOL</th>
<th>Total LOL after Warning</th>
<th>Incremental Breach to No Breach LOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to purchase of Rehabilitation Centre</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 &amp; II</td>
<td>44</td>
<td>17</td>
<td>34</td>
</tr>
<tr>
<td>III &amp; IV</td>
<td>44</td>
<td>17</td>
<td>34</td>
</tr>
<tr>
<td>After purchase of Rehabilitation Centre</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 &amp; II</td>
<td>14</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>III &amp; IV</td>
<td>14</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 9  Little Nerang Dam Potential Loss of Life for Dam Failure with Gate Operation Cases
Hazard Rating and Fallback Position Flood

Based on the incremental PAR of 6 after removal of the PAR from the rehabilitation centre and the medium severity of damage and loss assessed for Little Nerang Dam, the Hazard Category of the dam is Significant. As there is a potential for loss of life, the significant rating is required to be increased to a High C (ANCOLD 2000b).

The hazard rating for the PAR of 46 would be High C.

With the hazard rating of Significant and the PAR of 6, the required fallback flood capacity AEP would be about 1 in 6000 with no potential for loss of life. As the possible loss of life is recognised for the High C rating, the required AEP for the Acceptable Flood Capacity (AFC) is 1 in 10,000.

Using the incremental PAR of 46 prior to removal of the rehabilitation centre, the AEP for the AFC would be about 1 in 50,000.

Spillway Gate Reliability

During the evaluation of the spillway gate reliability in 1995, a number of dam owners worldwide were contacted and responses received from the following dam owners with drum gates: USBR, Greater Vancouver Regional District (GVRD); Scottish Hydro Electric (SHE); Ministry of Public Works (Spain) (MPWS); Sydney Water Board (SWB). Two experts were also approached for data: Dr Nelson Pinto (Brazil) (NP) and Prof J. Lewin (UK) (JL).

The responses and comments are shown on Table 10 for the events, which resulted in gates failing to lower due to mechanical causes.

The USBR experience has been that with aggressive maintenance including replacement of seals and hoses, the drum gates are extremely reliable. The automatic float systems have been replaced in a number of their dams by manual operation or electrical sensor operation.

Based on the responses and comments on Table 10, the probability of failure for the Little Nerang Drum gates was taken to be 1 in 50.

The estimated AEP of the flood for each of the spillway gate operating scenarios and combined gate and flood exceedence frequency is shown on Table 11, which indicates that the worst case scenario is for failure of both gates with a combined AEP of 1 in 17,500.

<table>
<thead>
<tr>
<th>Contact</th>
<th>No of Dams</th>
<th>Age yrs</th>
<th>Data and Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>USBR</td>
<td>9</td>
<td>60 to 70</td>
<td>Extremely reliable 1 malfunction: Worn seat seal</td>
</tr>
<tr>
<td>GVRD</td>
<td>1</td>
<td>40</td>
<td>1 malfunction: Worn control valve</td>
</tr>
<tr>
<td>SHE</td>
<td>2</td>
<td>44</td>
<td>3 malfunctions : Automatic valves Analysis 1:67 per gate</td>
</tr>
<tr>
<td>MPWS</td>
<td>1</td>
<td>35</td>
<td>None</td>
</tr>
<tr>
<td>SWB</td>
<td>1</td>
<td>35</td>
<td>1 malfunction: Worn ‘O’ ring on control valve</td>
</tr>
<tr>
<td>NP</td>
<td>-</td>
<td></td>
<td>1 in 100 operations</td>
</tr>
<tr>
<td>JL</td>
<td>-</td>
<td></td>
<td>1 in 500 operations</td>
</tr>
</tbody>
</table>

Table 10 Drum Gate Malfunction Data

It is clear from Table 11 that the dam was not able to pass the fallback position flood prior to the removal of the PAR from the rehabilitation centre but currently meets the ANCOLD fallback position AFC.

<table>
<thead>
<tr>
<th>Gate Case</th>
<th>AEP of Failure Flood (1 in X)</th>
<th>Gate Failure Probability</th>
<th>Gate &amp; Flood Freq. (1 in X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>250,000</td>
<td>1</td>
<td>250,000</td>
</tr>
<tr>
<td>II</td>
<td>250,000</td>
<td>1</td>
<td>250,000</td>
</tr>
<tr>
<td>III</td>
<td>7</td>
<td>1/2500</td>
<td>17,500</td>
</tr>
<tr>
<td>IV</td>
<td>3000</td>
<td>1/50</td>
<td>150,000</td>
</tr>
</tbody>
</table>

Table 11 Little Nerang Dam Block 11 Flood and Dam Failure Frequency Data (Critical Level with 44% Uplift)

Given the AEP of 1 in 7 for the flood reaching the critical stability level and the required AEP for the spillway design flood of 1 in 10,000 implies that the spillway gate failure for each gate could be as low as (7*1/10,000)^0.5 or 2.6E-2 (1 in 38) per gate before there is a concern over the gate reliability. This failure rate is clearly in the order of the historical failure rate shown on Table 10. Notwithstanding this, a further level of redundancy in the spillway gate operation is
being evaluated using a manually operated bypass for the Larner-Johnson valve. Furthermore, the maintenance work performed for the gates at Little Nerang Dam and the use of the Operation and Maintenance Manual and an Emergency Action Plan for all flood conditions are considered appropriate for ensuring that the assumed gate reliability is achieved.

Risk to Life and Comparison with ANCOLD Criteria

The data for gate failure probabilities, dam failure frequencies and potential loss of life was used to develop a simplified event tree for analysis of the flood failure events with the following scenarios:

- Both gates operating;
- One gate failure to operate;
- Both gates failure to operate.

The probability of dam failure at the critical level was assumed to be 0.5 and the analyses were performed for the total LOL with and without warning and the incremental LOL for the 44% and 50% uplift critical failure levels for Block 11.

Structural analysis of the dam for seismic loading has shown that the dam meets the current ANCOLD Criteria and the annual failure frequency was assumed to be 1E-5 in the risk analysis.

The results of the analysis using the 44% residual uplift critical level and the total LOL after warning the PAR are shown on Table 12.

Using the total annual failure frequency (F) shown in Table 12 and an exposure factor of 0.5 for the individuals in the downstream flood affected area, the Individual Risk was calculated to be 2.2E-5. A sensitivity analysis performed using the data for the 50% residual uplift gave an individual risk of 5E-5. These indicate that the individual risk is below the ANCOLD tolerable limit of 1E-4 for an existing dam (ANCOLD 1998).

Societal risk FN plots were developed using the data shown on Table 12 for each uplift critical level and LOL estimates for comparison against the ANCOLD Criteria, as shown on Figure 13.

<table>
<thead>
<tr>
<th>Description</th>
<th>Failure Freq.</th>
<th>LOL</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic Failure</td>
<td>1.0E-05</td>
<td>14</td>
<td>1.0E-05</td>
</tr>
<tr>
<td>Both Gates Fail</td>
<td>2.9E-05</td>
<td>7</td>
<td>3.9E-05</td>
</tr>
<tr>
<td>1 Gate Fails</td>
<td>3.3E-06</td>
<td>7</td>
<td>4.2E-05</td>
</tr>
<tr>
<td>Both Gates Operate</td>
<td>2.0E-06</td>
<td>5</td>
<td>4.4E-05</td>
</tr>
</tbody>
</table>

Table 12 Little Nerang Dam Risk Analysis Results with 44% Residual Uplift Critical Level and Total LOL after Warning

Figure 13 shows that the societal risk was above the tolerable limit for the conditions prior to removal of the PAR from the rehabilitation centre and for the condition where the uplift is allowed to increase to the 50% residual value in the Block 11 drains.

Clearly both of these conditions were not acceptable and provided strong justification for (a) removing the PAR from the flood affected zone and (b) ensuring that the monitoring of the uplift is maintained and necessary action taken to improve the drainage efficiency should the monitoring indicate an increase in uplift towards the 50% residual level.

Operation, Maintenance and Monitoring

Gold Coast Water have also taken steps to institute an intrusive operation and maintenance programme and to develop a flood monitoring procedure as follows.
Inspection and Maintenance Programme

- **Six Monthly**
  Routine inspection of control and float chambers, checking for operation, sludge removal, opening of outlets and inlets, counterweight operation, valve operation including Larner-Johnson valve and butterfly valves.

- **Annually**
  Lubrication and cleaning of all valve spindles, screws pulley pins, turnbuckles and wire cables. General maintenance of doors, access ladders etc.

- **2 Yearly**
  Inspections of the gate structures, hinges, seals, dogging devices and drum chambers.

**Flood Monitoring Procedure**

A simplified flood monitoring procedure has been developed based on the recorded depths of rainfall and dam water level. The focus of the monitoring is to provide a user friendly system for the dam operators with measurements taken from the on site rain and water level gauges. The procedure was developed using the data obtained from routing of the floods with AEPs from 1 in 2 to the 1 in 50,000 AEP events with the various gate operating scenarios and start reservoir levels to develop a series of graphs similar to that shown on Figure 14.

The flood monitoring procedure involves the following steps:

- Recording of reservoir level, gate status, rainfall and time for all storm events;
- Calculation of incremental and cumulative rainfall intensity;
- Estimation of AEP for the recorded rainfall;
- Comparison of the plotted water level versus time after start of the storm event applicable to the estimated AEP with the calculated data similar to Figure 14.

This comparison is used to determine (a) the likelihood of reaching the flood warning level and (b) likelihood of reaching the critical stability level to be used for warning the downstream PAR.

**Figure 14** Little Nerang Dam: 1 in 5 AEP Event; Case III Gate Operation; Water Level versus Time

5. **CONCLUSIONS**

The application of a detailed fault tree analysis for the radial gated Glenmaggie Dam spillway has been used in a risk assessment to assist in the evaluation of the requirements for remedial works and provide guidance for operation of the gated systems.

The drum gate operating system of Little Nerang Dam has been evaluated in some detail to provide the required operation and maintenance procedures necessary to ensure the risk is kept within the acceptable tolerable limits. The historical failure rate for these gates has been used in a simplified risk analysis performed for the gates to determine the societal risk. As a result of the risk analyses performed over the last few years, measures were taken by the dam owner to reduce the population at risk by purchasing downstream property as a means of reducing the risk to life.

**ACKNOWLEDGEMENTS**

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**REFERENCES**

2. ANCOLD 2000a, Guidelines on Selection of Acceptable Flood Capacity for Dams
3. ANCOLD 2000b, Guidelines on Assessment of the Consequences of Dam Failure