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USE OF RISK ANALYSIS FOR TAILINGS STORAGE FACILITY UPGRADE*

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1. INTRODUCTION

The QAL Red Mud Dam 2 (RMD2) is located approximately 25 km South East of Gladstone and 5 km west of the Boyne Island township in Queensland, Australia (Fig 1).



Fig. 1

QAL Red Mud Dam 2 Location (Google Pro ©2009)
Emplacement du bassin de boue rouge 2 de QAL

1	QAL red mud dam 2 (RMD2)	1	<i>Barrage de Boue Rouge 2 de QAL (RMD2)</i>
2	Gladstone	2	<i>Gladstone</i>
3	Boyne Island	3	<i>Ile de Boyne</i>

* *utilisation d' une l'analyse des risques pour l' amélioration du stockage des résidus miniers*

The components of RMD2 are shown on Fig 2. The dam embankments, which generally comprise Zone 1 clay core with Zone 3 outer shells constructed over rock foundation. Geofabric was provided between Zone 1 and 3 on the upstream side and a downstream filter for piping protection was provided on the lower section for all embankments and to the crest for Dam A/C and part of Dam D.

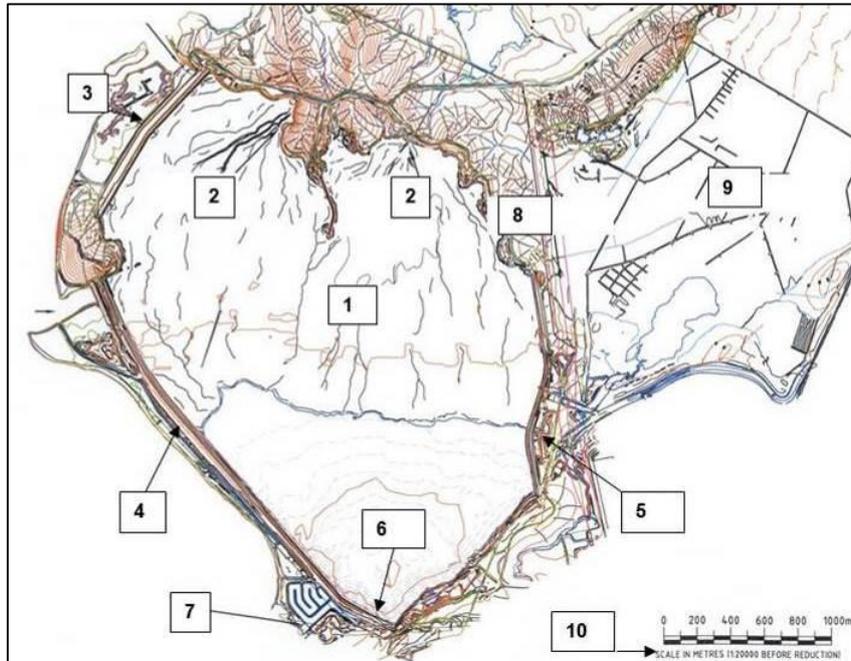


Fig. 2
Schematic layout of RMD2
Shéma du RMD2

1	Red Mud Dam 2	1	<i>Barrage de boue rouge 2 (RMD 2)</i>
2	Discharge Point	2	<i>point de rejet</i>
3	Dam D	3	<i>Barrage D</i>
4	Dam A/C	4	<i>Barrage A et C</i>
5	Dam E	5	<i>Barrage E</i>
6	Spillway & Outlet Works	6	<i>Deversoir et point de sortie</i>
7	Overflow and Labyrinth	7	<i>trops-plein et labyrinthe</i>
8	Water and power easement	8	<i>accès en eau et energie</i>
9	Red Mud Dam 1	9	<i>Barrage de boue rouge 1</i>
10	Scale before reduction	10	<i>échelle avant reduction</i>

Geosynthetic Clay Liner (GCL) was provided upstream in some embankments for seepage and piping control. Typical embankment zones are shown on the failure modes (Fig 3). In addition to the internal zoning, cement stabilised tailings was constructed upstream of Dam D for about 25 m with a depth of about 3.5 m for the upstream raise construction. This cement stabilised fill is expected to preclude the piping failure modes through the upper part of the embankment.

Dam A/C and Dam E will be raised to RL 22.7 m and include a 0.5 m high safety bund on the upstream and downstream edge of the crest. Dam D will be raised to RL 24.0 m using a general fill section placed onto the cement treated red mud (Fig 4). The labyrinth spillway will be raised from RL 20.65 m to RL 21.65 m.

2. RISK ANALYSIS

The risk analysis was undertaken in a workshop format using the following process:

- Define the purpose of the risk assessment;
The purpose of the risk assessment was to update the previous analyses completed between 2004 and 2010 accounting for the use of the safety bunds for preventing overtopping failure and the concerns over the seepage noted at Dam E.
- Determine the scope of the risk assessment;
The scope of the risk assessment included the piping, overtopping of the embankments and erosion of the spillway.
- Develop the risk assessment acceptance criteria;
The risk was evaluated in terms of acceptance criteria for societal and individual risk [1].
- Define the system to be analysed including the embankments, spillway and outlet works and evaluate the likely failure modes for the components and initiating events;
- Evaluate the flood frequency data;
- Evaluate available data for the components to understand the performance and behaviour under the loads to be applied when estimating the failure probabilities;
- Use simplified event trees (failure pathways) to calculate the risk. These were evaluated during the workshop with QAL personnel, reviewers and GHD personnel.

2.1. FAILURE MODES ANALYSIS

Failure of a dam or reservoir is defined to be the uncontrolled release of the stored water resulting from a breach of the dam or failure of an ancillary feature. A failure mode is the mechanism of failure. The Failure Mode Analysis (FMA) was completed using the following process.

- Screening of Initiating Events
 - A list of potential failure initiating events was developed and screened to remove those events that were considered to be unlikely to affect the safety of the tailings dams.
- Component Definition
 - The RMD2 was considered to be the main system with sub-components comprising the spillway and outlet works and Dams A/C, D and E.
- The primary and auxiliary function of each component was defined.
- Failure Modes Analysis (FMA)
 - A FMA was performed to determine the causes or mechanisms of failure from which the failure modes for further analysis were determined using the knowledge of the various components and their behaviour under each hazard or initiating event. All failure modes were screened for acceptance or rejection for further analysis. Typical piping failure pathways are shown on Fig 3.

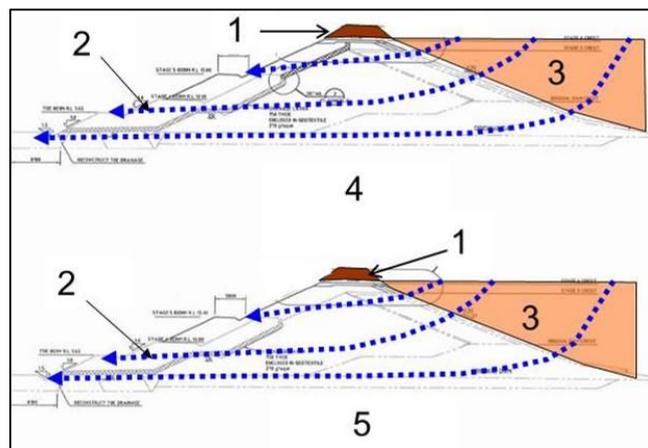


Fig. 3

Dam A/C and part Dam E typical failure pathways
Model de rupture classique de digue A,C et partiellement E

1	1 m raise	1	<i>rehausse de 1 m</i>
2	Failure Pathways	2	<i>direction des ruptures</i>
3	Red Mud	3	<i>boue rouge</i>
4	Dam A Chg 260 m to 1370 m and Dam E	4	<i>Barrage A de 260 m á 1370 m, et barrage E</i>
5	Dam A 1370 m to 2207 m and Dam C	5	<i>Barrage A de 1370 m á 2207 m et barrage C</i>

Table 1 shows the initiating events, failure modes and causes or mechanisms of failure for the embankment under hydrological loading that were considered in the risk analysis.

Table 1
QAL RMD2 Failure Modes Analysis (part table)
Tableau 1 QAL RMD2 Analyse du mode de ruptures (Partie de tableau)

Dam Failure Mode	Cause/mechanism of Dam Failure	Comments
Over-topping	Wave erosion of crest	Wind and wave analysis
	Overfilling with tailings - redirects flood flow to outer edge.	Event has occurred and analysis is to be based on current design.
Piping	Cracks in upper core and reservoir filling	Evaluated using assessment of cracks, seepage evaluation and construction practices
	Construction defects	

2.2. FLOOD HYDROLOGY

The rating curve for the labyrinth spillway was used for floodrouting the inflow floods from the 1 in 50 AEP event to the Probable Maximum Design Flood (PMP-DF) (Fig 4).

The data confirms that the embankment crest will be overtopped by 120 mm with the PMP-DF but that there will be a freeboard of 380 mm at the upstream safety bund. This presented a significant threat to the safety of the dam and the wave overtopping was evaluated for storm events up to the PMP-DF to ensure that the risk of overtopping erosion was acceptable.

The hydrological data was used to derive intervals for the risk analysis, as shown on Table 6.

2.3. RISK CALCULATION

The event trees/failure pathways and failure data were derived for the following areas.

- Piping
 - Embankment
 - Upper levels of the embankment above the GCL
 - Lower levels of the embankment below the GCL

- Original embankment
- Foundation
- Old river channel
- Normal cut-off sections
- Spillway
- Walls and outlet pipe
- Erosion
 - Spillway Floor and stilling basin
- Overtopping
 - Dam E
 - Dam A/C

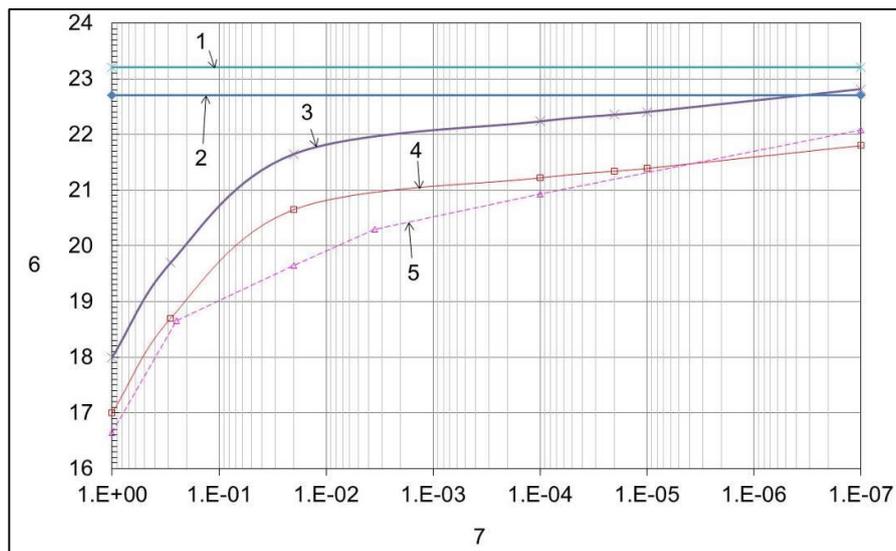


Fig. 4

QAL RMD2 Stage 6 to 8 Water Level versus Annual Exceedance Probability AEP

QAL barrage de boue rouge 2, phase 6 à 8, niveau d' eau et probabilité d' occurrence annuelle

1	Safety Bund Level	1	<i>niveau de securité de la digue</i>
2	Dam Crest Level	2	<i>niveau de la crête du barrage</i>
3	2013 Stage 8 Data	3	<i>2013-donnée de la phase 8</i>
4	2010 Stage 7 Data	4	<i>2010 donnée de la phase 7</i>
5	2004 Stage 6 Data	5	<i>2004 donnée de la phase 6</i>
6	Reservoir Level (m)	6	<i>niveau d' eau dans le reservoir</i>
7	Annual Exceedance Probability	7	<i>probabilité d' occurrence annuelle</i>

2.4. FAILURE SEQUENCE

The event trees or failure pathways were developed using the following general equation, which provides the probability of failure, conditional on the water level in RMD2 for which the annual water level probability for each water level interval (Tab 7) was applied to determine the annual failure probability.

$$P(\text{failure}) = \text{Probability of Initiation (Pi)} * \text{Probability of Continuation (Pc)} * \text{Probability of Progression (Pp)} * (1 - \text{Probability of Intervention (Pi)}) * \text{Probability of Breach (Pb)}$$

2.4.1. Initiation

- Piping

Piping initiation was based on evaluation of known weaknesses in the core zone or foundation. The Piping Toolbox [2] assisted in the assignment of the initiating probabilities for piping, which relies on the probability of a crack being present and then the probability of piping initiating through the crack for each water level.

- Wind and wave overtopping

The wave heights and run up were calculated for a number of wind and wave scenarios using the Coastal Engineering Manual [3]. The resulting potential overtopping discharge was estimated using the experimental and theoretical investigations for flow on sea dikes [4] for which the wave run up for the 2% exceedance was used. The results showed that the overtopping flow for Dam A/C would be 13 l/s/m for the Flood Range 3 and 110 l/s/m for the PMP-DF.

The potential for initiation of erosion was assessed using the allowable overtopping discharges for embankment seawalls and grass dykes [5]. The downstream slopes of the embankments at RMD2 are generally gravelly fill, which has a high resistance to erosion, from which it was assessed that overtopping erosion would initiate for flows in excess of 10 l/s/m. Initiation of erosion was, therefore, expected for the PMP-DF event where the overtopping flows are well in excess of the initiation flow.

2.4.2. Continuation

- Piping

Where filters are present, the following pathways were considered.

- Seals with little or No Erosion (PNE)
- Partial or no seal with Large Erosion (PLE) – evaluated to be 0.05
- Continuing Erosion (PCE) - Evaluated to be 0.01 based on the filter gradings

Where filters are not present, the effectiveness of the geofabric between Zone 1 clay and 3 general fill or the GCL was used to evaluate the continuation process of piping (Table 2).

Table 2
Continuation of Piping for Dam C, D and E >RL 15m with No Filters
Poursuite de l' érosion interne pour barrage C, D et E > RL 15m sans couche filtrante

Dam C, 0.3	Dam D 0.1	Dam E 0.95
Due to excessive differential settlement, the geofabric layer is more likely to be damaged	Upstream GCL and cement treated red mud. Main failure scenario is a poorly compacted layer, and the potential for the water to flow up and above the filter layer	No Filter and seepage is free flowing from embankment

- **Spillway erosion and piping**
The continuation of erosion at the spillway was determined by the flow characteristics of the spillway discharge (velocity, depth expected turbulence etc) and varied from 0.02 for Flood Range 1 to 0.5 for the PMP-DF.

The continuation of piping along the side wall and the outlet was based on the provision of the geofabric and granular filter layer placed during the Stage 6 works for which the probability was 0.02.

- **Dam Overtopping**
The continuation of overtopping of Dam A/C and Dam E caused by wind and waves was determined using the likelihood of the safety bund being breached, which for the PMP-DF was certain and Flood Range 3 was assessed to be between 0.5 to 1.0.

2.4.3. Progression

- **Piping**
The progression of piping was assessed to be 0.95 given the initiation and continuation stages of the process based on evaluation of the following factors:
 - The embankment material is expected to be plastic and capable of holding a roof.
 - Only dam D has a flow limiter with the cement treated red mud.
 - The majority of the embankment material is expected to be fine grained and erodible.

- **Spillway Erosion**
The progression of erosion was determined by the duration of the flood and varied from 0.01 for Flood Range 1 to 0.5 for the PMP-DF.
- **Dam Overtopping**
The progression of overtopping of Dam A/C and Dam E caused by wind and waves was determined using the likelihood of the flows back cutting into the pond, which was evaluated using the total overtopping discharge compared with breach flow discharges.

2.4.4. *Intervention*

It was assessed that there would be virtually no possibility of intervening in the failure process during the flood events.

2.4.5. *Breach*

- **Piping**
Likelihood of breach formation at the end of the piping sequence was assessed to be 0.95 based on the following failure modes
 - Gross enlargement
 - Sinkhole formation
 - Slope failure and overtopping
- **Erosion**
The erosion failure mode for the spillway was based on the flow back cutting into the reservoir and cutting down to the foundation level.
- **Overtopping**
Likelihood of breach formation at the end of the erosion overtopping sequence was assessed to be 0.95 based on (a) the depth of overtopping and (b) the duration of overtopping for the safety bund.

2.5. COMPARISON OF PROBABILITIES

The failure probabilities in the event trees were assessed using the Piping Toolbox [1] together with verbal descriptors and failure probabilities [7] (Tab 3). The table also provides in column 3 the equivalent for the QAL likelihoods.

When comparing the two probabilities, it must be borne in mind that the QAL events beyond the 1 in 100 (1%) are considered to be very unlikely given the duration of operation of the systems being evaluated. This raises the issue that the use of risk assessments when dealing with extreme events can present

difficulties for management to evaluate the risks given that other project risks have frequencies of more than 1%, whereas the TSF failure events are often controlled by significantly larger less frequent events.

Table 3
Mapping Scheme for Probability Estimates [7]
catégorie cartographique des estimations de probabilité [7]

Qualitative Description	Order of Magnitude Probability	Equivalent QAL Likelihood
Occurrence is virtually Certain	1	> 25% >0.25
Occurrence of the condition or event are observed in the available database	1 x 10 ⁻¹ (0.1)	10% to 25% 0.1 to 0.25
The occurrence of the condition or event is not observed or is observed in one isolated instance in the available database: Several potential failure scenarios can be identified	1 x 10 ⁻² (0.01)	1% to 10% 0.01 to 0.1
The occurrence of the condition or event is not observed in the available database. It is difficult to think about any plausible failure scenario, however, a single scenario could be identified after considerable effort.	1 x 10 ⁻³ (0.001)	<1% <0.01
The condition or event has not been observed and no plausible scenario could be identified even after considerable effort.	1 x 10 ⁻⁴ (0.0001)	

The application of risk assessment for evaluating tailings dams and fresh water dams is being accepted by many Dam Safety Regulators as an appropriate means for design and safety evaluation of the dams. There is a need, therefore, for decision makers within organisations where quantified risk assessments are being used for evaluating structures to familiarise themselves with the application and appropriateness of the various guidelines and risk acceptance criteria for their structures.

2.6. CONSEQUENCE ASSESSMENT

The potential Population at Risk (PAR) and life loss was made for breaching of the Dam E towards the north and Dams A/C and D to the South. Breach analyses were completed for the Sunny Day failure and PMP-DF from which the remaining events were evaluated for the risk estimation. The Inundation mapping for the PMP-DF breach of Dam A/C is shown on Fig 7 where

the 1 in 100 AEP flood extent is shown in blue and the PMP-DF is shown in brown.

The population at risk varied from 0 for the low decant level breach events up to 68 for the PMP-DF breach of the southern embankments. The loss of life was evaluated using the approach given by USBR DSO-99-06 [8] and was found to be less than 1 potential fatality owing to the shallow depths of about 500 mm and relatively low velocities.

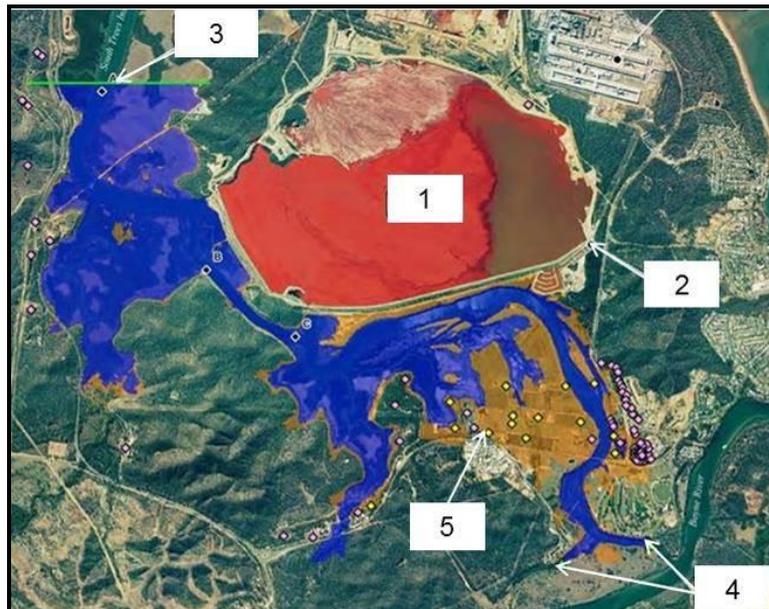


Fig. 7

PMP-DF breach failure for Dam A/C

Précipitation Probable Maximal, Rupture par fissure du barrage A et C

1	RMD2	1	<i>Barrage de boue rouge 2</i>
2	Spillway	2	<i>déversoire</i>
3	Downstream Boundary	3	<i>condition limite à l' aval</i>
4	Upstream Boundary	4	<i>condition limite à l' amont</i>
5	Population at Risk	5	<i>Population à risque</i>

2.7. RISK ANALYSIS RESULTS

The individual risk was calculated to be $6E-6$ using a fatality rate of 0.15, which is below the ANCOLD tolerable limit of $1E-4$ for an existing dam. The overall risk analysis results for each Dam are shown on Table 6.

Table 6
 QAL RMD2 risk data for Stage 8 operation
Données sur les risques QAL RMD2 lors de la phase 8

Embankment Section	Annual Failure Probability	Percent of Total	Risk (lives/yr)	% Total
Dam A	2.54E-06	4.8%	6.15E-07	4.1%
Dam C	2.06E-06	3.9%	2.07E-07	1.4%
Dam D	8.28E-07	1.6%	8.37E-08	0.6%
Dam E	4.67E-05	88.8%	1.40E-05	92.7%
Spillway	4.41E-07	0.8%	1.94E-07	1.3%
Total	5.26E-05	100.0%	1.51E-05	100.0%

The annual failure probabilities and risk for each reservoir level range are shown on Table 7.

Table 7
 QAL RMD2 annual failure probabilities and risk for Stage 8 operation
QAL RMD2 probabilités de rupture annuelle et risque lors la phase 8

Flood Range	Annual Failure Probability	Percentage of Total	Risk (lives/yr)	Percentage of Total Risk
2 to 3m below Spillway Crest Level	1.79E-05	34.0%	4.48E-06	29.7%
SCL to 2m below SCL	1.34E-05	25.5%	3.92E-06	25.9%
Flood Range 1	1.44E-05	27.3%	4.37E-06	28.9%
Flood Range 2	5.05E-06	9.6%	1.61E-06	10.7%
Flood Range 3 (10,000 to PMP-DF)	1.79E-06	3.4%	6.83E-07	4.5%
PMP-DF	1.00E-07	0.191%	4.59E-08	0.3%
Totals	5.26E-05	100.0%	1.51E-05	100.0%

The risk for the piping through the embankments above RL 15 m is shown on Table 8, which confirms that the majority of the risk is associated with piping above RL 15 m for Dam E, which contributes 87% of the total risk.

Table 8
 QAL RMD2 Summary data for piping through the embankment above RL 15 m
QAL RMD2 Sommaire des données de l' érosion interne à travers le remblai avec un niveau supérieur à 15 m

Dam	Risk (lives/annum)	Percent of Total Risk (%)
A/C	2.72E-7	2.5%
D	6.62E-8	0.5%
E	1.31E-5	87%

2.8. CONCLUSIONS FROM THE RISK ANALYSIS

The Societal and individual risks were found to be below the ANCOLD tolerable limits for existing dams.

The use of the risk approach enabled the design for the labyrinth spillway and the use of the safety bunds to be evaluated and approved for the Stage 8 construction, despite the concerns over the seepage noted at Dam E and the potential for high reservoir levels during the PMP design flood.

The potential for overtopping failure during the extreme floods was evaluated using current wind and wave analysis methods to determine the overtopping discharges and compare this with trigger flows for onset and continuation of erosion. The analyses clearly showed that the extreme floods (PMP-DF), while having a relatively high probability of breach were small contributors (0.3%) to the total risk.

Dam E was found to contribute 92.7% of the total risk of dam failure with 87% being attributed to the seepage observed above RL 15 m. While the overall risk was below the limit of tolerability, the significant contribution to risk of this seepage area confirmed the requirement for ongoing visual observations for signs of potential increased seepage and onset of piping on this dam during the operation of the TSF.

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SUMMARY

The Queensland Alumina Limited (QAL) tailings storage facility (TSF) comprises four embankments up to about 20 m high storing a total of 13.5 million m³ of water at the spillway level. The original spillway was raised in 2010 using a labyrinth spillway to increase the discharge capacity while maintaining the existing embankment crest level.

The current capacity increase by raising the labyrinth level 1 m incorporated a minimalist approach for raising two of the embankments including the use of the safety bunds for wave overtopping protection. Flood routing found that the main embankment crest for these embankments would be overtopped by 120 mm and the freeboard at the safety bund would be 280 mm when passing the probable maximum design flood (PMP-DF). The potential for overtopping failure during the extreme floods was evaluated using current wind and wave analysis techniques to determine the overtopping discharges and compare this with trigger flows for onset and continuation of erosion. The analyses clearly showed that the extreme floods (PMP-DF), while having a relatively high probability of breach were small contributors (0.3%) to the total risk.

Significant seepage was noted on one of the four dam walls forming the TSF where the internal filter layer was curtailed to accommodate future development. This was also the location where the construction process resulted in a relatively pervious layer through the embankment. There are also significant variations in cross section for the four dam walls for which the risk analysis was the only means of evaluating the piping performance of each wall under the increased flood loading.

The use of the risk approach enabled the design for the labyrinth spillway and the use of the safety bunds for wave overtopping protection to be evaluated and approved for the Stage 8 construction, despite the concerns over the seepage and the potential for high reservoir levels during the PMP-DF.

Keywords: Risk Analysis, failure modes analysis, piping, overtopping failure, safety bunds

RÉSUMÉ

Les barrages de stockage de boue rouge de la compagnie Queensland Alumina (QAL) comprennent 4 digues qui peuvent atteindre une hauteur de 20 m et contenir jusqu' à 13.5 million m³ d' eau au niveau de la crête du déversoir.

Le déversoir original a été réhaussé en 2010 par un déversoir en labyrinthe pour augmenter sa capacité tout en maintenant constant le niveau de la digue.

L' augmentation de la capacité par le rehaussement du niveau du déversoir labyrinthe a inclut une approche minimal pour le réhaussment de 2 des digues. En particulier cette approche a adoptée l' utilisation de digue de sécurités pour protéger du débordement lié aux vagues.

Une analyse du bilan hydrique a démontré que la crête de la digue principale est dépassé par 120 mm et la revanche de la digue de sécurité est à 280 mm durant la crue probable maximal. La possibilité d' une rupture liée a un débordement durant un crue extrême a été évalué par l' analyse du débit de débordement associé avec une analyse du vent et des vagues. Ce débit a été comparé avec le débit nécessaire a la formation de l' érosion de la digue.

Cette analyse a clairement montrée que bien que les crues extrêmes est une chance relativement élevée de développer une rupture de la digue elles ne forment qu' une petite contribution (0.3 %) du risqué total.

Un important problème d' infiltration a été observé sur l' un des quatre barrages de stockage de boue rouge où la couche filtrante interne a été raccourci pour s' adapter aux projets futurs. C' était aussi à ce même endroit que durant la construction une couche relativement perméable a été installée à travers la digue. On trouve aussi des variations considérables dans la coupe transversale des 4 murs des barrages. Une analyse des risques était la seule méthode capable d' évaluer le risque d' érosion interne sous la force d' une crue.

Lors la phase 8 de la construction, la conception du déversoir labyrinthe ainsi que de la digue de sécurité a été évalué et autorisé par une méthode basée sur une analyse des risques bien qu' il y ait eu des inquiétudes sur l' infiltration et le haut niveau d' eau durant la crue maximale probable.

Mots-clés: *analyse des risques, l'analyse des modes de rupture, de l' érosion interne, rupture par débordement, digue de sécurité*