Probabilistic dam break assessment and flow slide analysis for tailings storage facilities

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ABSTRACT

Dam breaks leading to a flow slide on the scale of Mt Polly, Los Frailes, Merriespruit and Stava have been shown to have multiple root causes that combined as a chain of faults and events that led to failure. These failures all experienced issues with regard to operation, management, construction quality, unrecognised foundation or materials behaviour as well as structural failure. When combined these issues had the effect of removing support to a mass of poorly consolidated tailings which underwent static liquefaction and flowed with disastrous consequences. While forensic investigation of the root causes of a dam break provides invaluable insight to failure development the key issue is how we can use the results of the investigation to analyse, track and ultimately stop, the progression towards a dam break and flow slide on a current operation. A fault-event analysis process provides a useful semi-quantitative probabilistic method for understanding the relative contributions of the root causes and the way in which they can combine to precipitate a failure. But it is also vital, when assessing the risks associated with a tailings storage facility, to work through the consequences of a dam break and flows slide. This requires simulation of the outflow rate of the tailings through the dam break over time and prediction of the lateral spread and distance of the outflow. The simulation also needs to bring into consideration the rheological properties of the flowing tailings and the uncertainty of these properties along with the uncertainty of other key parameters including the width of the breach and the volume of the material that liquefies and flows. This paper sets out through a worked example a probabilistic model for flow slide modelling that incorporates probability density functions for the main variables. When combined with the fault-event analysis the flow slide model enables the risk of flooding specific infrastructure, as well as the depth of flow, to be determined on a semi-quantitative probabilistic basis. It is demonstrated how, together with the fault-event analysis, the flow slide analysis enables the development of management protocols and infrastructure protection works that, if implemented properly, will ensure that the chain of faults that could lead to a dam break can be broken, and a flow slide prevented.

Keywords: Dam break, flow slide, tailings dam failure

INTRODUCTION

A semi-quantitative risk assessment and a probabilistic analysis approach been developed for tailings facility dam break and flow slide analysis. The approach applies three primary tools:

- Fault tree analysis
- Event tree analysis
- Probabilistic flow slide analysis

The above tools are described below.

Fault tree analysis

A Fault Tree Analysis which will enable probability to be propagated from day to day management and performance of the tailings dam to one of five flow-slide trigger faults which have been identified through assessment of past flow slide failures. These are:

- Static instability of the confining embankment. An example of this mode of failure is Los Frailes tailings storage facility (TSF) in 1998 in Spain
- Dynamic instability of the confining embankment. An example of this mode of failure is the El Cobre TSF in Chile in 1965
- Overtopping of the confining embankment. An example of this mode of failure the Merriespruit TSF failure of 1994 in South Africa
- Piping failure as a result of layering within the confining embankment. An example of this mode of failure is Bafokeng TSF in 1974 in South Africa.
- Failure of a delivery pipe or a buried drainage structure. An example of this mode of failure is Stava TSF in 1985 in Italy.

In developing the fault trees the chain of sub-faults that could precipitate a trigger fault is defined to a level where a management intervention could eliminate the fault at the first step of its development.

In assigning probabilities to the likely effectiveness of management intervention cognisance needs to be taken of the prevailing mine and mining economic climate as it has become clear that while flow slide failures occur on average every two years the scale and prevalence of these failures increases during times of enforced austerity during which resources applied to tailings operations are inevitably reduced and complacency sets in.

An example of a fault tree applicable to slope instability is indicated in Figure 1

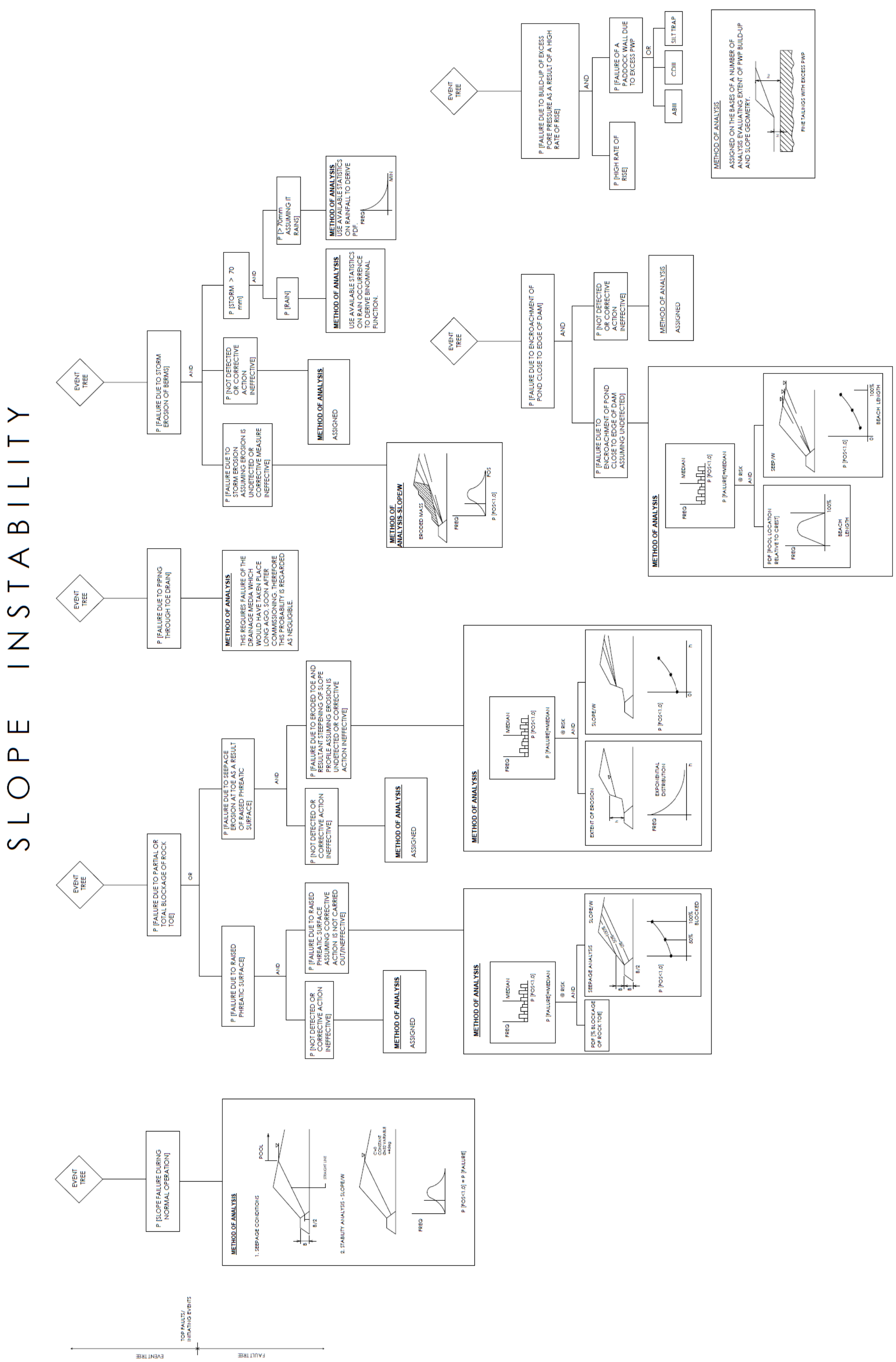

Figure 1: Example of a fault tree for the stability trigger mode of failure

Event tree analysis

An Event Tree Analysis which will enable probability to be propagated to establish the probabilities of environmental damage, loss of production and loss of life should a flow slide result from the dam break.

Event trees begin with the top fault and proceed with the assigning of probabilities associated with the following questions that define progressively developing events given a top fault:

- Does a slide ensue? Probabilities assigned to this event depend on the location of the flow slide and the nature (coarse or fine) and state (consolidated or unconsolidated) of the tailings likely to become unsupported as a result of the top fault.
- Are there people present at the failure or in the flow path? Probabilities assigned to this event depend on whether the paddock is operating and the flow direction and the infrastructure likely to be affected by the flow slide.
- Will there be a plant stoppage and therefore a production loss? Probabilities assigned to this event take into consideration whether vital infrastructure will be impacted by the flow slide and whether the flow slide affects an operational paddock.
- Mortalities? The probability for this event is generally taken as 0.3 on the basis that if there are people present in the flow path there is a 30% probability that they will be killed.

Flow slide analysis

The application of dam break analysis methods to tailings flow slides differs from dam break analyses applied to water dams in that it is necessary to consider the effect of the rheology of the flowing tailings mass on the flow characteristics. In 1980, in response to a request from Impala Platinum Limited, owners of the Bafokeng tailings dam which failed with a flow slide in 1974, Professor G E Blight, of the University of the Witwatersrand, developed a flow slide analysis approach that incorporates:

- The rheology of the tailings
- The fact that the tailings surface is not horizontal (he advocated it could be approximated with a parabolic shape)
- The influence of the topographic ground slope along the flow path of the flow slide.
- Newtonian laws.
- Continuity of flow.

The approach is set out by Blight et al (1981) and entails breaking the flow path into sections and solving the force-mass-deceleration between the sections. The paper presents a back analysis of the flow slide at Bafokeng.

The approach of Blight et al has been developed to generate a model that is probabilistic and to incorporates alternative modes of progressive development of the flow slide and from these determine the potential outflow “hydrographs”.

The objective in the modelling is to determine the average and 95th percentile residual spread and average and 95th percentile height of the flow mass once this becomes stationary and from this gauge the potential extent of influence and damage.

FLOW SLIDE ANALYSIS METHODOLOGY

The following aspects form the basis of the flow slide analysis methodology:

Newtonian principles

Figure 1 shows a free-body diagram through the flowing mass along the apex of the flow. Indicated are the ordinates, velocities, weights, centres of gravity etc. Newton's first law is used to calculate the downstream section dimensions from the upstream section dimensions beginning at the breach and working down the flow direction. Newton's second law is used to calculate the velocities and therefore the deceleration (or acceleration depending on the ground slope) from one section to the next. Due to the fact that this is the flow of a slurry as opposed to water the flow profile across the flow mass will not be horizontal. It is assumed that the flow profile across the flow slide can be approximated by a parabola of the equation:

$$z = Dy^2 + Ey + F \tag{1}$$

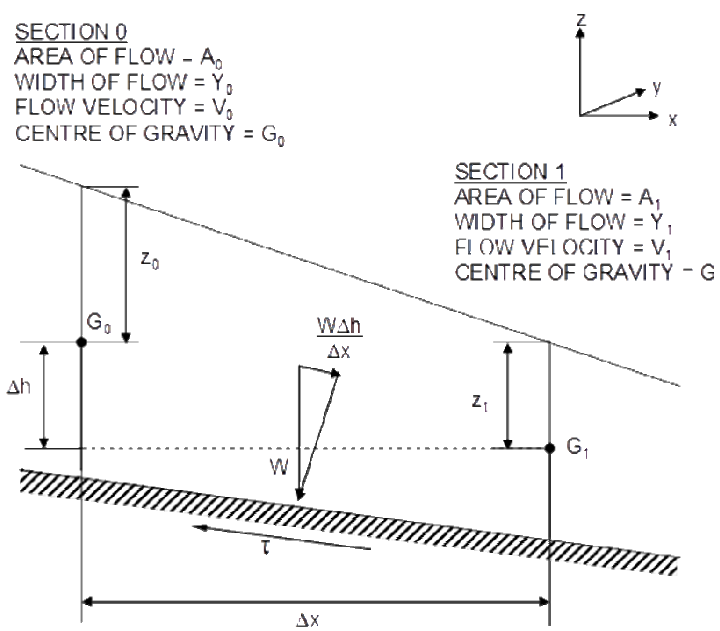

Figure 1: Free body diagram of the flow mass

Continuity

Continuity is maintained through the calculations and the end of the flow slide is determined when the volume in the flow slide equals the volume released by the TSF.

Rheology

It is assumed that the slurry is a Bingham slurry and therefore that it has a yield stress and the viscosity may be approximated linearly with shear rate.

Probabilistic approach

The following input parameters are required for the flow slide analysis:

- Volume of flow released by the TSF.
- Width of the breach
- Rheological parameters as defined by the Bingham yield stress and the Bingham viscosity.
- The curvature of the flow profile.
- Post liquefaction angle of friction of the tailings which determines the residual angle of the crater formed during the flow slide.

Without extensive testing analysis it is not feasible to establish deterministic values for the above parameters. In fact the amount of testing required is impractical given the potential dimensions of the crater. A more practical approach is to make use of probabilistic calculation methods to establish confidence limits. To this end the model has been set up in Excel and makes use of the probability density functions available in the Excel Add-in @Risk. Over two hundred Monte Carlo simulations are applied per run in the course of which values are randomly selected with appropriate correlation coefficients from probability density functions assigned to the parameters and the flow slide solved. In line with least bias theory uniform distributions have been assigned to the parameters. A uniform distribution requires input of a minimum and a maximum value for the parameter to be modelled and operates on the assumption that any value between the minimum and the maximum has an equal probability of occurrence. The minimum and maximum for each parameter depends on the nature of the tailings and these are set for each section.

Outflow hydrograph

Observations of available data on past flow slide failures shows that the resulting crater could be approximated by a truncated cone such as illustrated in Figure 3. Progressive development of the crater determines the outflow hydrograph of the flow slide. The observations suggest that there are at least three potential modes by which the flow slide may develop once liquefaction has initiated. These are indicated in Figure 4. The outflow hydrographs for Modes 1 and 2 begin with low flows since the initial wedges are of lower volume that the final wedges so flow rates increase with time. Conversely, Mode 3 has the wedge with the largest mass developing first so the outflow is at a maximum at the start of the flow slide.

The failure mode that is likely to apply to a particular situation will depend on the characteristics of the liquefied tailings with shear strength, rheology and the amount of water involved in the flow slide being some of the key parameters. Since there is uncertainty as to precisely how these will influence the mode of failure all three are analysed and the worst case is taken forward in a study.

In the random generation process correlation coefficients have been incorporated between the parameters and the volume. If, for example, a volume towards the lower end of the volume range is generated this would imply that the material has a higher shear strength and higher rheology but also that the width is likely to be lower and the residual angle of the crater steeper. The reverse would apply for a volume towards the upper end of the range. These influences have been built into the model.

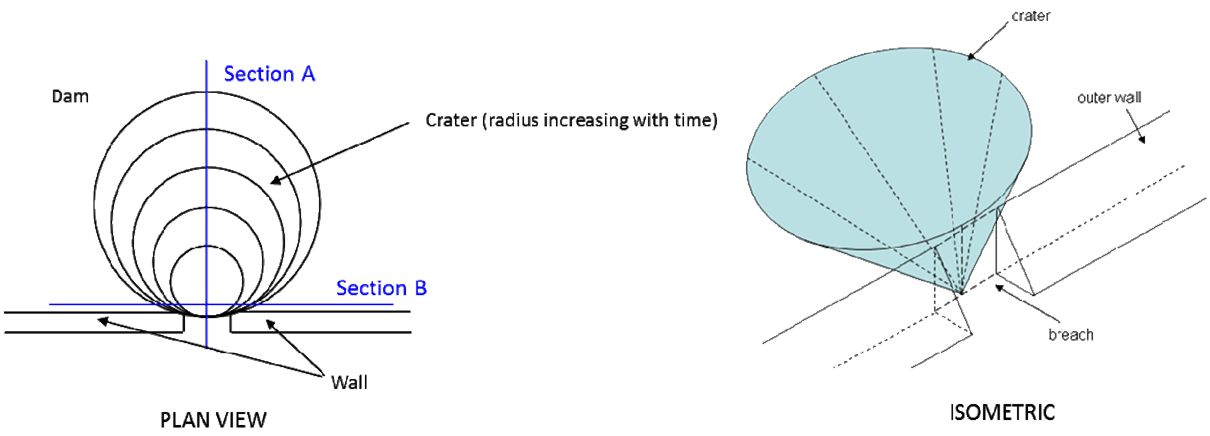

Figure 3: Plan and isometric of the potential crater based on a truncated cone

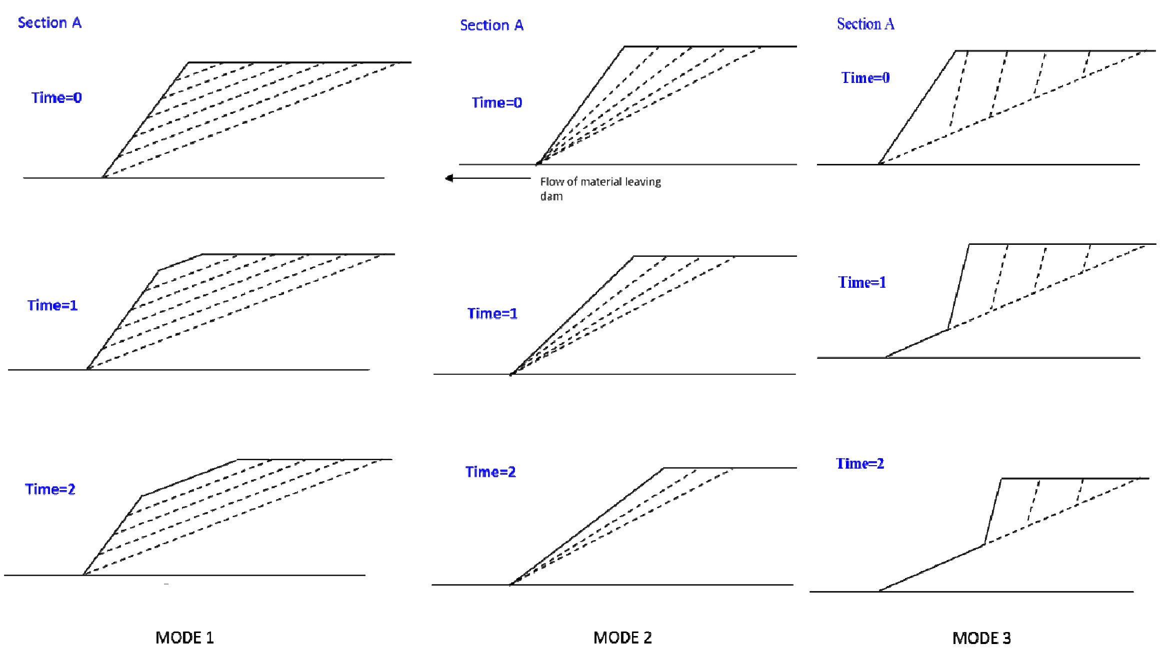

Figure 4: Three progressive failure modes

FLOW SLIDE FLOW PATH

The flow slide flow path will be determined by the topography of the ground down the flow direction with flow concentrating in the topographically lower parts of the cross section. Most often the flow direction can be estimated from contours of the topography below the flow slide. This simplifies the parabolic equation for the surface of the flow by eliminating the coefficient E in equation (1) yielding the following equation for the parabola:

$$z = Dy^2 + F \tag{2}$$

The D parameter determines the degree of curvature of the surface and the F parameter determines the elevation of the parabola along the centreline of flow.

BACK ANALYSES OF PAST FAILURES

The flow slide model has been applied to a number of flow slide failures to back calculate parameters and observe the extent to which the model is able to predict the spread and depths of the flow slide. Two are presented in this paper.

Bafokeng 1974

The flow slide failure at Bafokeng in 1974 resulted in the release of some 3 million cubic metres of fine tailings as a result of failure of the outer confining embankment through geotechnical piping failure. The flow slide emerged on the side of the TSF and immediately turned to follow the natural contours taking out the headgear and winding house of shaft adjacent to the TSF. Figure 5 shows the TSF the day before the failure and Figures 6 and 7 shows the failure and aftermath.

Figure 5: Bafokeng the day before the flow slide

Figure 6: Isometric photo immediately after the failure

Figure 7: Aerial photo immediately after the failure

The volume of flow, width of breach and residual slope of the crater were all known from aerial survey data. The D parameter and Bingham parameters were calibrated. The most representative mode of failure was found to be Mode 3.

The resulting output from the flow slide model is indicated in Figure 8.

Analyses were carried out for 20 sections although the results indicated that tailings would flow beyond the 20th section. In fact the tailings flowed some 40 km to the Vaalkop dam. The plan in Figure 7 shows the 25th percentile (cyan) and 75th percentile (orange) spreads

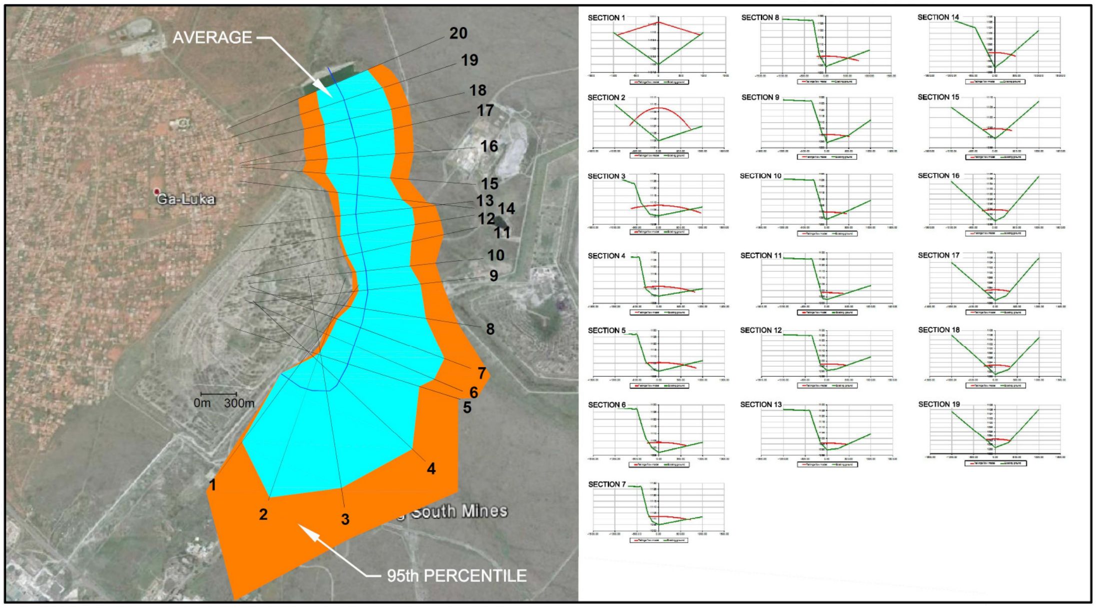

Figure 8 Results of the Bafokeng back analysis

Merriespruit 1994

The Merrispruit failure occurred in 1994 in South Africa. Approximately 600,000 cubic metres of tailings flowed out of the TSF. Figures 9 and 10 show photographs of the flow slide.

Figure 9: View of the aftermath of the Merrispruit flow slide

Figure 10: View of the Merriespruit flow slide close to the crater

The volume of flow, width of breach and residual slope of the crater were all known from aerial survey data. The D parameter and Bingham parameters were calibrated. The most representative mode of failure was found to be Mode 2.

The resulting output from the flow slide model is indicated in Figure 11.

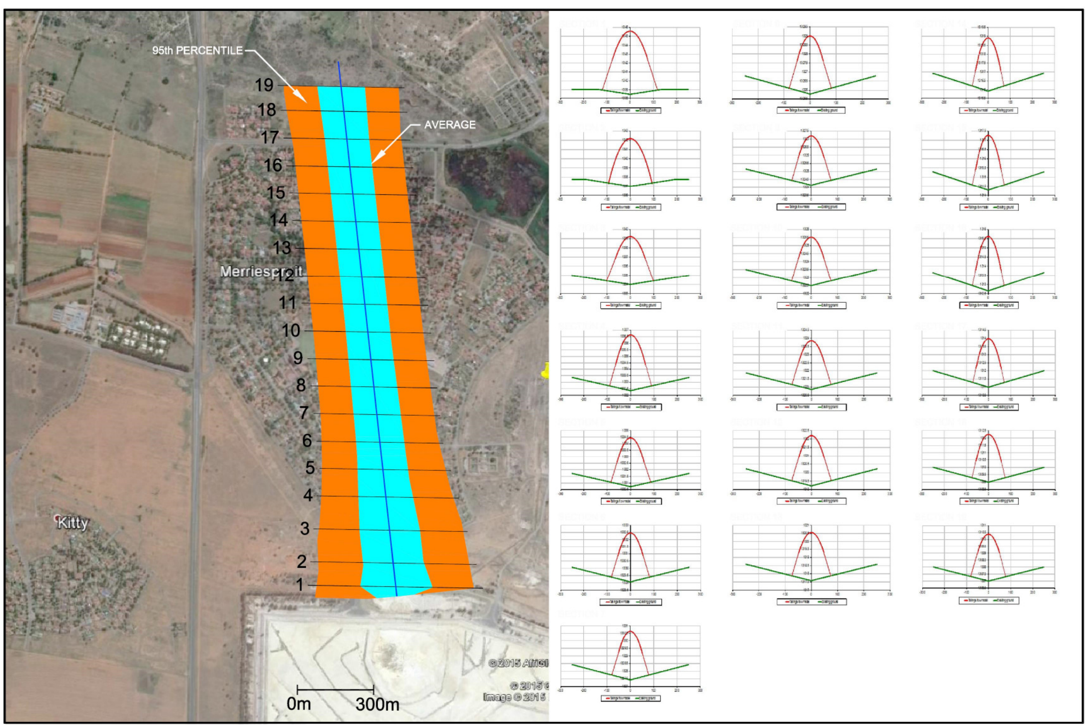

Figure 11 Results of the Merriespruit back analysis

CALIBRATION OF PARABOLA USING LABORATORY TESTS

In carrying out predictions of flow slide failures using the probabilistic approach it is feasible to make reasonable estimates of the upper and lower bounds for the volume of outflow by considering the geometry and depth of the TSF. Evaluation of past failures indicates it will be between 5% and 50% of the volume of the facility. Similarly it is feasible to make a reasonable estimate of the maximum and minimum width of flow since evaluation of past failures indicates that it is generally between 75m and 300m. A reasonable estimate of the range for the residual angle of the crater can be made from past failure where angles between 2 degrees and 12 degrees have been observed. In this respect cognisance should be taken of the fineness of the tailings and the rate at which the TSF has increased in elevation. Finer and higher implies a flatter residual angle. Similarly the Bingham parameters can be set with a minimum Bingham yield stress of between 1 and 20 Pa for fine rapidly rising tailings and between 10 and 50 Pa for coarser tailings. Bingham plastic viscosity is likely to be between 0.001 and 0.02 Pa-s for fine rapidly rising tailings and between 0.03 and 0.06 Pa-s for coarser tailings.

The parameter that is more difficult to estimate is the D parameter for the parabola. This author has had some success in correlating rheology with the D parameter in small scale flow slides such as indicated in Figure 12 where the dimensions of the box containing the tailings was 0.3 by 0.5 by 0.4m deep.

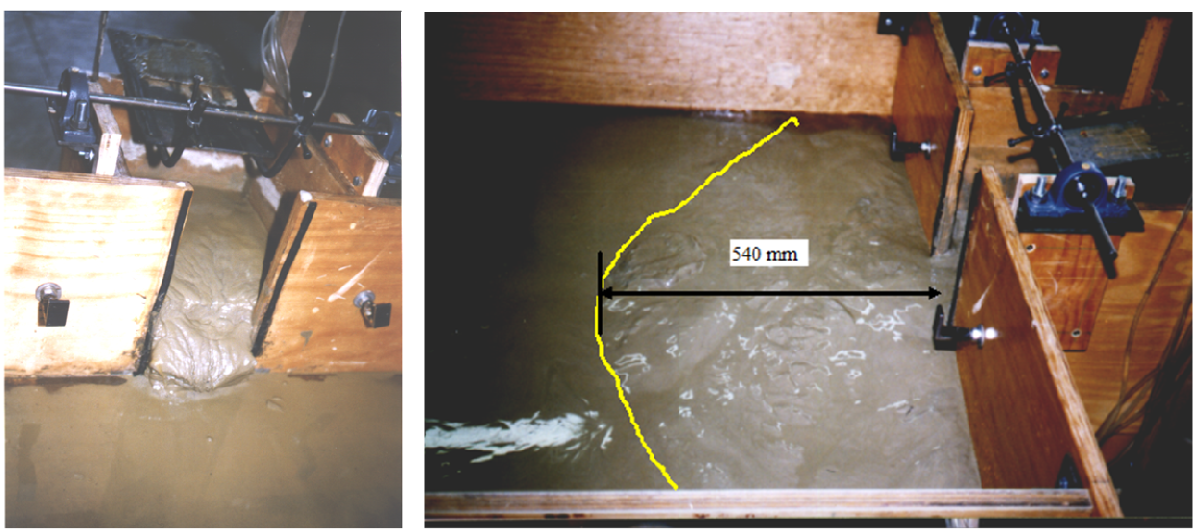

Figure 12: Photos showing small scale flow slide in a lab

In the small scale tests the tailings are mixed to a selected consistency, poured into the box and the side of the box opened to allow the tailings to flow out. A range of consistencies is tested. In each case the rheology of the tailings is measured before as well as after the failure (by sampling from the flows slide mass). Sections are taken through the flow mass so as to measure the flow profile at each section. The flow slide model is run with varying parameters until predicted sections representatively agree with the measured sections. It has been found that a single D parameter allows a reasonable fit down the length of the flow slide. Figures 13 and 14 show the results for two flow slides at two different tailings consistencies.

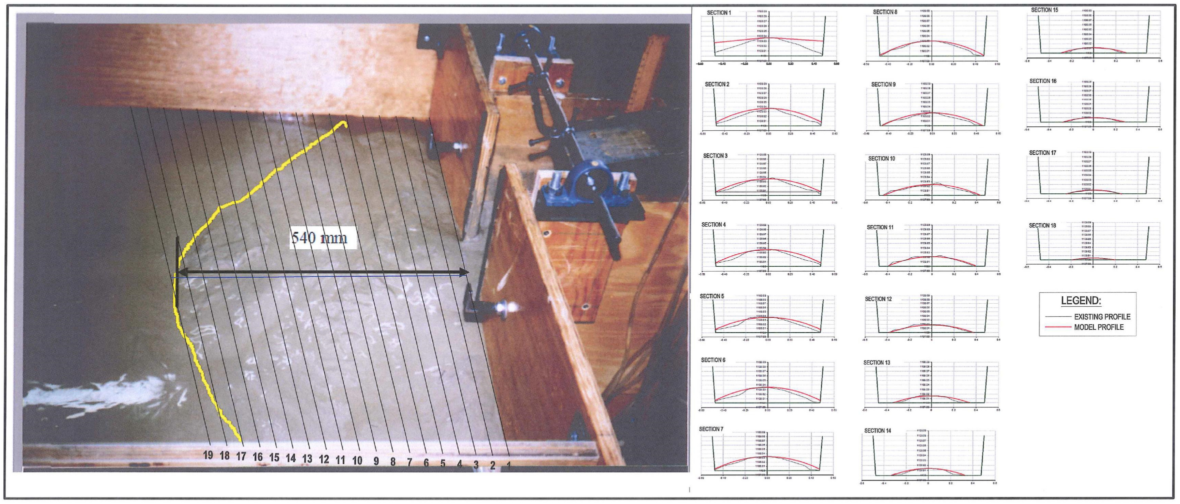

Figure 13: Back analysed lab flow slide higher rheology

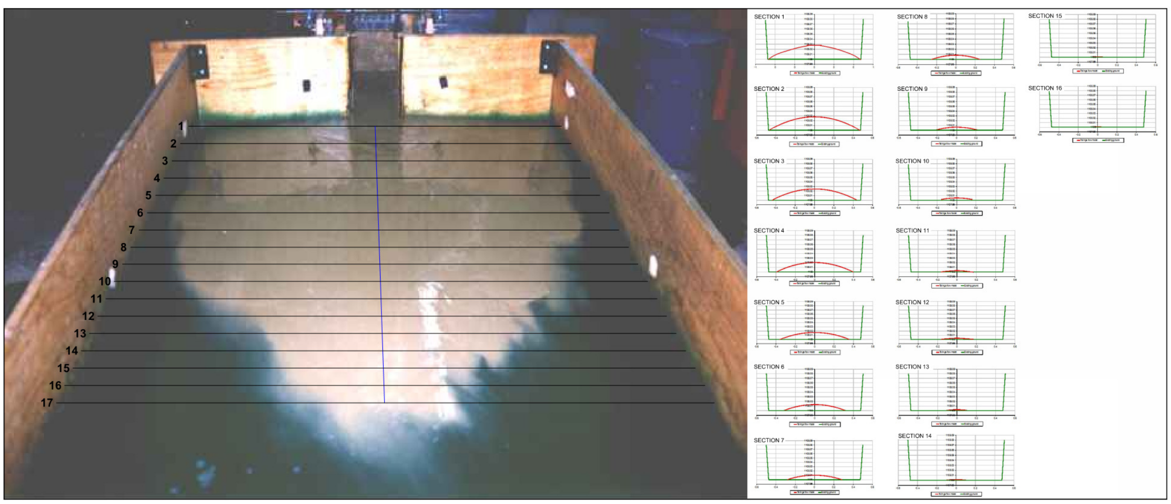

Figure 14: Back-analysed lab flow slide – lower rheology

The flow slide model enables calculation of the stream power at each section with time during the failure. The D parameter is inversely proportional to the stream power but proportional to the yield stress. By comparing the stream power in the full scale model with that in the lab scale model a scaling for D based on stream power is established. This is carried out for each rheology tested in the lab.

CONCLUSIONS

The application of probability and uncertainty to the prediction and analysis of dam break and flow slide failures for tailings storage facilities have been described. Prediction of the probability of a dam break has focused on five primary trigger failure modes and the propagation of faults that could lead to each trigger failure mode through a Fault Analysis. This is complemented by an Event Analysis to assess the potential severity of a flow slide should this develop as a result of a trigger failure. The fault event analysis approach simplifies the Boolean calculation of probabilities as these propagate through the fault and event trees.

Having understood the probability of failure and its consequences it is then necessary to evaluate the geometry of the flow slide that may result from the dam break. A method of flow slide analysis has been described. This makes use of Newtonian mechanics to predict the geometry of the mass during and at the end of the flow slide. The solution is made possible by the assumption that the flow slide will have a parabolic cross-section. The method requires estimates of the flow volume, the breach width, and rheological characteristics of the tailings as well as the residual angle of the crater. Since these parameters are unknown to any significant level of accuracy a probabilistic approach for incorporating ranges of these parameters has been described. . The efficacy of the model has been demonstrated through two back analyses of flow slides. A methodology for the estimation of the parameter that defines the parabola using lab-scale flow slides has been described.

REFERENCES

Blight, G. E., Robinson, M. E. and Diering, J. A, C., "The flow of slurry from a breached tailings dam", Jnl of the South African Institute of Mining and Metallurgy, January 1981