Thank you for the hard work put into the review and consultations. I am in agreement with most of the work in the draft standard and believe the section on monitoring can be expanded.

I attach a peer reviewed paper I wrote on more accurate monitoring that you are welcome to refer to or attach to the standard.

Many tailings dams are monitored for movement. This type of monitoring does not prevent failure. It is more important to measure the cause of failure – in particular the weight of water in the slopes and in ponds. Each tailings dam is unique and requires a bespoke monitoring network with recognised triggers and set targets. Then mitigation and preventative measures can be implemented. This is applicable to dams under construction and those under care and maintenance.

I am happy to contribute more if you are interested.

The South African government has not participated in the proceedings because of the timing of the Johannesburg consultation and deadline. South Africa combines Christmas and summer holidays and there is very little response from government between December 10$^{th}$ and January 6$^{th}$. If you are sincere about involving South African regulators then I recommend they are given an extension to comment until the end of February. As South Africa has over 100 years of mining exposure and over 1000 tailings dam, many above poor communities I strongly recommened they are included in the review. Please let me know if you need help in contacting the relevant bodies.

# Tailings dam risk reduction using accurate pore pressure monitoring

**Dr Kym L Morton**

**KLM Consulting services Pty Ltd**

(Corresponding author kmorton@klmcs.co.za)

South African Institute of Mining and Metallurgy, Tailings Storage Conference 10-13th February 2020 Johannesburg South Africa

**Abstract**

The January 2019 Brumadinho tailings dam failure in Brazil which killed over 250 people has created worldwide focus on what can be done to reduce tailings dam failures. South Africa has had its own tailings dam failures; notably the Merriespruit failure in Virginia in 1994, where 17 people were killed and many houses destroyed.

Modern techniques for tailings dam monitoring emphasise the measurement of movement of the slopes using radar, LIDAR and prisms; however these techniques only measure the reaction of slopes to instability factors and do not address the causes or assist with reducing risk.

The biggest preventable cause of slope failure is too much water, either in the pond or from the weight (measured as pressure) of water in the tailings slope faces. Pore pressure monitoring is an accurate method to measure the weight of water in a slope and enables early intervention to delay or prevent failure. Pore pressure monitoring methodology and techniques are described with recommendations on a standardised but bespoke monitoring network for each high risk tailings dam.

The mechanisms of failure are discussed and the best practice for monitoring required to predict failure is presented. Open pit slope stability techniques can be used to manage dam wall stability. The success of accurate monitoring design depends on the location, construction and management strategy for a tailings storage facility (TSF). Different monitoring networks are required depending on the type of dam and the impact of the catchment on its water balance.

Pore pressure monitoring is proposed as an effective method to predict instability as it addresses the cause of the potential failure. Big Data techniques are now available to manage multi-point monitoring sites and telemetry can transmit real-time information which can then be depicted in a dashboard to present knowledge and identify risk. This can be used to prevent failures and act as early warning systems for those that cannot be prevented. An example of a monitoring network, installation and reporting is given including recommendations for implementation and transmission of real-time information linked to action.

## Introduction

The January 2019 Brumadinho tailings dam failure in Brazil, which killed over 250 people, has created worldwide focus on what can be done to reduce tailings dam failures. South Africa has had its own tailings dam failures notably the Merriespruit failure in Virginia in 1994 where 17 people were killed, and many houses destroyed. The main cause of failure is excess water in the wrong place. Addressing the water distribution and removing the water pressure will prevent failures.

Once the slopes of a tailings dam have been established, either during the building of an early section of the completion of a final lift , the only factor that can be controlled to reduce the risk of failure is the weight (measured as pressure) of water in the slopes of the tailings dams.

Causes of tailings dam failures include over-topping, seepage, extreme weather, slope instability and seismic events (Azam and Li 2010). All these causes are driven by excess water in the wrong place. The main preventable cause of tailings dam failure is slope instability (Cenderelli 2000). The presence of water within the tailings dam slopes reduces the stability of the slopes of the tailings dam by modifying the shear stresses on the potential failure surfaces.

Modern techniques for tailings dam monitoring emphasise the measurement of movement of the slopes using radar, LIDAR and prisms; however these techniques only measure the reaction of slopes to instability factors and do not address the causes or assist with reducing risk.

Water pressure in a slope can be measured by recording pore pressures at specific locations within the dam slopes. This paper describes the distribution of pore pressures within a typical tailings dam slope and gives a recommended methodology for measurement and control of pore pressures within the dam slopes at risk of failure.

**Typical tailings dam construction**

The main types of tailings dams are classified by either the method of construction or purpose:

1. Upstream construction

2. Downstream construction

3. Centreline construction

4. Water retention.

Figure 1 shows the upstream, downstream and centre line methods of construction.

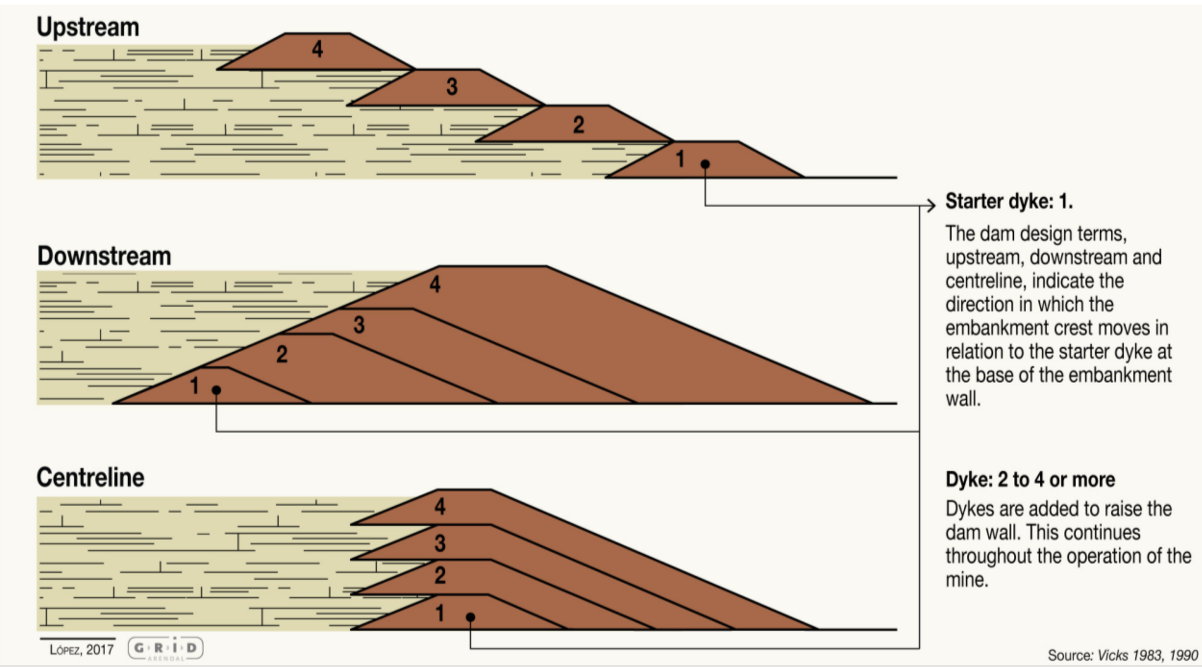


**Figure 1 Types of tailings dams construction using sequential raising (Vicks 1983)**

The dam slopes are constructed of a combination of the tailings material and other coarser materials for construction.

Figure 2 shows the near construction of a tailings dam nearing completion

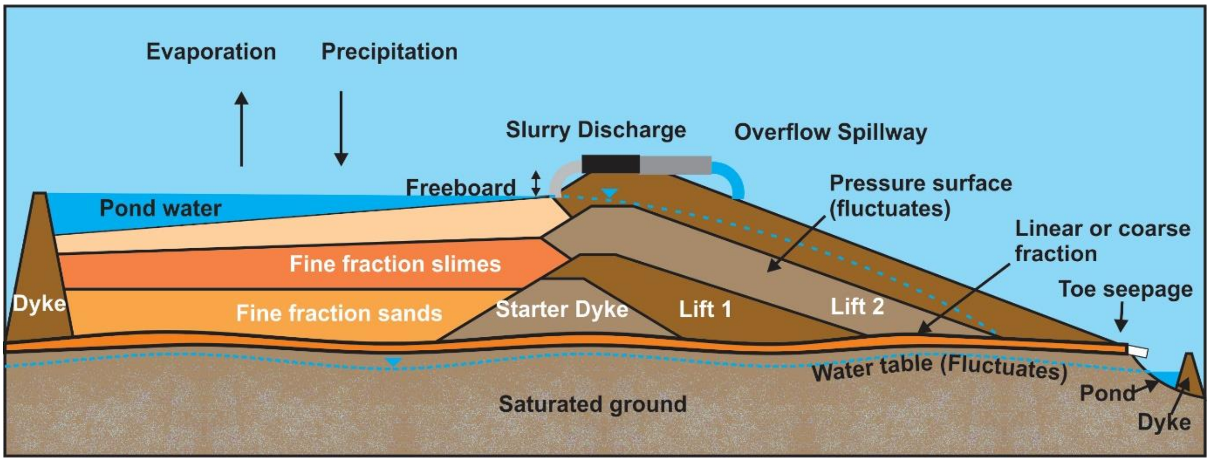


**Figure 2 Final construction of a tailings dam (Adapted from GARD http://www.gardguide.com)**

The figure illustrates the pond in the centre of the tailings dam and the pressure surface of the seepage face within the tailings dam wall. There is also an additional pressure surface under the dam created by the groundwater below the dam.

Older tailings dams were often constructed by depositing tailings into depressions or into riverbeds, they therefore can have weak unstable foundations with no lining and therefore hydraulic connection to underlying aquifers. The base of the tailings dam can often be recharged from buried streams fed from upstream runoff.

Figure 3 illustrates a tailings dam sited in a valley.

**Figure 3 Cross valley tailings impoundment at Highland Valley Copper, BC, Canada (Courtesy of Teck)**

Figure 4 shows the surface and groundwater distribution around a schematic tailings dam . It illustrates the U shaped path groundwater follows beneath the tailings dam and that the tailings dam water regime is connected to the catchment's water regime.  This means the monitoring of water pressures in and around a tailings dam needs to be designed specifically for the dam and the valley within which it sits.

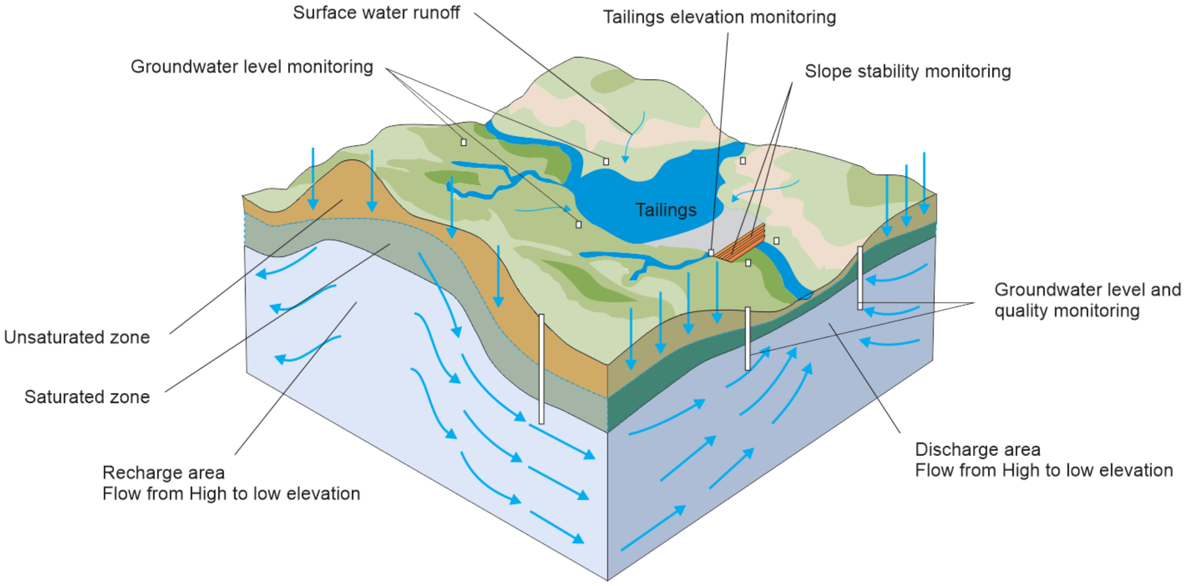


**Figure 4 The schematic diagram for a tailings dam with safety monitoring**

Tailings dams can also be re-opened and new dams built on old.  Over hundreds of years of mine tailings dam construction  each is unique and requires bespoke monitoring based on its location, climate and construction.  Accurate pore pressure monitoring can be used to measure the stability of each slope and each section of slope of the tailings dam.

**Pore pressures and effective stress**

Failure in a slope, known as volume deformation, will present (under various pressures and stresses) as three possible scenaria:

1. Compression of water in the pores of the material
2. Compression of individual particles (sediments etc)
3. Re-arrangement of particles, usually to a more compact configuration.

As described in Morton et al 2008, the stress state for any point in a slope is governed by the principal stresses and the acting water pressure (measured as pore pressure). Figure 5 shows the directions of stress acting on a hypothetical plane within a saturated medium.

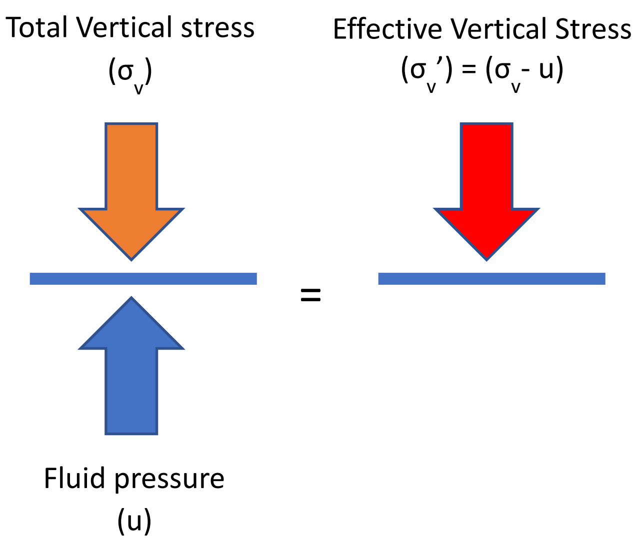


**Figure 5 Directions of stress acting on a hypothetical plane**

The primary effect of groundwater pressures is through effective stress. Rearrangement of particles (aka failure of the slope) is caused by changes in the effective stress. The stress state at any given point and any time is governed by the principal stresses and acting pore pressure. The Mohr-Coulomb Equation, derived from the Coulomb -Terzaghi Equation states:

$$\tau = c + (\sigma - p)tan\emptyset$$

Where

$\tau$ = shear strength

$\sigma$ = total normal stress

$p$ = pore water pressure

$\emptyset$ = internal angle of friction

$c$ = cohesion

Strength, and therefore stability of the slope, comes from the cohesion and the weight (the operational shear strength) of the materials making up the slope. Weakness comes from the pore water pressures and internal (operational) angle of friction. Any reduction in the effective stress (σ = σ -*p*) will reduce the shear strength of the slope material . Decrease in the effective stress strengthens drainage, therefore for stability analysis it is essential to know the distribution of pore pressures in the slopes.

Once pore pressures are plotted as lines of equal head (*h*), known as equipotentials, the pressure gradient of the slope will be like figure 6

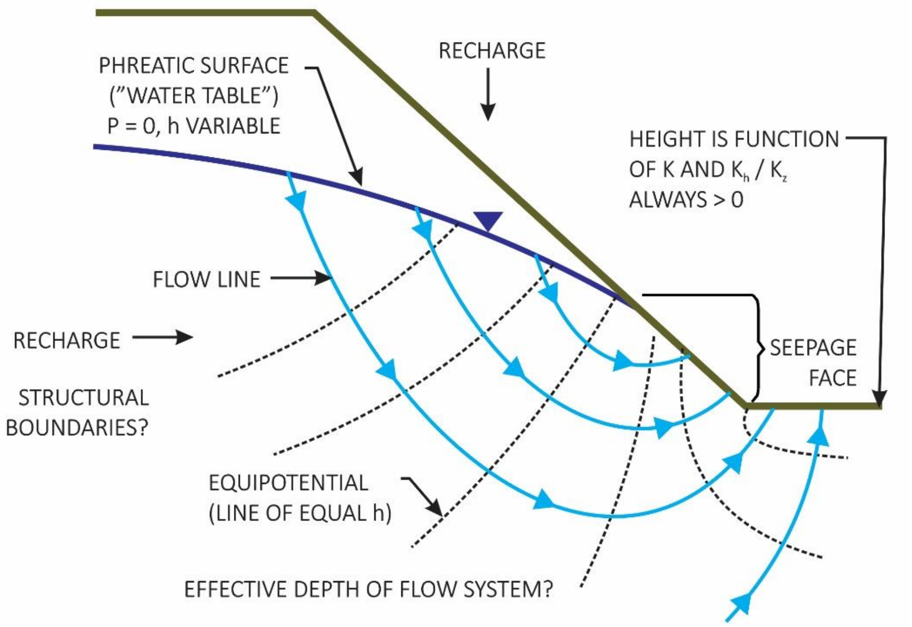


**Figure 6 Distribution of pressure gradients within a slope of a tailings dam (Adapted Morton et al 2008).**

The figure shows the flow lines are orthogonal to the equipotentials plotted from the pressure readings for a hydraulically isotropic slope. In real life most slopes are not isotropic, and the pattern is usually very distorted – making it even more relevant to measure pore pressures in-situ. Measured pore pressure distribution can be used to accurately model the stability of the slope and establish the optimum phreatic surface for the dam wall.

The pore pressures monitoring data and interpretation can also be used to set targets for maximum allowable pressures so that real time monitoring can provide an early warning system of slope instability. The slope instability can then be reversed through drainage or pumping of the water from the slope and pond.

**Measurement of pore pressures**

Pore pressures can be measured using pressure transducers, often of the sealed vibrating -wire point type piezometers grouted into coreholes drilled into critical sections of the slopes of the tailings dam retaining walls.

Figure 7 shows a typical pressure transducer of the vibrating wire piezometer type.


**Figure 7 example of a vibrating wire piezometer prior to insertion (Geokon)**

Nested piezometers can be used to plot pore pressure distribution in three dimensions.  The location and construction of the nested piezometers depends on the construction and size of the slopes, but generally three rows of three nested piezometers are a best practice design for the slopes of most  tailings dams.  Figure 8 shows a wireless transmitter that is used to transmit the data to a central dashboard.


**Figure 8 Wireless transmitter sim card installation (Solinst)**

The borehole diameter depends  on the type of piezometer being constructed. The drilled diameter needs to be large enough to accommodate the gravel pack, seal and tremie pipe used to feed in the sealant during  installation.  Piezometers can be installed in angled holes, preferably sub- horizontal when installed from the face of the monitored slope. The head measurement represents the vertical hydraulic head at the measuring point.  The cables transmitting the pressure readings are connected at surface to a data logger or sim card for either regular download of data or sending measurements in real time to a central visualisation on a dashboard.

For monitoring the water pressures around and underneath the tailings dam  grouted-in piezometers can be used in vertical or angled boreholes . Figure 9 shows a design for nested grouted-in pressure transducers in a sub horizontal corehole. (Read and Stacey 2009).

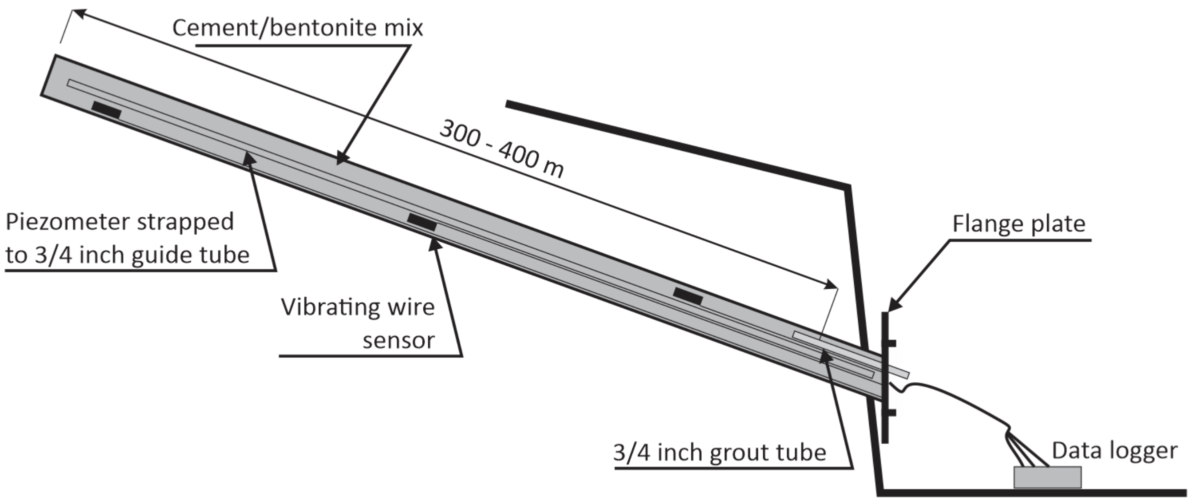


**Figure 9 Nested grouted-in pressure transducers in a Sub -horizontal core hole (Read and Stacey 2009**)

Figure 10 shows the installation design for vertical boreholes using either one borehole or three.

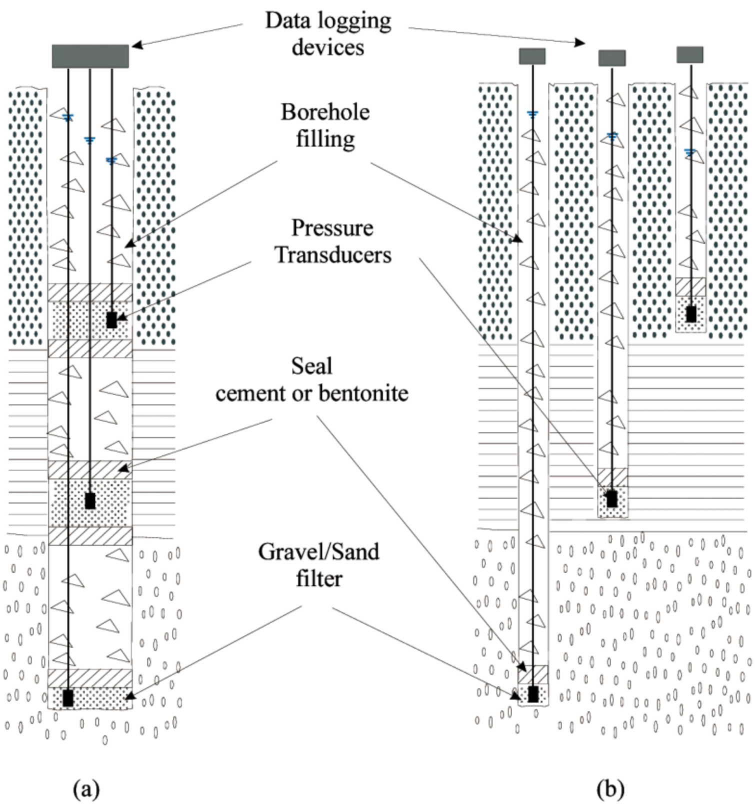


**Figure 10 Nested grouted-in pressure transducers (a) in one borehole and (b) in a cluster of boreholes (Morton et al 2008)**

**Design of a monitoring network layout**

The monitoring network design depends on the shape and construction of the tailings dam and its location within the overall water catchment that contributes to its water balance.

The water balance of a tailings dam is affected by the rainfall input to its pond and any surface runoff entering the dam foundations from upstream. The groundwater levels around, below and upstream impact on the water balance of the tailings dam therefore they also need to be monitored and managed to increase safety. Each dam is unique and therefore requires a bespoke monitoring network based on a full understanding of the water inputs , both surface and underground.

Figure 11 shows the layout of an accurate monitoring network around an individual tailings dam in plan.


**Figure 11 Tailings and upstream monitoring (adapted from Inmarsat)**

An accurately instrumented tailings dam will include monitoring of:

1. Rainfall
2. Pond levels
3. Upstream surface and groundwater flows and pressures
4. Downstream surface and groundwater flows and pressures
5. Pore pressure monitoring within all the tailings dam's slopes

This data is converted to information and then resultant plots of pressures can be used within dashboards to review the actual pressures compared to the required pressures. Trends that show increasing pressure can be used to implement pressure reduction actions such as drainage or pumping. Dashboards can then be shared to inform decision makers of increasing pressures which can then be reduced by increasing drainage of the unstable slope.

**Conclusion**

Accurate and well distributed pore pressure monitoring of a tailings dam is essential to the understanding of the main factor which controls tailings dam stability. Reducing pore pressures by drainage of pumping will increase safety and if implemented early will prevent failure. This method is more accurate and successful than the simple monitoring of slope movement. When a slope moves it is often too late to reverse the imminent failure, intervention by monitoring and then active management of water pressure can prevent failure before a catastrophic event.

**References**


Azam S Li Q 2010 Tailings Dam Failures: A Review of the Last One Hundred Years Geotechnical news, Canada

Cenderelli, D.A. (2000). Floods from natural and artificial dam failures. In: Wohl, Inland Flood Hazards: human, riparian, and aquatic communities (pp 73-103). New York: Cambridge University Press

Morton KL Muresan MC Ramsden F 2008 Importance of pore pressure monitoring in high walls. SAIMM conference on surface mining August 2008. SA ISSN 0038-223X/3.00 Jnl of the South African Institute of Mining and Metallurgy Volume 108 November 2008

Read J & Stacey P 2009 Guidelines for Open Pit Slope Design, CSIRO

Vick S 1983 Planning, design, and analysis of tailings dams (Wiley series in geotechnical engineering)

Vick S 1990 Planning, design, and analysis of tailings dams