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Incorporating operational flexibility into mine waste management

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Abstract

A case study is presented that describes the benefits of optimised slope monitoring of an in-pit tailings storage facility embankment. As the tailings storage design project quickly advanced from concept to construction, the original tailings facility design criteria and embankment performance requirements were progressively modified to meet mine operational requirements. An embankment slope monitoring program was developed to facilitate safe tailings disposal in close proximity to mining operations.

1 Introduction

In-pit tailings storage facilities (TSF) are common for iron ore mining operations in the Pilbara region of Western Australia. The approach often ranks favourably compared to other concepts based on capital and operating cost requirements, environmental impact, and the landform geometry at closure. The viability of an in-pit option depends on several factors including the:

- potential presence of mineralisation in and around the pit which may be economic
- potential impact to groundwater quality
- stability of pit walls and potential impacts on any adjacent infrastructure or future mining operations.

Compared to other tailings disposal options, relative disadvantages to an in-pit TSF include:

- higher risks to personnel and operations where mining will occur adjacent to the TSF
- reduced flexibility in mine planning due to the requirement to create a large mining void for tailings and the associated potential requirement to store more mine waste ex-pit
- higher potential for conflicts with operations related to potential discovery of additional ore in and around the TSF
- potential seepage to underground workings from the TSF.

These risks can be effectively mitigated through adequate mine planning, design and monitoring.

This paper outlines the value of a targeted geotechnical monitoring program to provide sufficient flexibility in mine operation for continued safe operation under changed conditions. A case study is presented that demonstrates operational flexibility that arose from an optimised slope monitoring programme of an in-pit TSF.

The pace of development at Cloudbreak Operations by Fortescue Metals Group (FMG) required a high degree of flexibility in the Daydream In-pit TSF design, construction, and operation. In particular, changes to the mine plan and the constraints imposed during construction resulted in the embankment constructed to contain tailings being put under different operating conditions than originally anticipated.

To facilitate safe mining and tailings disposal operations in close proximity, an embankment monitoring plan was developed. The monitoring program involved the installation of monitoring equipment and implementation of an inspection, management and reporting plan.

2 Daydream in-pit tailings storage facility design

Tailings management for in-pit TSF involves the controlled deposition of tailings into an abandoned mine pit to maximise the density of the deposited tailings. Water recovery from the storage is typically carried out to optimise the settled tailings density and mitigate potential environmental impact from seepage (Lane, 2008). Where embankments are required to separate future mining areas from the TSF, water recovery and the management of tailings deposition can be critical components to the safe and effective operation of the facility.

2.1 Daydream in-pit TSF design concept

The Daydream in-pit TSF was the first in a series of in-pit TSFs at Cloudbreak Operations designed to contain tailings residue resulting from beneficiation of iron ore. The design included an earthen embankment to be constructed using mine waste within the Daydream pit. The embankment was designed to retain tailings and allow drill and blast and Surface Miner Operations (SMO) downstream of the TSF. The area to be mined was approximately 180 m from the downstream toe of the embankment and the duration of mining was anticipated to be in the order of 3–4 months.

The anticipated post-mining pit floor shape was to slope from east to west, with the embankment to be located at the southeast margin of the pit in an east to west alignment. The embankment height would thus be 7 m at the eastern end and a maximum of 24 m at the western end.

The design was such that the downstream batter of the embankment, particularly the lower lifts, was to be constructed of coarse, relatively free draining mine waste to reduce the potential for a raised phreatic surface within it. It was proposed that the horizontal width of this layer should not be less than 20% of the total embankment width at the level where the materials were to be placed. Figure 1 illustrates the design embankment profile.

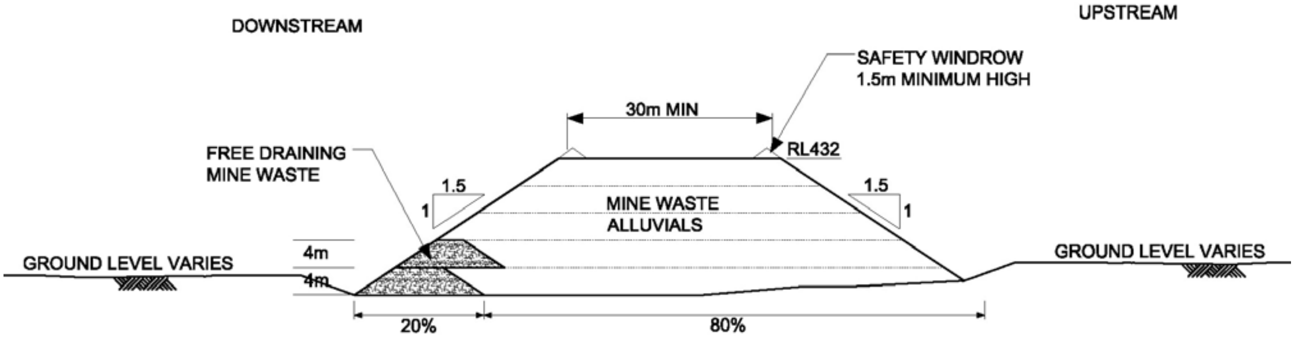

Figure 1 Design embankment profile

Construction work was to be undertaken by mine operations and the construction sequence was to comprise:

1. Paddock dumping of the waste over the full embankment width in each lift, including selective placement of free draining mine waste at the downstream toe.
2. A dozer was to flatten the tops of the paddock dumped stockpiles to provide a horizontal running surface for the placement of the next lift.
3. The haul trucks placing new mine waste were to traffic the full embankment width, with the exception of the outer 4 m on each lift.
4. Steps (1) to (3) were to be repeated until the embankment reached its full height.

The materials to be used in construction were intended to be coarser, free draining mine waste for the downstream toe region and finer grained mine waste comprising overburden material of mixed colluvial and alluvial origin for the bulk of the embankment fill.

The TSF design concept incorporated a tailings deposition plan that involved spigotting of tailings from the eastern end of the in-pit TSF, including from the embankment, and recovery of supernatant water from the western end of the pit. The tailings were to be pumped to the TSF as thickened slurry at approximately 60% solids and tailings beaches were to be developed from the eastern end. A ramp at the western end facilitated access to a proposed pontoon-mounted return water pump.

It should be noted that blasting and mining in close proximity to the toe of the embankment was not part of the original design intent.

2.2 Daydream in-pit TSF construction and operation

At the commencement of construction, the mined out pit floor was deeper than anticipated and the embankment was redesigned to have a maximum height of approximately 30 m at the eastern end, reducing in height towards the west. The shallowest section of the pit was near the middle, and tailings deposition had already commenced into the western end of the pit, with no water recovery. A temporary embankment was constructed midway across the pit to allow construction of the main embankment.

The design and construction of the Daydream in-pit TSF was significantly modified. The construction methodology adopted included building the embankment up in 1.5 to 2.0 m thick layers. These layers were moisture conditioned, and were traffic-compacted using dump trucks and supplemented with compaction using a padfoot roller. Due to operational constraints, departures from the design included:

- the rockfill blanket drain at the toe was constructed as designed, but was partially blocked by material that rilled down the batter slope during construction of the final embankment fill layers
- the final embankment geometry was slightly wider at the crest and with steeper slopes than originally designed. The as-built geometry included a crest approximately 32 m wide and an overall embankment height of 29 m, measured from the downstream side.

Embankment construction was delayed and progress was slow as the earthworks construction equipment and personnel were utilised for other work on site, including mining. In addition, the excavation and removal of iron ore in the footprint of the embankment delayed construction and increased the embankment height and fill volume requirements from the original design.

FMG completed construction of the 30 m high embankment at the southeast end of the Daydream in-pit TSF in June 2009 (Figure 2). Due to operational issues, the tailings slurry was delivered at lower % solids than planned and a significant amount of water was periodically flushed through the slurry pipeline.

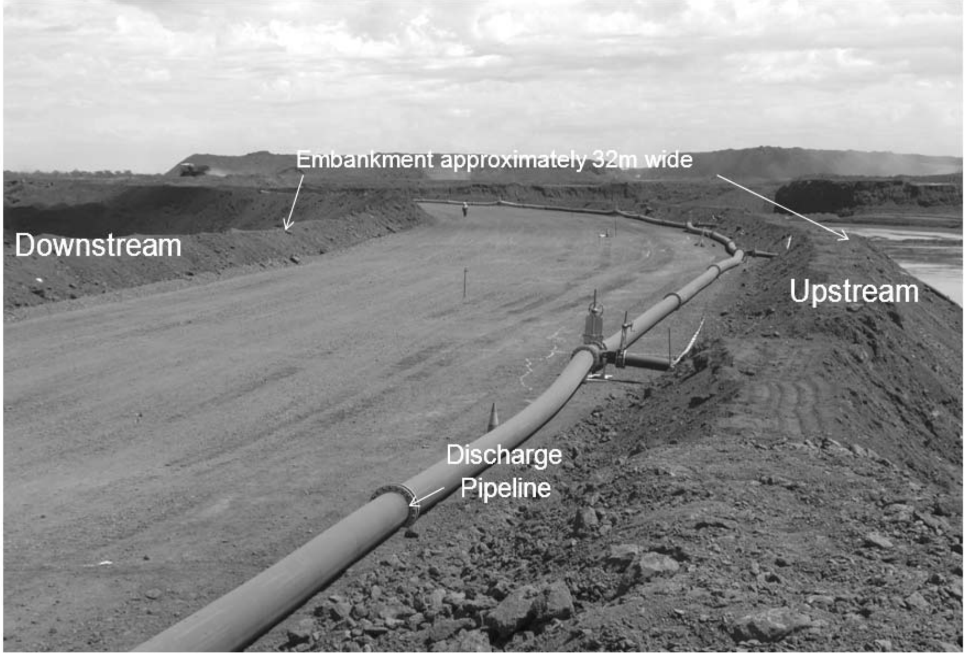

Figure 2 Photograph of as-built embankment at the Daydream in-pit TSF

The changes to the design, construction, and operational requirements were incremental over the course of the project and, taken together, resulted in a significant departure from the original concept. In particular, the change in tailings deposition position from the originally planned east end to the west end of the facility, resulted in water ponding against the constructed embankment during the operational phase. In addition, the relatively low % solids of the tailings slurry resulted in relatively flat tailings beach development, which impinged on FMG's ability to 'push' the supernatant pond from the embankment area.

Prior to mining downstream of the embankment, cracks were observed on the embankment crest. Several cracks were sub-parallel to the inside crest and up to approximately 40 mm wide, while others were transverse and extended partway across the embankment. Lesser arcuate cracking was evident from the upstream to downstream side of the embankment at its deepest section. Several measures to mitigate risks associated with the embankment stability were recommended by the design consultant and undertaken by FMG. The key measure to provide flexibility and safety to mining operations was the development of an integrated embankment monitoring system.

3 Daydream in-pit TSF embankment monitoring program design and installation

The monitoring system was designed to monitor slope deformation on the embankment to:

- Evaluate the need for on-going monitoring and assessment of existing cracks and inspection of embankment for evidence of seepage or slumping, particularly after blasting.
- Evaluate the need to review and/or modify the mining schedule, should embankment seepage or evidence of additional embankment distress be observed.
- Facilitate economic extraction of the remaining ore, as per the mine plan.

3.1 Monitoring program design

The monitoring system consisted of:

- Visual monitoring (inspection to identify for tension cracks etc.).
- Survey prisms (ATS).
- Crack extensometers.
- Borehole inclinometers.
- Vibrating wire piezometers (VWP).
- Slope stability radar (SSR).

The visual monitoring and radar can be regarded as 'blanket' monitoring techniques; that is, they are not directed at one particular target. The location of the radar itself is usually controlled more by operational factors (not obstructing moving plant) than geotechnical considerations, as there will usually be a number of suitable locations where the radar can be placed so as to be facing the monitored slope at a suitable angle.

The survey prisms installed on the Daydream embankment were installed by FMG before the comprehensive monitoring system was developed. The assessment of prism monitoring data was integrated into the monitoring system.

The location of the crack extensometers was determined in this case by the existing cracks on the top of the Daydream embankment. Crack extensometers were installed on the cracks, which had been determined by visual observation to be the most active.

Three VWP sensors were installed at the base of the embankment at evenly spaced intervals.

Four inclinometers were installed through the embankment. The location of borehole inclinometers with respect to the expected failure surface is critical. It has been demonstrated on many occasions (e.g. Beer and Narendranathan, 2009) that without an understanding of the expected failure mechanism and the likely size of any possible failure, it is easy to install inclinometers in a location where they will provide no useful information or warning of impending failure. In the case of the Daydream embankment, experience, backed up by stability modelling, indicated that the most likely failure surface lies relatively close to the downstream face of the embankment at its deepest section. The optimal location for the inclinometers was determined to be as close as practicable (from an installation viewpoint) to the downstream edge of the top of the embankment. Figure 3 shows the as-built embankment geometry and chosen instrumentation locations.

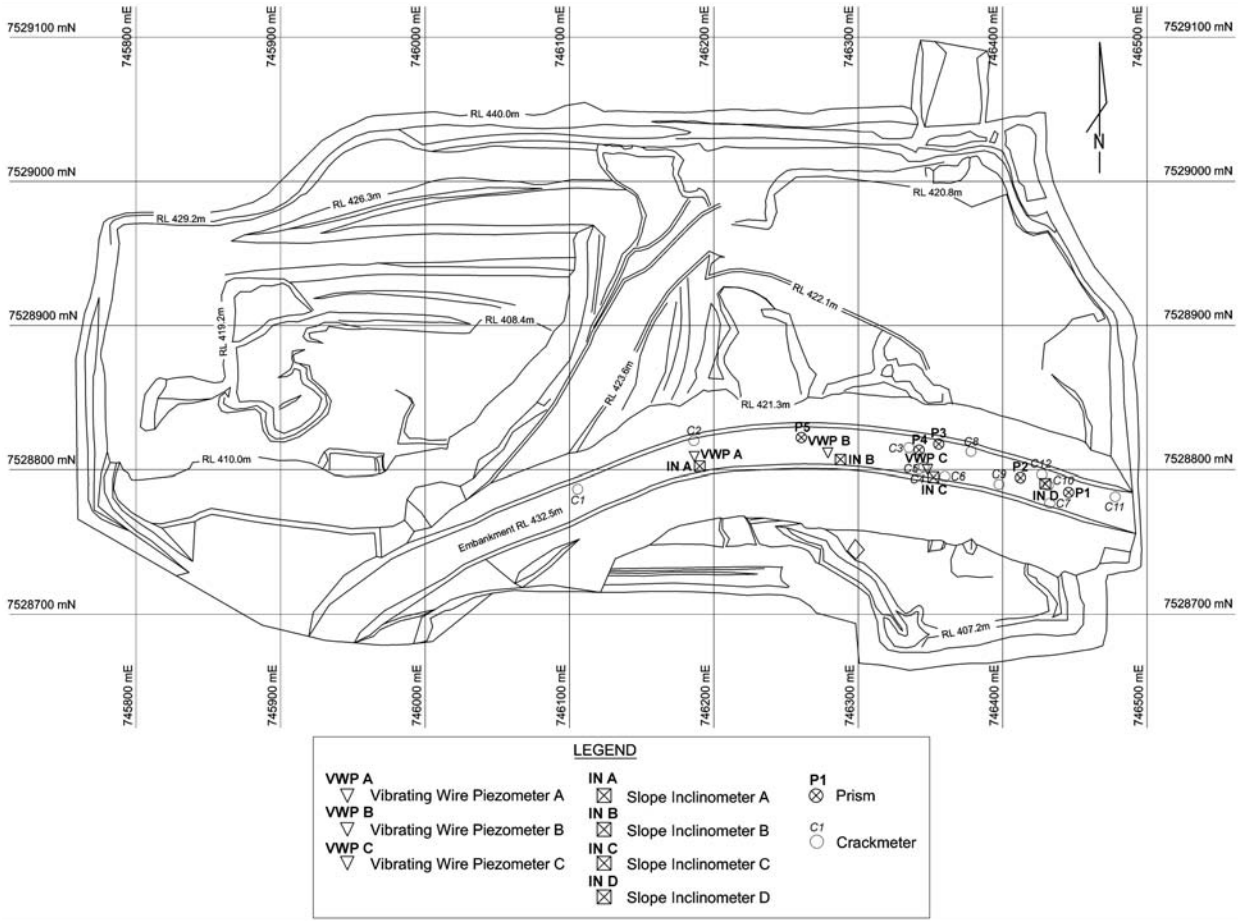

Figure 3 Instrumentation layout at the Daydream in-pit TSF embankment

3.2 Embankment stability model review

The embankment slope stability model from the concept design stage was updated in accordance with the as-built construction details. The updated model was used in the development of the instrumentation design. The Newmark (Newmark, 1965) analysis was used to assess the as-built stability scenario. The Newmark analysis puts forward a methodology that can assess slope deformation for deterministic models.

3.3 Instrument installation

A risk assessment was undertaken to address issues associated with the access of drilling equipment onto the embankment for the installation of instrumentation. An evacuation and rescue plan was developed using the results of this risk assessment.

The readouts for the VWPs and the crack extensometers were installed on the east abutment of the embankment to permit safe access under worst case conditions.

Once the instrumentation was installed, a second risk assessment was undertaken to address all issues associated with working downstream of the Daydream In-pit TSF embankment. The conclusions of this risk assessment and the subsequent mitigation measures were communicated to all personnel that would be working in the vicinity of the embankment.

3.4 Telemetry and alarms

The radar, crack extensometers and VWPs monitoring the Daydream embankment were all suitable for connection to an automatic alarm system, due to the nature of the information being collected and the use of data telemetry. In the case of the Daydream embankment, only the radar and the crack extensometers were actually configured to trigger alarms. Examination of the VWP data indicated a tendency to respond to water levels in the tailings pond behind the embankment, rather than respond to the rainfall events. Given that VWP response to water level changes and rainfall events was also gradual in nature, it was considered that setting alarm triggers on VWP data values was not as critical as utilising the radar and crackmeter data. However, the VWPs were triggered to alarm if the phreatic surface rose more than 0.1 m.

The alarm settings were established based on the embankment slope stability model. To effectively set alarm thresholds for the monitoring equipment, it was important to quantify the as-built stability, material parameters etc for the embankment. As the initial model was done deterministically (using Limit Equilibrium techniques), this proved somewhat challenging due to; as a result of the wide variability of parameters within the embankment, i.e. degree of compaction, material types and phreatic surface.

3.5 Model calibration

The Newmark analysis was used to assess the as-built factor of safety (FOS) of the embankment. In essence, the Newmark Analysis provides a methodology that correlates the magnitude of slope deformation to the peak particle velocity induced as a result of mining induced vibrations from blasting, and back calculating the intrinsic factor of safety.

The first blast that was undertaken, post embankment construction, was on 24 November 2009. The vibration resulting from this blast was detected by the various monitoring instruments that were installed on, and within, the embankment. It should be noted that the initial blast was used to perform the ‘first pass’ model calibration, subsequent blasts were used to refine the model.

The resulting maximum deformation, as depicted in Figure 4 was recorded from Inclinometer A, which showed approximately 2.0 mm of displacement occurring as a result of the blast, which registered a PPV of 19.5 mm/s.

It should be noted that this displacement occurred over a period of five days and could be considered, for the purposes of the Newmark analysis, to be creep, i.e. the embankment showed a ‘delayed’ response, that was induced by the blast.

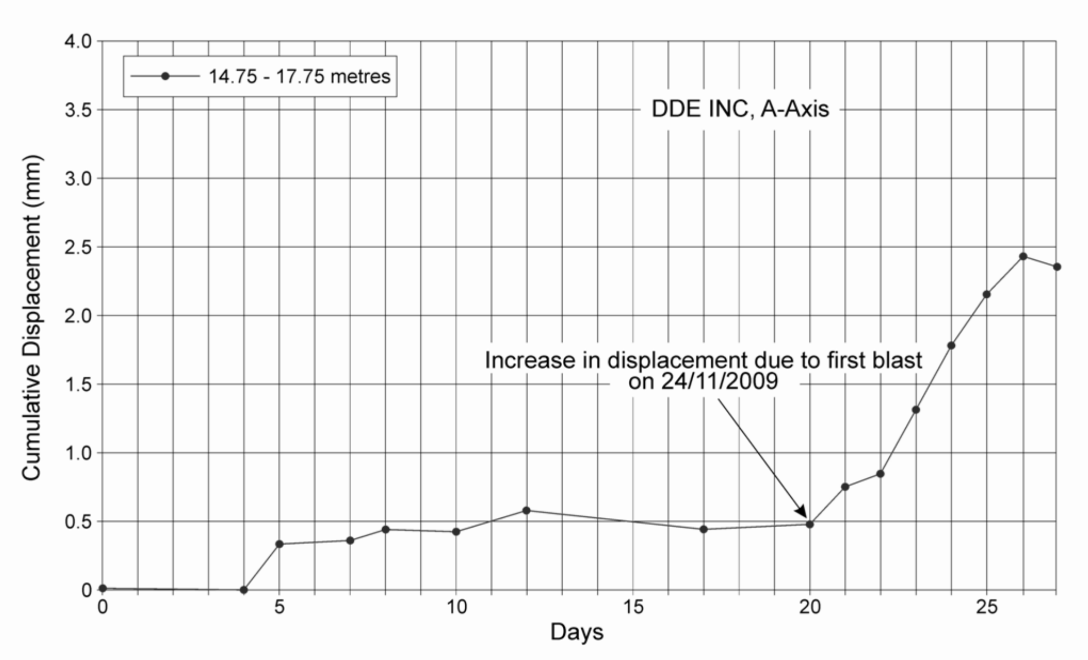

Figure 4 Inclinometer A displacement measurements showing blasting related deformation

3.5.1 Critical acceleration

Based on the measured magnitude of deformation of 2.0 mm (Dn), the critical acceleration for the embankment can be back calculated thus, after Newmark (1965):

$$ppv^2 / Dn = 2a_c \tag{1}$$

where:

Dn = is the total slope displacement.

ppv = is the peak particle velocity.

Hence, a_c = 95 mm/s^2.

3.5.2 As-built FOS

The as-built FOS can be back calculated thus, after Newmark (1965):

$$FS = \{(a_c / \sin\beta) / g\} + 1 \tag{2}$$

Where:

a_c = critical acceleration in metres per second squared (m/s^2).

FS = static FOS.

Hence, FS ~1.0.

Please note: This calculated factor of safety was based on the maximum recorded deformation from inclinometer A, it was conservatively assumed that this applied ubiquitously to the entire embankment.

3.6 Monitoring frequency

The following tasks were completed on a daily basis by the onsite geotechnical engineer at the Daydream in-pit TSF embankment:

- Visual inspection of the embankment for any changes, particularly in those areas not covered by monitoring instrumentation.
- Inclinometer surveys of two of the four functioning inclinometer installations. This results in each of the installations being read every second day.
- Downloading of crackmeter and VWP data from the embankment data-logger.
- Review of radar data for the preceding 24 hour period.

The results of the monitoring were submitted to the FMG mine manager in the form of a daily report. This report also commented on the observed response of the embankment (if any) to events such as blasting adjacent to the embankment, or rainfall events.

The FMG mine manager communicated the salient information, if any, at the pre-shift handover meetings. Typical communications would inform of any issues such as alarms triggered and resulting access restrictions.

On a weekly basis, a detailed monitoring report was produced. This summarised the overall trends observed over the preceding week and included graphical representations of the monitoring results. Interpretation of the results was also undertaken on a weekly basis by the site geotechnical engineer. The interpretation attempted to link observations from the different monitoring techniques to events which may have affected the embankment, and explain the observations in a way that provided guidance to the mine management.

At the weekly monitoring report level, ongoing trends in monitoring data was assessed and, if there were any warning signs of developing instability, these would be discussed in the report and recommendations for continuing to work safely would be made. The appropriateness of the alarm levels for the SSR, the crackmeters and the VWPs were also re-assessed on a weekly basis.

4 Interface with mining operations

Monitoring results were communicated to mining operations through a combination of alarms and monitoring reports as follows.

4.1 Alarms

The radar, crack extensometers and VWPs monitoring the Daydream embankment are all suitable for connection to an alarm system, due to the nature of the information being collected and the data telemetry already described. In the case of the Daydream embankment, only the radar and the crack extensometers were actually configured to trigger alarms. Examination of the VWP data indicated a tendency to respond to water levels in the tailings pond behind the embankment, rather than respond to the rainfall events which experience had indicated had a causal connection with slope movements. Given that VWP response to water level changes and rainfall events was also gradual in nature, it was considered that setting alarm triggers on VWP data values would not be as meaningful as utilising the radar and crackmeter data.

4.1.1 Radar

Six different categories of alarm are generated by the radar: red, orange, yellow, grey, green and blue. Of these, only the red and orange alarms are triggered by slope movement; the others are triggered by problems either with the radar computer or data telemetry systems. The yellow, green and grey alarms effectively indicate that real-time monitoring of the slope is no longer occurring. The blue alarm indicates a malfunction, but the radar continues to operate, and orange and red alarms may still be triggered in this case. The alarm is generated by a computer situated in the office, which gives an audible signal. The computer can also be configured to display a message corresponding to each alarm, informing Dispatch as to who to contact and what actions should be undertaken in response to the alarm. The red and orange alarms are considered to be the most serious, as they are triggered by real or apparent slope movements. These were initially set to trigger when movements exceeded 5 and 3 mm respectively over five hours. These initial threshold levels were assigned based on prior experience at other mine sites with similar slope stability issues.

False alarms occurred during episodes of high winds and rains, which caused localised rilling. To accommodate such events without triggering an alarm the threshold levels were reset to 20 and 15 mm over a five hour period.

So that personnel were aware of the correct response to each type of radar alarm, a ‘Daydream Embankment Monitoring Radar Alarm Procedure’ was distributed to all personnel working in the Daydream embankment area. This procedure defined the mandated actions subsequent to the triggering of the SSR alarms. Each category of alarm is associated with a different action; the red to grey alarms initiating immediate evacuation of all personnel from the area in the immediate vicinity of the embankment. The level of response required was communicated by UHF radio from FMG dispatch to all site personnel.

4.1.2 Crack extensometers

Data are recorded from each crack extensometer every two hours and recorded on the installed datalogger. If a threshold value for recorded movement is exceeded, then an alarm is sent in the form of an SMS text message from a modem connected to the datalogger to a nominated recipient list. The text message lists the identity of the crackmeters whose movements have exceeded the threshold. The threshold levels, to trigger an alarm, have been set at 10 mm on the upstream, and 5 mm on the downstream over a 24 hour period. The nominated recipients include mine dispatch and the site geotechnical engineer. In the event of an alarm being received, the site geotechnical engineer would inspect the embankment and attempt to cross-reference the reported movements with those recorded by the SSR. If the movements were consistently recorded by both systems, the procedure for the relevant radar alarm is followed.

Additionally, the modem returns a status SMS report at 06:15 every morning listing the absolute values of crackmeter movements.

An example of the type of information transmitted in a Weekly Report is the Weekly Report issued on 30 December 2009.

4.2 Weekly report for 30 December

A heavy rainfall event occurred during this week resulting in 24 mm of rainfall over a five hour period. The instrument responses were reported as follows.

4.2.1 Slope stability radar (SSR)

An area of the embankment crest, to the east, showed an increased rate of movement in comparison to the remainder of the slope. This movement was due to the development of a local rainwater erosion gully, and associated sloughing, related to the rainfall event. The radar displacement graph from 21/12/09 to 29/12/09 is shown on Figure 5. The radar screen capture from 21/12/09 to 29/12/09 is shown on Figure 6.

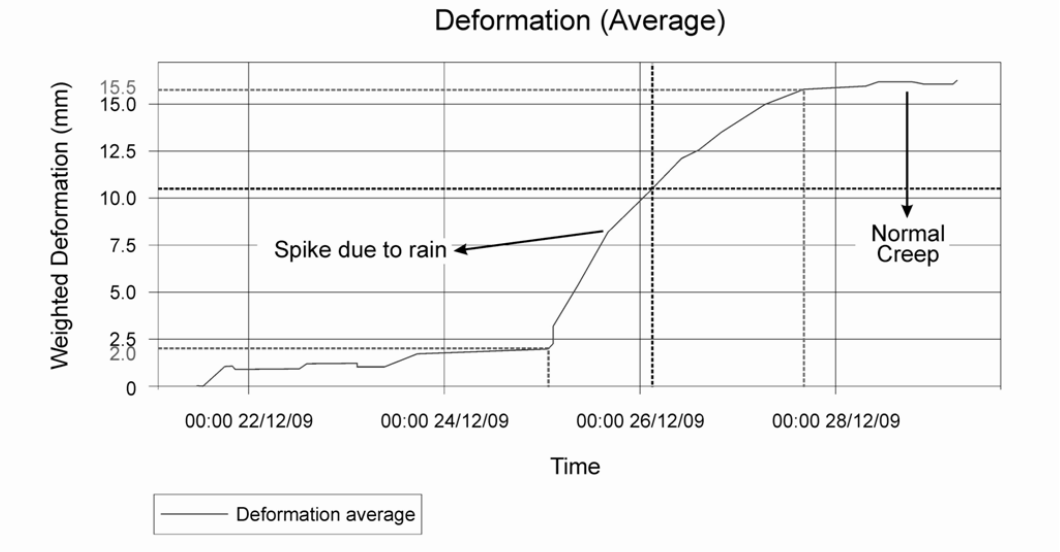

Figure 5 Slope stability radar displacement plot

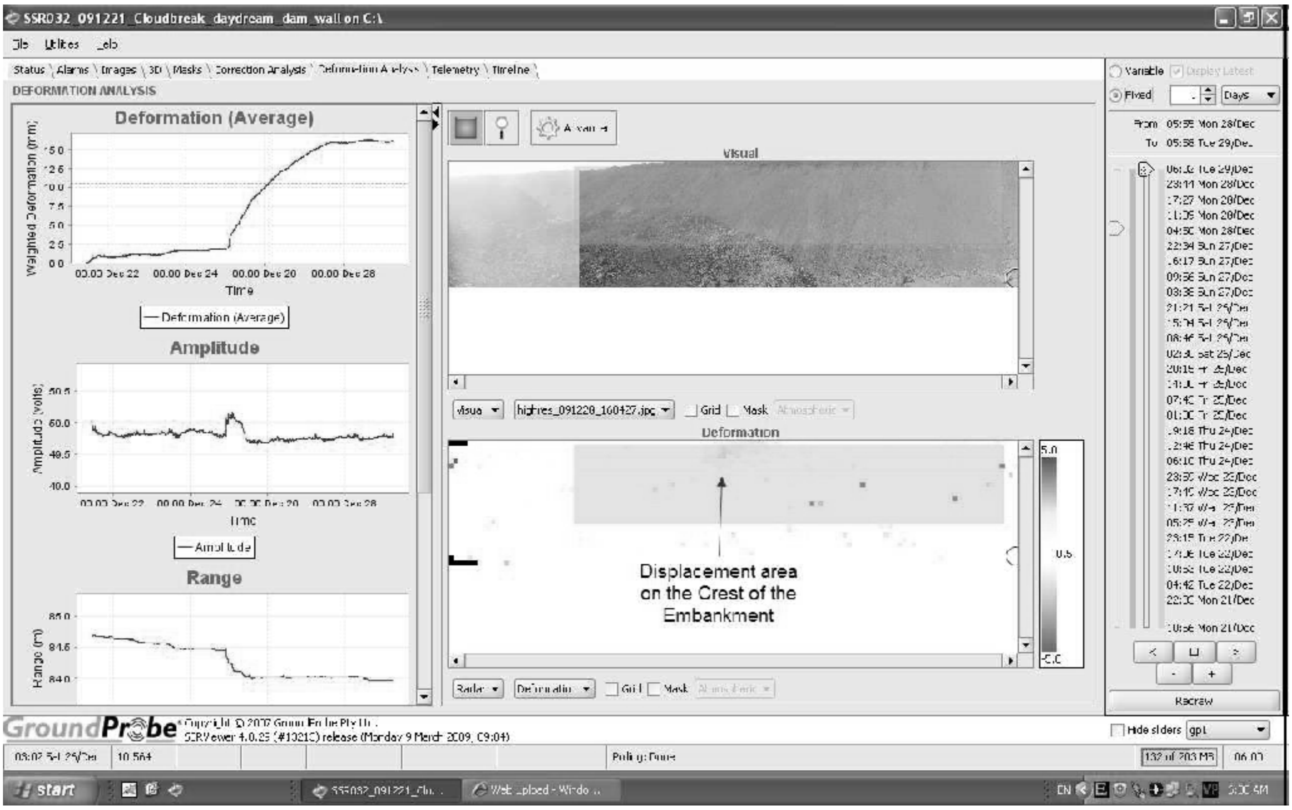

Figure 6 Radar screen capture from 21/12/09 to 29/12/09

4.2.2 Inclinometers

As the result of the rainfall event, the probe could not pass beyond 14 m downhole depth within inclinometer C. It was assessed that the deluge of water had caused a local collapse within a localised zone at the borehole. No changes in displacement were noted in other inclinometers.

4.2.3 Vibrating wire piezometers (VWP)

VWP A reacted in response to discharge of tailings and ponding of water next to the embankment in the week preceding the rainfall event (Figure 7). Even so, the plot shows that the rainfall event resulted in a phreatic peak occurring on 25 December. This is particularly significant as instrument reaction, as well as modelling exercises, have indicated that the embankment stability was particularly sensitive to variations in phreatic surface.

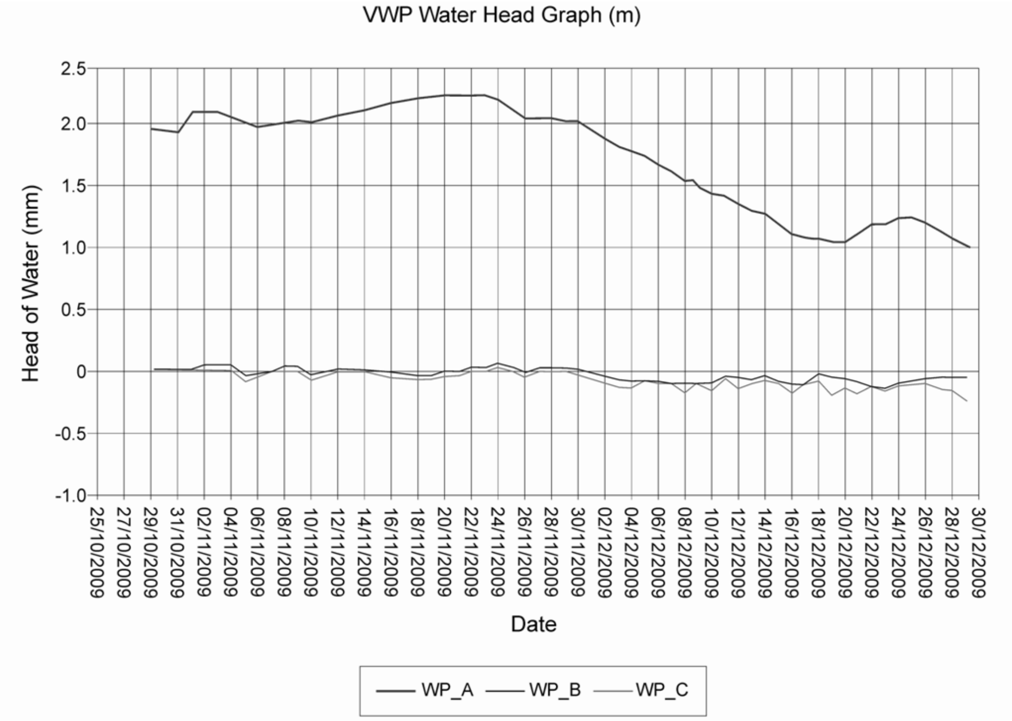

Figure 7 Vibrating wire piezometer results

4.2.4 Outcomes arising from monitoring results

The slope movements and increase in pore pressure at VWP-A had already been reported in the relevant daily report for 25 December. As a result of these noted increases, mining activity was suspended below the embankment. The radar and VWP data were closely monitored over the following few days until the radar plot indicated that movement had ceased and the VWP plot showed pore pressure levels were returning to their pre-rainfall event levels. Mining activity was re-commenced on night shift on 27 December, when the radar indicated that movement had ceased. This response was documented in the 30 December weekly report.

5 Summary and conclusions

The flexibility of the Daydream in-pit TSF design, construction and operating concept was tested by FMG's fast tracked mining program at the Cloudbreak Iron Ore Mine and modifications to the mine plan that resulted in changed design criteria. An embankment slope monitoring program was developed to assess provide feedback to mining operations personnel to ensure safe working conditions. The level of monitoring and development of an effective communications procedure meant that interruptions to mining were minimised and mine production rates maintained.

The monitoring data indicated that generally the slope was stable, except for limited movement during periods when the phreatic surface was elevated.

To date the embankment continues to be stable and monitoring has not indicated any further movements or changes in water pressure since the case described in Section 4.

Acknowledgements

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