

COMMISSION INTERNATIONALE
DES GRANDS BARRAGES

VINGT CINQUIÈME CONGRÈS
DES GRANDS BARRAGES
STAVANGER, JUIN, 2015

USE OF RISK ANALYSIS FOR FLOOD UPGRADE DESIGN AND CONSTRUCTION RISK*

Malcolm BARKER

Principal Engineer Dams, GHD Brisbane

Iain LONIE

Senior Engineer Dams, GHD Brisbane

AUSTRALIA

1. INTRODUCTION

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 State Dam Safety Regulator has introduced guidelines for evaluating the required Acceptable Flood Capacity (AFC) for a dam, which is the capacity required to safely discharge a design flood of a severity based on the consequence of dam failure [1]. Dams which cannot safely discharge the AFC require upgrading and the guideline has three methods for assessing the AFC, including the use of risk assessment. The risk assessment procedure incorporates the *as low as reasonably practicable* principle (ALARP) and considers the safety of the dam for all potential failure modes including hydrological loading. The method is based on the ANCOLD Risk Assessment Guidelines [2].

Where the risk profile is above the limit of Tolerability (Fig 8), risk reduction options are required to bring the risk profile down to the limit of tolerability. The risk assessment procedure is then used to assess compliance with the ALARP principle by formulating additional risk reduction options that would bring the risk

* *Utilisation de l'analyse des risques pour la conception de la prévention du risque de crue et du risque de construction*

profile further below the limit of tolerability. This includes undertaking a cost-benefit analysis for the upgrade options required to reduce the risk profile below the limits of tolerability.

As an alternative to the cost-benefit analysis, an equivalent percentage AFC has been developed using the risk analysis for the upgrade design [3]. The percentage AFC using risk analysis is the percentage reduction in the flood frequency data over the full range of floods that is required to lower the risk to the tolerable line or achieve the percentage AFC compliance levels required by the State Dam Safety Regulator. This approach was also used for the evaluation of the coffer dam level required to reduce the risk to an acceptable level for the construction period and included consideration of flood seasonality.

2. DAM DESCRIPTION

Maroon Dam has a maximum height of 47 m and a crest length of approximately 457 m. A plan of the existing dam and the outline of the proposed Stage 1 upgrade is shown on Figure 1.

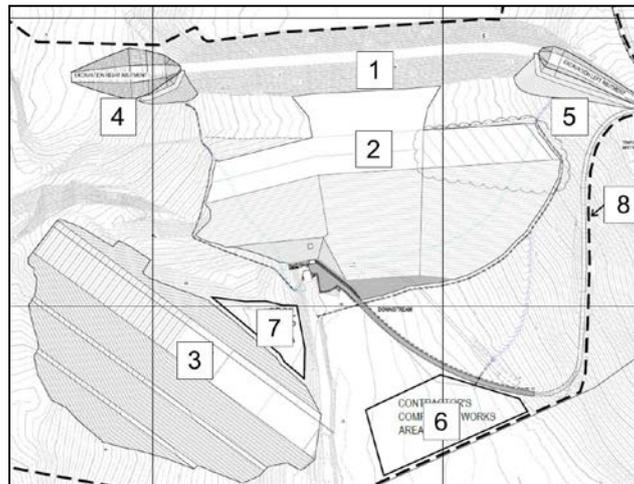


Fig. 1

Maroon Dam plan of existing dam and outline of proposed Stage 1 upgrade
Plan du barrage Maroon actuel et des améliorations proposées en phase 1

1	Embankment	1	<i>digue</i>
2	Raised Berm	2	<i>Surélévation de la berme</i>
3	New Spillway Channel	3	<i>nouveau chenal du déversoir</i>
4	Right bank coffer dam and grouting	4	<i>Batardeau sur la rive droite</i>
5	Left bank coffer dam and grouting	5	<i>Batardeau sur la rive gauche</i>
6	Laydown Area	6	<i>Aire de dépôt</i>
7	Spoil Dump	7	<i>Depot de déblais</i>
8	Site Boundary	8	<i>Limite du site</i>

2.1. DAM SAFETY ISSUES

The following dam safety issues were identified and evaluated in the risk analysis:

- Piping through the abutments above the levels where grouting and the pressure relief system had been installed during the original construction.
- Piping through the embankment resulting from filter Zone IIA having fines well in excess of 5%, thereby allowing the filter to hold a crack with reduced effectiveness in preventing piping through the embankment.
- Embankment instability through the identified weak clay layers on the abutments and river bed area.
- Spillway erosion in the unlined channel.
- Overtopping breach of the embankment by the revised PMP-DF.

3. GEOLOGY, GEOTECHNICAL INVESTIGATIONS AND CLAY SEAM MODELLING

The site geology in terms of the general distribution of rock types under the foundations can best be understood from the long section shown on Figure 3, which is diagrammatic but illustrates the main features.

The section shows the rhyolite (referred to as porphyry) capping the ridges on the two upper abutments with three dolerite sills (referred to as basalt) on both abutments above river level and three sills below river level. It also shows clay seams containing slip surfaces within the clay shales, siltstones and sandstones.

During construction, the foundation clay seams resulted in substantial slope failures when excavating the outlet conduit and led to extensive investigations using test pitting, drilling, sampling and testing of the clay zones to determine the nature and extent on site. The weak clay layers were tested and found to have a residual friction angle of 8° , however following expert review [4], this was increased to a peak of 13° to account for shearing through the rock mass in the foundation. The weighting berms were then added on the upstream and downstream sides of the embankment to improve embankment stability (Fig 2).

In order to critically evaluate the embankment stability issues for the design of the upgrade works, a detailed three dimensional geological model of the foundation area was developed using the available design investigation borehole data, grout hole drill data and more recent investigation boreholes. The model included more than 200 data logs and was used to take cross-sections along the dam axis and a number of sections with associated potential failure planes identified in the geological model. Section UA located in the original river bed

area is shown on Figure 4 and has a potential failure plane at 165 m in the foundation below the downstream shoulder.

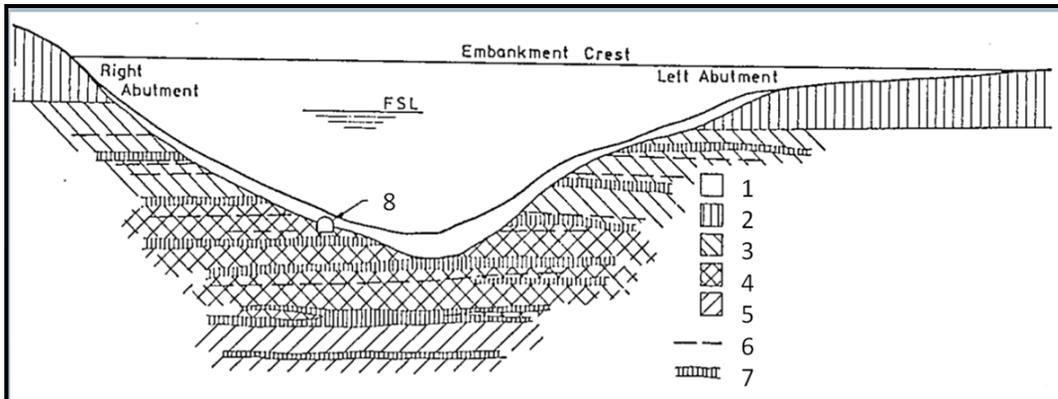


Fig. 3

Maroon Dam geological section on dam axis looking upstream [4]

Barrage Maroon -coupe géologique le long du barrage regardant vers l' amont

1	Overburden	1	Couverture
2	Rhyolite	2	Rhyolite
3	Clay shale, siltstone	3	Schist argileux , siltite
4	Clay shale, siltstone, sandstone	4	Schist argileux , siltite, grés
5	Sandstone	5	Grés
6	Clay seams	6	Filon d' argile
7	Dolerite	7	Dolerite
9	Conduit	9	Conduite

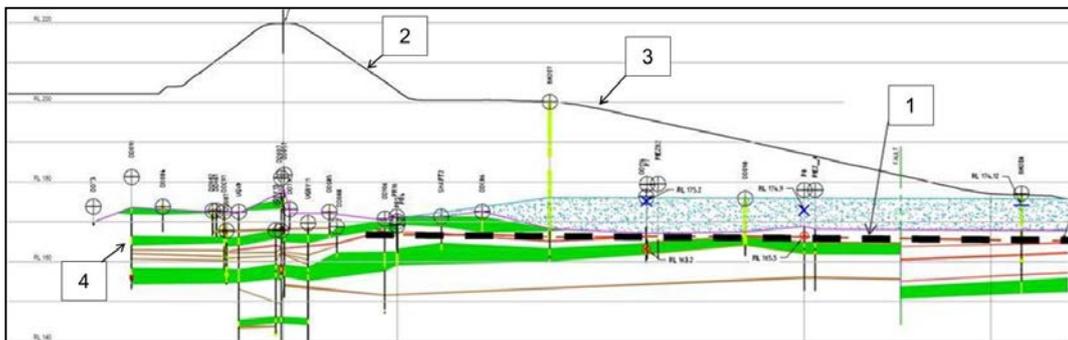


Fig. 4

Geological model of slope stability section UA, maximum section

Modèle géologique de stabilité de pente UA, coupe maximale

1	Potential Failure Plane	1	Plan de rupture potentielle
2	Embankment	2	Digue
3	Weighting Berm	3	Poids de la Berme
4	Rhyolite	4	Rhyolite

3.1 SHEAR STRENGTH AND SLOPE STABILITY ANALYSIS FOR FOUNDATION WEAK LAYERS

The shear strength of the weak layers in the foundation was a critical factor in understanding the potential for dam failure at higher reservoir levels. The strengths were evaluated along the possible failure surfaces identified at each slope stability section using a subjective probability approach accounting for the following:

- Clay origin
 - landslide clay formed along the landslide failure plane
 - clay zone within the parent claystone rock
 - shear zone clay within parent rock claystone or siltstone
- Extent of each clay zone along the potential failure surface
- Waviness/undulations along the failure surface

The proportion or weighting of the three clay origin types (landslide clay, clay zone and shear zones) along each specific potential failure plane was evaluated based on the geological profile. Given the uncertainty in the foundations, this was estimated for three likely weighting scenarios (lower, expected and upper weighting), as shown on Table 1 for the highest section of the embankment UA. These proportions given as percentages were used to estimate the combined strength along the failure surface for use in the slope stability analysis, accounting for the effective roughness angle along the layers, using the approach described in Fell et al [5].

Table 1
Variation of weak zones along the potential failure plane in Section UA at
RL 165 m
*Variation des zones de faiblesse le long du plan de rupture potentiel dans la
section UA à RL 165 m*

Zone	Lower weighting	Expected weighting	Upper weighting
Landslide Clay	30%	20%	17%
Clay Zone	60%	50%	36%
Shear Zone	10%	30%	47%

The strength along each failure plane was calculated using the average friction angle from laboratory testing and the joint roughness value with the expected, lower and upper weighting, as shown on Figure 5 for Section UA.

Slope stability analyses were completed for each selected section with the program Slope/W using the strength data for the various embankment zones and the piezometric pressure evaluated using the 55 hydraulic and 10 vibrating wire piezometers in the embankment and foundation. The results for Section UA are

shown in Table 4 for the existing section and upgraded dam with various water levels up to the dam crest level. Judgemental probabilities of slope failure were assigned in the risk analysis using the results from the stability analysis.

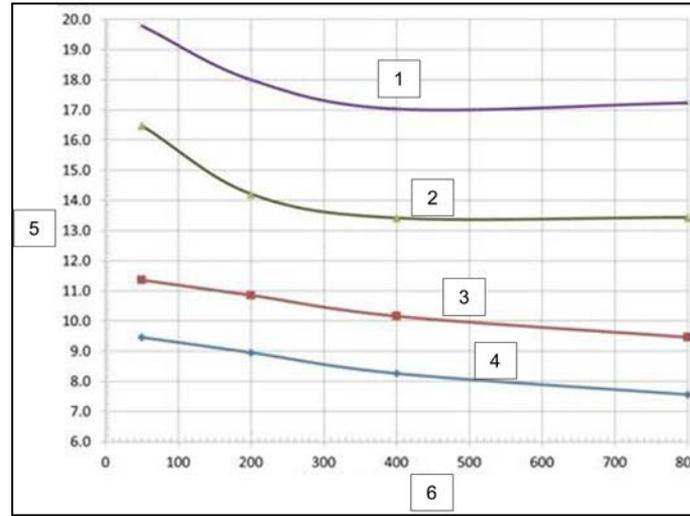


Fig. 5

Section UA stability analysis strength data for potential failure plane at RL 165 m
Section UA analyse de stabilité des données de la résistance du plan de rupture potentiel pour un niveau de 165 m

- | | | | |
|---|----------------------------------|---|------------------------------------|
| 1 | Upper Strength with roughness | 1 | Résistance maximale avec friction |
| 2 | Expected Strength with roughness | 2 | Résistance prévue avec friction |
| 3 | Lower strength with roughness | 3 | Résistance minimale avec friction |
| 4 | Lower strength no roughness | 4 | Résistance minimale sans friction |
| 5 | Friction angle (degrees) | 5 | Angle de frottement (degrés) |
| 6 | Effective normal stress (kPa) | 6 | Contrainte normale effective (kPa) |

Table 4

Maroon Dam Section UA stability analysis results for flood and normal loading

Résultats de l'analyse de la stabilité de la section UA pour le barrage Maroon en charge normale et sous une inondation

Stage	Clay seam strength	Water Level (m)		
		207.14	217.5	219.89
Existing	Min no roughness	1.14	0.98	0.93
1		1.27	1.10	1.04
Existing	Min	1.30	1.10	1.05
1		1.45	1.24	1.20
Existing	Expected	1.54	1.36	1.27
1		1.75	1.55	1.45

4 HYDROLOGICAL ANALYSIS

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 (Fig 6). This figure also shows some of the key reservoir levels used for the risk analysis and the starting reservoir level at the commencement of the annual series floods.

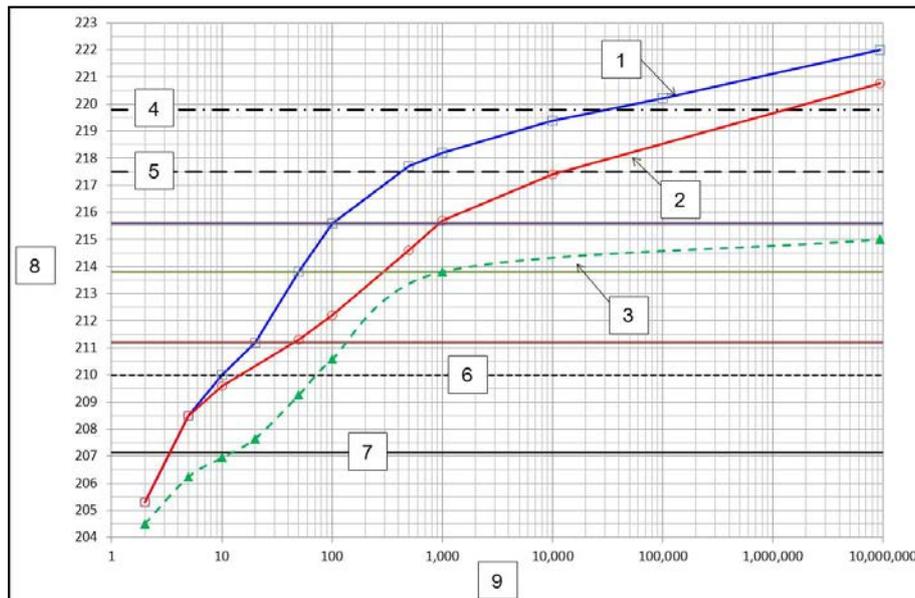


Fig. 6

Maroon Dam flood frequency analysis
Barrage Maroon analyse de la fréquence des crues

- | | |
|--|---|
| 1 Summer flood frequency curve | 1 <i>Fréquence des crues estivales</i> |
| 2 Winter flood frequency curve | 2 <i>Fréquence des crues hivernales</i> |
| 3 Starting water level for annual series | 3 <i>Niveau d' eau initial des séries annuelles</i> |
| 4 Dam crest level 219.8 m | 4 <i>Niveau de crête du barrage 219.8m</i> |
| 5 Spillway Crest Level 217.5 m | 5 <i>Niveau de crête du déversoir 217.5m</i> |
| 6 Historic High water level 209.9 m | 6 <i>Niveau d' eau historique à 209.9m</i> |
| 7 Full Supply Level 207.15 m | 7 <i>Cote de retenue normale 207.15m</i> |
| 8 Reservoir Level (m) | 8 <i>Niveau dans le réservoir (m)</i> |
| 9 Flood AEP (1 in X) | 9 <i>Probabilité d' excédence annuelle (1in X)</i> |

Figure 6 shows the following:

- The frequency distributions are all almost linear on the log normal plot for floods between 1 in 5 AEP and 1 in 100 AEP, and floods between 1 in 1,000 AEP and the PMP-Design Flood.

- The linearity of the flood frequency distribution between the 1 in 1,000 AEP event and the PMP-DF allowed these two events to be used to define the percentage AFC compliance over this range of floods. The AFC percentage compliance flood was evaluated using the approach given by the Dam Safety Regulator in the Department of Energy and Water Supply (DEWS) AFC guidelines [1] by proportioning the AFC inflow flood hydrograph to obtain the required flood level after flood routing through the spillway, as discussed below.
- The spillway level of 217.5 m is not exceeded for any floods more frequent than the 1 in 450 Exceedance Probability for the annual flood frequency data. This means that the reservoir is effective in acting as flood retention storage and the AFC percentage compliance flood was determined for these events using the percentage of the flood volume rather than proportioning the AFC inflow flood hydrograph.

5. RISK ASSESSMENT AFC COMPLIANCE

The potential failure modes for the risk assessment compliance were based on those developed for the Portfolio Risk Assessment completed for Seqwater by URS [6]. These included piping, slope instability, overtopping and spillway erosion. The risk analysis model was run for the existing dam configuration, which showed that the risk was above the ANCOLD limit of Tolerability (Fig 9) and the majority of the risk (70-98%) occurred with reservoir levels below the dam crest level. The highest risks were abutment piping and embankment instability (Table 4).

Table 4
Maroon Dam failure mode risk contributions by percentage
Contributions aux risques du mode de rupture pour le barrage Maroon en pourcentage

Failure Mode	Risk Percent Contribution (%)
Overtopping flood	1.50
Slope stability flood	29.24
Slope stability normal	0.15
Piping embankment flood	0.55
Piping embankment earthquake	0.21
Piping foundation flood	68.26
Spillway erosion flood	0.08

Dams that cannot safely discharge the acceptable flood capacity, require upgrading by the dam safety regulator in accordance with the timing shown on Table 5.

The AFC percentage compliance evaluated using the proposed risk analysis approach is the percentage scaling of the flood hydrograph data over the full range of floods that is required to lower the risk to the tolerable line or achieve the percentage AFC compliance levels given on Table 4. An example of the percentage scaling for the PMP-DF required to reach the dam crest level is shown on Figure 7.

Table 5
 Guidelines on acceptable flood capacity for water dams [1]
Directives sur la capacité hydraulique acceptable pour les barrages [1]

Tranche	Required minimum flood discharge capacity	Date by which the required minimum flood capacity is to be in place
1	25% of AFC or at least 1:2000 AEP for erodible dam embankments (whichever is the bigger flood)	1 October 2015
2	65% of AFC	1 October 2025
3	100% of AFC	1 October 2035

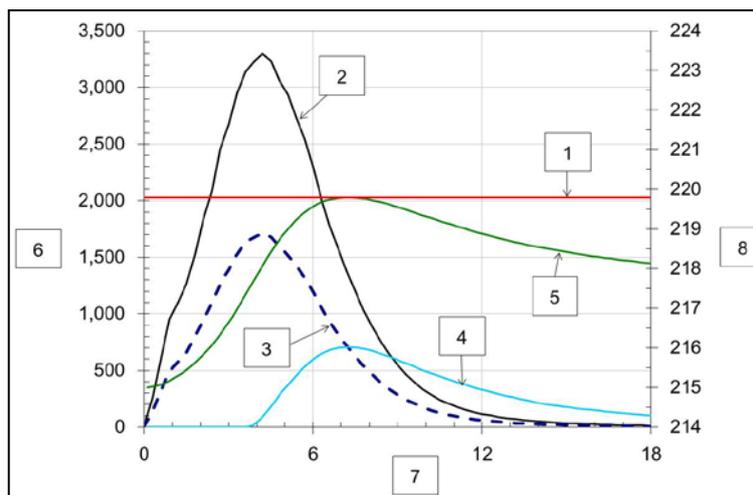


Fig. 7

Maroon Dam PMP-DF Scaling
Barrage Maroon - Crue probable maximale réduite

- | | |
|-------------------------------------|---|
| 1 Dam Crest 219.8 m | 1 Crête du barrage 219.8 m |
| 2 PMP-DF 6 Hour Duration Flood | 2 Crue probable maximale de 6hr |
| 3 Scaled PMP-DF | 3 Crue probable maximale de 6hr-à échelle réduite |
| 4 Total Outflow (m ³ /s) | 4 Débit total (m ³ /s) |
| 5 Water Level (m) | 5 Niveau d' eau (m) |
| 6 Flow (m ³ /s) | 6 Débit (m ³ /s) |
| 7 Time (hrs) | 7 Temps (hrs) |
| 8 Reservoir Level (m) | 8 Niveau (m) |

The risk model was used to evaluate the percentage compliance as follows:

- The starting reservoir level was determined for the probabilistic flood frequency data (Fig 6).
- The reservoir level over the full range of floods from 1 in 2 AEP event to the PMP-DF was calculated using the percentage AFC flood volume for floods below the 1 in 100 AEP, and routing of the floods for floods above the 1 in 1,000 AEP using the starting reservoir level for each flood.
- The percentage for the flood frequency data was changed until the Societal Risk was at the Limit of Tolerability.
- The Societal Risk was estimated using the DEWS compliance values of 25 percent and 65 percent compliance

The analyses showed that the requirement for passing 25 percent of the AFC flood by 2015 could be achieved (Fig 8) and upgrading would not be required by 2015. Notwithstanding this, the decision was made to continue with the dam upgrade on the basis that the existing risk plots above the Limit of Tolerability and the requirement for balancing risk across the Seqwater portfolio of dams.

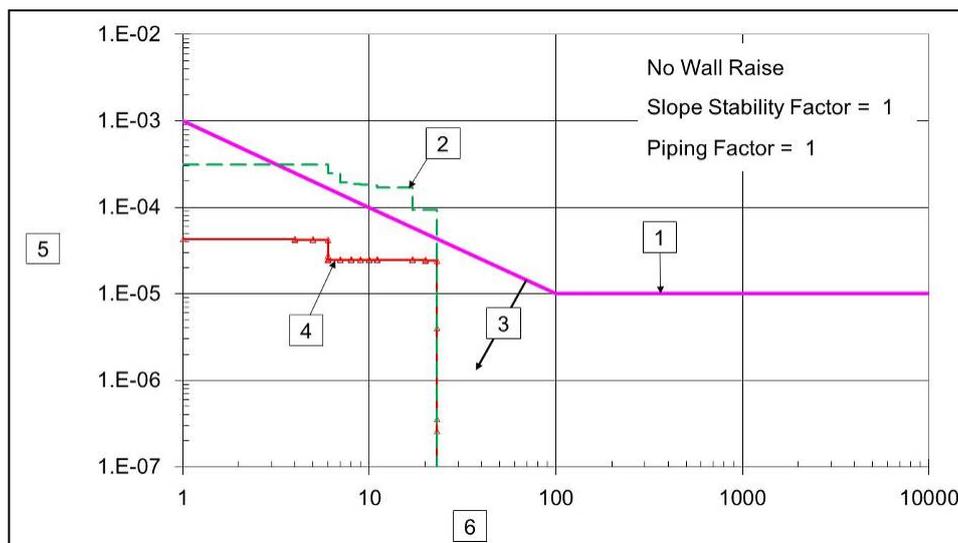


Fig. 8

Maroon Dam societal risk for 25 percent compliance
Barrage Maroon risque pour la société pour une conformité à 25%

- | | | | |
|---|--|---|---|
| 1 | Ancold Limit Of Tolerability | 1 | ANCOLD limite de la tolérabilité |
| 2 | Existing Risk | 2 | Risque actuel |
| 3 | ALARP | 3 | ALARP |
| 4 | 25% AFC Compliance | 4 | Conformité à 25 % AFC |
| 5 | Annual probability of failure with loss of life >N | 5 | Probabilité annuelle de rupture avec pertes humaines >N |
| 6 | Loss of Life N | 6 | Pertes humaines (N) |

6. CONSTRUCTION RISK

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, the excavation of the abutments will necessitate lowering the embankment crest level on both abutments. The excavation will require partial removal of the core zone leaving the upstream and downstream rockfill zones as the means of preventing overtopping in the event of a flood that exceeds the level of the excavated embankment. The estimated levels for the excavation on the abutments are shown on the flood frequency curves developed for the summer peak flood frequency data from November to March and the off peak winter season from April to November (Fig 9).

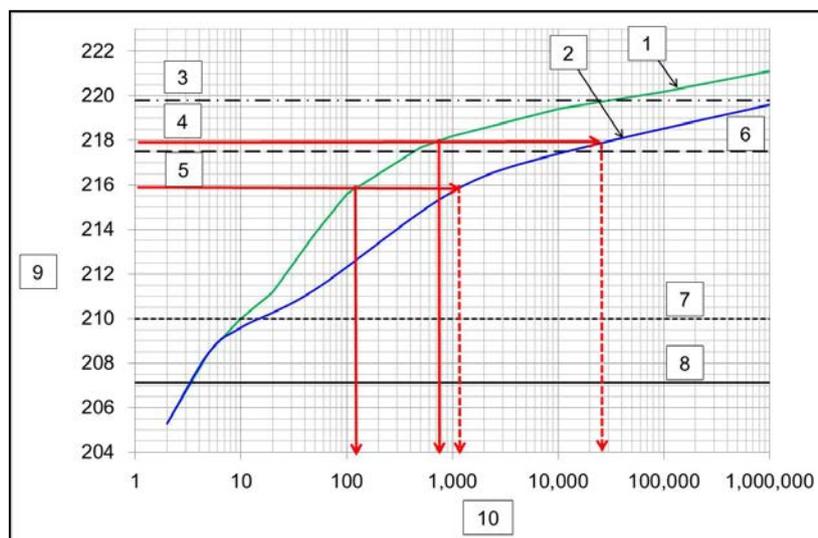


Fig. 9

Maroon dam construction flood frequency data

Barrage Maroon analyse de la fréquence des crues durant construction

1	Summer (Dec to March) flood frequency	1	<i>Fréquence des crues estivales</i>
2	Winter (April to Nov) flood frequency	2	<i>Fréquence des crues hivernales</i>
3	Dam crest level 219.79 m	3	<i>Niveau de crête du barrage 219.79m</i>
4	Right bank excavation 218 m	4	<i>Excavation rive droite 218m</i>
5	Left bank excavation 216 m	5	<i>Excavation rive gauche 216m</i>
6	Spillway crest level 217.5 m	6	<i>Niveau du réservoir 217.5m</i>
7	Historic peak 209.9 m	7	<i>Niveau d' eau historique à 209.9m</i>
8	FSL 207.15 m	8	<i>Hauteur normale maximum 207.15m</i>
9	Reservoir Level (m)	9	<i>Niveau du réservoir</i>
10	AEP (1 in X)	10	<i>Probabilité d' excédence annuelle (1in X)</i>

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, from which it was assessed that a coffer dam level at 217 m would be adequate for the construction works (Fig 10), where the societal risk is below the existing risk. The societal risk is also shown for the Cofferdam at this level for the Summer period, which clearly shows that the risk is unacceptable with the 217 m crest level of the coffer dam.

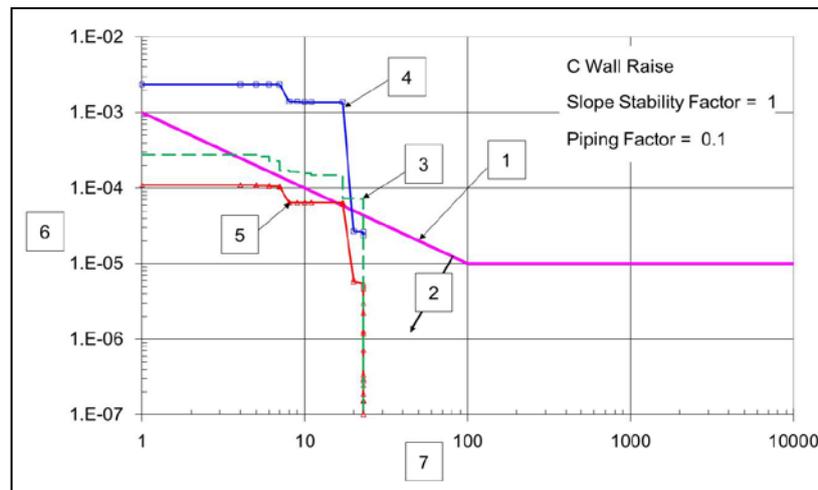


Fig. 10

Maroon Dam construction societal risk with coffer dam at EL 217 m
Barrage Maroon risque pour la société de la construction avec un batardeau à 217 m

1	ANCOLD Limit Of Tolerability	1	<i>ANCOLD limite de la tolérabilité</i>
2	ALARP	2	<i>ALARP</i>
3	Existing Risk	3	<i>Risque actuel</i>
4	Risk with coffer dam at 217 m and Summer flood frequency	4	<i>Risque avec un batardeau à 217 m et fréquence des crues estivales</i>
5	Risk with coffer dam at 217 m and Winter flood frequency	5	<i>Risque avec un batardeau à 217 m et fréquence des crues hivernales</i>
6	Annual probability of failure with loss of life >N	6	<i>Probabilité annuelle de rupture avec pertes humaines >N</i>
7	Loss of Life N	7	<i>Pertes humaines (N)</i>

7. CONCLUSIONS

Extensive geological modelling and analysis was successfully used to evaluate the nature and extent of low strength clay seams in the foundation of

Maroon Dam. The model provided the most accurate representation of the materials along the predicted failure surface and realistic modelling results for embankment stability.

Probabilistic methods were used to determine the reservoir starting level for flood modelling, which was subsequently used for AFC compliance analysis using a risk analysis approach.

The use of the risk analysis showed that the flood risk is significantly reduced for works completed in the winter season and the use of a coffer dam constructed to 1 m below the dam crest level at 217 m results in the societal risk being lower than the existing risk for the construction period.

REFERENCES

- [1] DEWS, Guidelines on Acceptable Flood Capacity for Water Dams, Department of Energy and Water Supply, Queensland Government, Brisbane 2003
- [2] ANCOLD Guidelines on Risk Assessment 2003
- [3] GHD 2013, Maroon Dam, Parapet Wall Detailed design and Embankment Stability Review, GHD, Brisbane, August 2013.
- [4] NUTT, K D, Maroon Dam Embankment and Foundation 1975
- [5] FELL, MACGREGOR, STAPLEDON, BELL, Geotechnical Engineering of Dams, CRC Press, 2005
- [6] URS (2013), Seqwater Dams Portfolio Risk Assessment Maroon Dam, Prepared for Seqwater, 29 January 2013.

SUMMARY

Maroon Dam is a 47 m high zoned earthfill dam completed in 1974. The dam is a multi-purpose reservoir, which was constructed to provide potable water supply, irrigation, flood mitigation and recreation.

An Acceptable Flood Capacity (AFC) study and foundation stability assessments were completed by GHD in 2011 and 2012. This work included detailed evaluation of the monitoring data from piezometers, survey monuments, inclinometers and seepage weirs. In particular, the piezometric pressure data provided a good basis for estimating the response under extreme flood loading.

A detailed foundation model was developed showing the variability of the clay strengths along potential failure surfaces. Simplified probabilistic analysis

was completed to derive strength estimates for the foundation clay zones. The likelihood of embankment failure under various flood loads was calculated using these strength estimates and this was used for evaluation of the AFC upgrade options using a risk analysis approach.

As an alternative to the cost-benefit analysis for evaluating risk reduction options, an equivalent percentage AFC has been developed using the risk analysis for the upgrade design. This approach was also used for the evaluation of the coffer dam level required to reduce the risk to an acceptable level for the construction period and included consideration of flood seasonality. The analysis confirmed that a coffer dam level 1 m below the dam crest level would provide an acceptable level of risk for the construction completed during the winter period.

This paper provides an overview of the dam and issues that were addressed in the upgrade option selection, followed by details of the approach used to determine the percentage AFC compliance using the risk analysis and the construction risk.

Keywords: Maroon Dam, Risk Analysis, Acceptable Flood Capacity, Construction Risk

RÉSUMÉ

Le barrage Maroon est un haut barrage en terre zone; construit en 1974. Le barrage a des objectifs multiples, il fournit une source d' eau douce , d' irrigation, d' atténuation d' inondation et une zone de loisir.

Une étude de la capacité acceptable de crue ainsi qu' une étude de la stabilité des fondations ont été complétée par GHD en 2011 et 2012. Ces études ont inclus une évaluation détaillée des données de suivi des piezomètres, un arpentage des structures, des infiltration du déverseoir. En particulier les données de pression piezometric ont formé une excellente base pour estimer la réponse du barrage sous la force d' une crue extreme.

Un modèle détaillé des fondations a été développé , ce modèle montre la variabilité de la résistance de l' argile le long des surfaces de rupture potentiel.

Une analyse simplifiée de probabilité a été complète pour estimer le résistance de l' argile dans la zone des fondations. La probabilité d' une rupture de la digue sous la force de différentes crues a été estimée en utilisant ces valeurs de résistance. Cela a ensuite permis d' évaluer les options d' améliorations du barrage en utilisant une méthode d' analyse de risque.

Comme alternative à une analyse des coûts et bénéfices pour évaluer les options de réduction des risques, un pourcentage équivalent de la capacité acceptable de crue a été développé en utilisant une analyse de risques lors de la conception des améliorations.

Cette approche a aussi été utilisée lors de l' évaluation du niveau du batardeau requis pour réduire le risque à un niveau acceptable durant la construction, la fréquence de crues saisonnières a été aussi prise en compte.

Cette analyse a confirmé qu' un batardeau à un niveau de 1 m sous la crête du barrage fournit un niveau de risque acceptable lors de la construction durant la période hivernale.

Cet article donne une vue d' ensemble du barrage et des problèmes qui ont été traités lors de la sélection des options d' amélioration. Cet article fournit aussi les détails de la méthodologie utilisée pour déterminer le pourcentage de conformité de capacité acceptable de crue en utilisant une analyse de risque.

Mots-clés: *Barrage Maroon, analyse des risques, la capacité d'inondation acceptable, risque de construction*