Analysis and Monitoring of Stage 5 Deformations at QAL Red Mud Dam No. 2

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SUMMARY: Connell Wagner was commissioned by Queensland Alumina Limited (QAL) to implement a monitoring program for the Number 2 Red Mud Dam, located 14km south of Gladstone. The aim of the program was to obtain data associated with stability, deformation, pore water pressures and seepage during and after construction several downstream raises.

Dam safety inspections and subsequent geotechnical investigations in 2001 showed that deficiencies in the clay core and/or the presence of a granular layer had caused the water table to rise within the embankment. To address potential problems, modifications were made to the proposed stage 5 raising and the frequency of dam wall monitoring was increased.

This paper presents the analysis and assessment of monitoring devices before and during the Stage 5 raising. As part of the monitoring program, finite element models were developed at the monitoring locations to determine the likely deformations of the inclinometers due to the Stage 5 raising and operation of the dam. A back-analysis was performed by calibrating the deformation analyses with the monitoring results at Stage 4 to obtain reliable soil elastic parameters for the finite element models. These were then able to provide an indication of the expected future horizontal and vertical deformations at each of the monitoring sites. Using the inherent variability of the soil parameters, trigger limits were derived to indicate procedures to be followed if specified criteria is exceeded.

INTRODUCTION

Queensland Alumina Limited owns and operates a major alumina refinery at Parsons Point Gladstone. QAL currently pumps a by-product of the refinery process known as red mud from the refinery to the Number 2 Red Mud Dam (#2 RMD) on Boyne Island, 14km south of Gladstone.

The original number 2 Red Mud Dam was constructed between 1973 and 1976 and is formed by a combination of natural hillside and constructed earth embankments. Since 1991 the dams have been progressively raised by six 2m downstream stages. Geotechnical instrumentation were installed in June 1999 to monitor the dam wall response during the future construction stages, and operation of the dam

Dam inspections carried out in September 2001 showed wet spots on the slope of the embankments and ponded seepage on the upper berms. These inspections and subsequent investigations confirmed the presence of intermittent gravel layers within the clay core.

Based on the results of the inspections and investigation, modifications were made to the Stage 5 raising and the frequency of dam wall monitoring increased. Finite element models were created and calibrated with the results of the Stage 4 monitoring of inclinometers along the dam wall. To provide QAL with a set of procedures to follow based on embankment movement deformation analyses were carried out using the variability in soil parameters to establish a series of “trigger limits” at each monitoring location. The trigger limits, green, amber and red defined actions to be followed if the horizontal deformation is exceeded.

BACKGROUND

The Number 2 Red Mud Dam consists of three major constructed earth embankments and minor saddle dams that are wedged between metamorphic and sedimentary formations of the Curtis Island Group. The embankments have been progressively raised by six 2m downstream stages (originally designed in 1989) that have been continuously constructed as the mud level rises. The Stage 5 raising was completed in 2003. At the end of Stage 6 the embankment dams will be close to 20m above the natural surface.

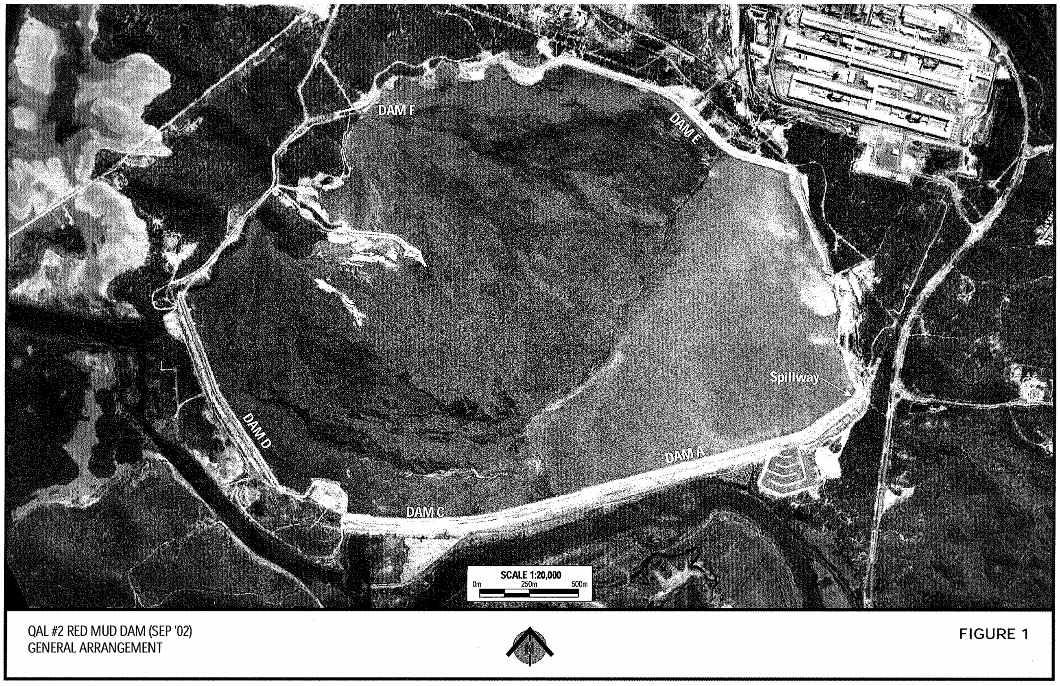

Figure 1 – QAL Red Mud Dam Number 2

Just prior to the Stage 4 dam raising geotechnical instrumentation was installed at critical sections along the dam walls. The monitoring equipment was installed to capture data associated with stability, deformation, pore water pressures, and seepage during the future construction stages, and operation of the dam.

The No.2 Red Mud Disposal Dam is a referable dam and requires periodic inspections. Dam inspections carried out by Connell Wagner in September 2001 observed wet spots at the top of the dam wall and ponded seepage on the upper berms. The governing mechanism of the wetting was attributed to seepage through the clay core due to deficiencies in the clay core and/or the presence of a granular layer. A subsequent investigation commissioned by QAL confirmed the deficiencies of the dam core material and intermittent gravel layers.

Based on the inspection and investigation results the frequency of monitoring was increased and further seepage and slope stability analyses were carried out. The results of these analyses showed that the dam wall may have potential problems in the long term at the Stage 6 operation level with the current design at the time. Remediation measures, to improve the long-term stability, were proposed. The extent of the measures varied for each dam depending on the computed factors of safety, the mud deposition next to the dam wall, material properties, extent of seepage and consequences of failure. The remediation measures are detailed below.

- Construction of a seepage cutoff trench and lining at the upstream face of the dam
- Construction of a drainage layer enclosed in geotextile along the existing batters and benches that were constructed in the Stage 5 development on the downstream side of the dam
- Construction of additional stabilising berms at the toe of the dam embankment

The above modifications were incorporated into the design for the Stage 5 construction works. Periodic readings and analysis of inclinometer data was undertaken during the Stage 5 raising from 24/05/02 to 21/05/03. Finite element models were used to predict future movements at each location. This paper addresses the assessment of the inclinometer data, and the finite element analysis used to predict the future movements.

MONITORING DATA ANALYSIS

Monitoring instrumentation was installed before the 2000 Stage 4 raising. Inclinometers were installed to capture data associated with the stability and deformation of the dam. Table 1 details the inclinometers installed at each dam location.

Table 1 QAL Red Mud Dam No.2 Inclinometer Locations

Location	Instrument Number	Comments
A750	INC 1	Located near wet areas on embankment
A1000	INC 2	Closest point to former channel of South Trees Inlet
C400	INC3	Alluvial area
C500	INC 4	Former channel
D1040	INC 5	Alluvial area
D1140	INC 6	Former channel

The inclinometer readings up to July 2000 showed no significant movements observed. The subsequent reports indicated that much of the data was distorted due to installation effects and/or physical or noise disturbances.

Readings obtained in May 2002 for the Stage 4 level showed some inconsistencies. Excessive movements were recorded at five of the six inclinometer locations. While there were obvious errors in the readings and its reliability, there was significant concern as to the movements which would have initiated the buckling of the inclinometer casing. A check reading was taken in July 2002 to confirm this was not an operation error.

Although the inclinometer readings showed excessive movements, inconsistencies in the plots clouded a definitive solution. Confusing or unexplainable results are common problems to all inclinometers. The commonly encountered errors that affect the quality of the inclinometer data are the so-called "zero-shift" error and rotation errors due to spiraling of the casing. When readings are obtained in a slightly inclined casing, a correction for the apparent drift is necessary. Rotation produces a more irregular pattern in the displacement-versus-depth profile. Both of these effects may mask shear movements occurring at discrete zones within the embankment.

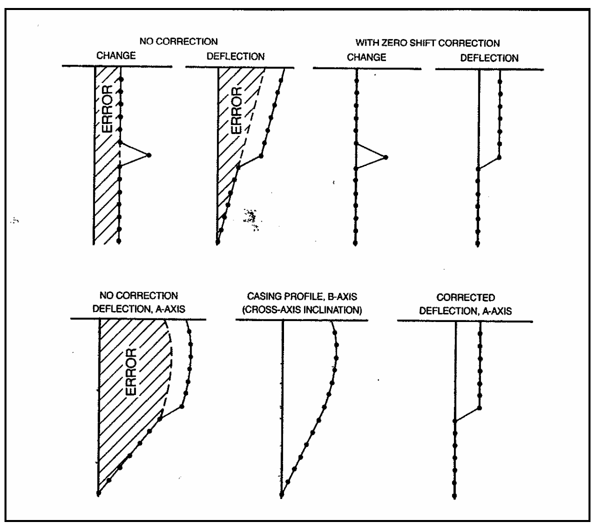

Figure 2 – Commonly Encountered Inclinometer Errors (Singh, B and Varshney, R, S, (1995))

The data collected for #2 RMD exhibited rotation and inclination errors, and several other anomalies that skewed the results. Much of the distortion was attributed to buckling of the inclinometer during the high dam operation level and subsequent raising in the Stage 5, which produced some consolidation of the foundation layers. To enable a sensible assessment of movements within the dam wall, the inclinometer data was analysed taking into account the following assumptions

1. Movements of 20mm within the XW Shale layer is physically unlikely
2. Oscillating movements of 20mm is unlikely to occur. This phenomenon may to occur in high permeability soils such as sand and gravel layers and also boulder fills reorienting itself during settlement
3. Considerable movement within the upper layers of the loose fill can be ignored
4. Movement parallel to the dam wall can be attributed to the rotation of the inclinometer in that the direction due to torsional effects rather than true movements in that direction. Therefore movement along the A axis for each location is considered to be of greater importance in the assessment

GEOTECHNICAL MODEL AND CALIBRATION

Using historical geotechnical data gathered from investigations prior to the installation of the inclinometers, deformation analyses were carried out to determine Stage 4 trigger limits. Trigger limits can be described as a set of procedures to be followed if specified criteria are exceeded.

Monitoring results observed in May 2002 showed that the Stage 4 trigger limits had been exceeded. However, as previously described, site inspections and investigation revealed that the clay core was not as competent as previously assumed. QAL implemented corrective measures during the Stage 5 raising but the Stage 4 trigger limits had to be refined to allow for the reduced strength parameters, higher phreatic surface and Stage 5 loading.

Based on the results of the 2002 geotechnical investigation and published references on soil properties correlation, the soil parameters for the Stage 4 calibration were determined. The deformation model was calibrated for the Stage 4 development at Section A750, A1000 and D1040. These sections were chosen since they provided the most consistent monitoring results, i.e. readings with the least errors. The calibration involved comparing the rationalised inclinometer readings with the results of the revised Stage 4 deformation analyses. Table 2 compares the maximum horizontal deformation (mm) from the inclinometer readings, Stage 4 analysis (using assumed soil parameters) and Stage 4 calibrated analysis.

Table 2 Comparison of Back analysis and inclinometer readings

	Max. Horizontal Deformation (mm)		
Inclinometer	**1 (A750)**	**2 (A1000)**	**3 (D1040)**
Inclinometer Reading*	30	15	15
Stage 4 initial (using assumed soil parameters)	6	6	14
Stage 4 calibrated (with high water table and lower soil strength)	16	15	21

*This reading neglects the obvious inconsistent reading in the top loose fill placed as a working platform during placement of the inclinometers.

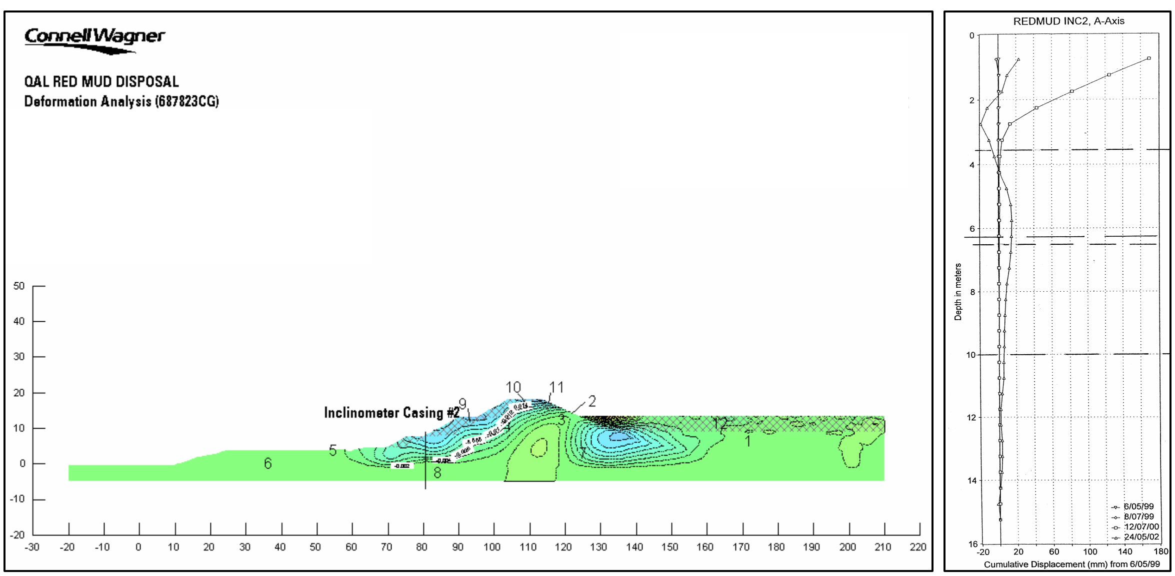

Figure 3 – Stage 4 Model Calibration

The comparison between the inclinometer readings and calibrated SIGMA/W model were shown to be in better agreement, although this result varies depending on the inclinometer. Further reduction in the soil strength parameters, to provide a closer calibration, would be unrealistic and furthermore not consistent with the results of the field investigations. Nevertheless, the above calibration was considered accurate enough to allow the calculation of the trigger limits for the Stage 5 raising.

DEFORMATION ANALYSIS and STAGE 5 TRIGGER LIMITS

To provide QAL with an indication of the likely horizontal deformation associated with the Stage 5 raising of the dam, further analyses were carried out using the calibrated Stage 4 soil parameters.

The analysis was carried out using the stress and deformation analysis computer program, SIGMA/W. Initial stress conditions for each section were determined using linear elastic soil properties. The deformation due to the addition of Stage 5 embankments and red mud has been calculated using Elastic-Plastic parameters. Table 3 presents a summary of the maximum expected deformations of each inclinometer following the Stage 5 raising, from the SIGMA/W analysis

Table 3 Maximum Expected Inclinometer Deformations

Inclinometer Location	Maximum Horizontal Deformation (mm)
INC1 (A750)	26
INC2 (A1000)	24
INC3 (C400)	8
INC4 (C500)	7
INC5 (D1040)	19
INC6 (D1140)	19

This was consistent with the appropriate methods (hand calculation) based on shear beam theory presented in Herzog (1999).

The results shown above provide an indication of the expected horizontal deformation of each of the inclinometers. The deformation analyses showed that the greatest horizontal deformations, due to the Stage 5 raising, are likely to occur along Dam A. These results were also supported by independent limit equilibrium slope stability analyses which indicated that Dam A possessed the lowest factor of safety for the Stage 5 raising.

The values extracted from the inclinometers provide the magnitude and rate of movement within the dam wall during raising. However, on their own, these results do not give an indication of the severity of the movements, particularly since the deformation is dependent on size of the raise and the subsurface profile. Therefore action limits (depending on the severity of movement) were adopted to compare against observed values.

To determine a set of "trigger limits" for the Stage 5 raising, a probabilistic approach was required taking into account the variability of soil parameters. The maximum expected inclinometer deformations were calculated using the average soil parameters. Therefore the results shown in Table 3 and shown in Figure 4 can be considered to be the "green trigger limit"; the most probable dam movement. To determine an "amber and red trigger limit" variance in the soil's unit weight, undrained shear strength and elastic modulus were determined/estimated.

Kulhawy (1992) provides guidance on the variability of soil properties. Table 4 summarizes the coefficient of variance for the material properties used in the Stage 5 trigger limit determination.

Table 4 Inherent Variability of Soil Parameters

Property	Mean Coefficient of Variance (%)
Unit Weight γ, ?(kN/m^3)	7.1
Undrained Shear Strength, Cu (kPa)	33.8
Elastic Modulus (kPa)	33.8 (Inferred)

Note: Poisson's Ratio, the soil friction angle and the coefficient of earth pressure at rest have remained unchanged

Since the data set from the previous investigations were not statistically significant and do not provide an accurate estimate of the soil's variability, the values in Table 5 were adopted to determine the amber and red trigger limits. This assumes that the soil parameters can be described using a normal distribution. Table 5 provides a description of the trigger limits and the value of the soil parameters used.

Table 5 Description of Movement Trigger Limits

Trigger Limit	Movement Description	Soil Parameters
Green*	Less than the most probable movement prediction	Mean value
Amber	Between the most probable and upper bound movement prediction	Mean value reduced by one standard deviation
Red	Greater than the upper bound movement prediction	Mean value reduced by 1.65 standard deviations

Note: *Provides acceptable factors of safety from limit equilibrium analysis

Using the criteria adopted in Table 5, displacements corresponding to each trigger limit were determined for each dam/inclinometer section. Table 6 provides a summary of the trigger limits for the Stage 5 raising. These values were compared against actual monitoring readings during the Stage 5 raising.

Table 7 Stage 5 Trigger Limits for Monitoring Purposes

Trigger Limit	Action	Trigger Limit – Horizontal Deformation (mm)					
	Inclinometer Number	**1**	**2**	**3**	**4**	**5**	**6**
Green	No cause for concern	30	25	10	10	20	20
Amber	Movements causing concern -increase frequency of monitoring -Monitoring at 1 month intervals	45	40	15	15	30	30
Red	Increase reading frequency -initiate contingencies and actions -monitoring at 2 week intervals	60	50	20	20	40	40

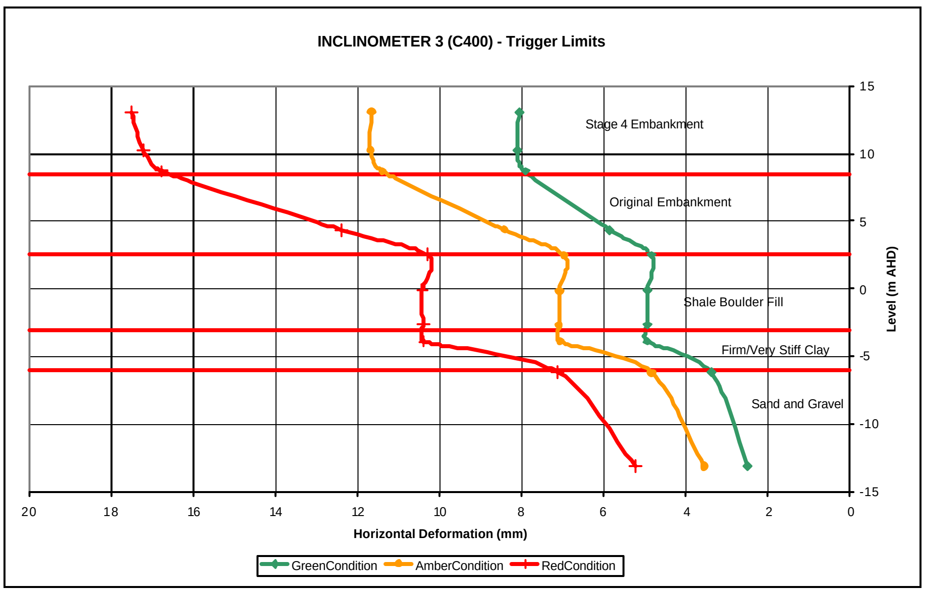

Figure 5 – Dam Section C400 Trigger Limits

VERIFICATION

To monitor the lateral displacements of the embankment during the Stage 5 raising, Connell Wagner analysed and assessed inclinometer data obtained on 11/11/02, 13/01/03, 03/04/03 and 21/05/03 and compared it against the Stage 5 trigger limits.

During the monitoring period all significant movements were considered with particular attention being paid to the movements that occurred within the vicinity of the slip surfaces determined by stability analyses, i.e. the location/depth of the movement was compared with the location of the critical slip surface.

Correcting the inclinometer data for "zero-shift" and rotation errors and assessing movements within the critical slip surface only; a clearer indication of the dam movements was able to be derived.

The monitoring results during the Stage 5 raising show that dam wall movements ranged between 10mm and 30mm. These values did not exceed the "green trigger limit" criteria set out in the preceding section. The results shown above were considered to be in reasonable agreement with the results of the deformation analyses. Table 8 provides a comparison between the calculated and observed horizontal deformations.

Table 8 Observed versus Calculated Horizontal Deformation

Inclinometer	Horizontal Deformation (mm)		
	SIGMA/W Calculated	**Green Trigger Limit**	**Observed**
INC1 (A750)	26	30	30
INC2 (A1000)	24	25	15
INC3 (C400)	8	10	10
INC4 (C500)	7	10	10
INC5 (D1040)	19	20	15
INC6 (D1140)	19	20	15

The comparison between the observed and calculated horizontal deformations shows that the calibrated finite element model was able to accurately predict the movements for the Stage 5 raising; proving to be an invaluable tool during the monitoring period.

CONCLUSIONS

In summary this paper has shown that the combined use of inclinometers and finite element models in the monitoring of embankment deformations can be successful as long as an approach that carefully questions both the field and analytical results is adopted.

The monitoring of QAL Red Mud Dam No.2 has shown that inclinometers are sensitive instruments that require the end-user to analyse the validity of the results without concluding that the equipment is at fault. Problems that are common to all inclinometers, such as "zero-shift" and rotation errors, were exhibited in the inclinometers at Red Mud Dam No.2. These errors tended to accentuate and mask "real" shear movements in the embankment and as such a careful examination of the results was required.

The use of inclinometers as a tool to monitor the movements within the dam wall has been complemented through the use of finite element models that were calibrated against actual deformations. The predicted movements correlated with the limit equilibrium factors of safety and hand calculated estimates using shear beam theory. The results of the Stage 5 raising has shown that a carefully constructed finite element model that is calibrated against actual conditions can provide a reasonable assessment of dam wall movements.

ACKNOWLEDGEMENTS

The author would like to thank the following people and organisations for their contributions to this paper. Dr Burt Look, Connell Wagner Brisbane for valued advice, project direction and assistance. Ross Tanner, Connell Wagner Gladstone, for data collection. The author would also like to acknowledge the assistance of Queensland Alumina Limited who made the results of the monitoring program available for this paper.

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