Paste 2019 – AJC Paterson, AB Fourie and D Reid (eds)

doi:10.36487/ACG_rep/1910_10_Cooper

# Tailings properties affecting the stacking angle of cyclone underflow

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## Abstract

*The storage capacity and rate of rise of a tailings storage facility (TSF) constructed utilising the tailings to form the TSF is dependent on the outer side slopes of the facility. A number of TSFs in South Africa are operated utilising cyclones to construct the outer wall zone of the TSF. The outer slope is dependent on the stacking angle of the cyclone underflow and hence it is critical that the design of the TSF accurately estimates the stacking angle. There are no clear guidelines to make this estimation other than to compare to similar projects. This methodology has resulted in a few TSFs in which the stacking angle was either over- or underestimated leading to an inaccurate life assessment. This paper hypothesises that the yield stress of the underflow has the most significant effect on the stacking angle. The hypothesis is tested by measuring various tailings properties on a tailings operation in relation to the stacking angle achieved to attempt to develop a method to predict the stacking angle for future projects.*

**Keywords:** *tailings, cyclones, stacking angle, yield stress*

## 1 Introduction

The majority of tailings storage facilities (TSFs) in South Africa are constructed utilising the tailings to form the outer walls. A number of these TSFs are constructed utilising cyclones, either in the upstream or downstream direction. The primary objective of using cyclones is to segregate the tailings to form a well-drained outer wall zone utilising the cyclone underflow which then impounds the cyclone overflow. This methodology can improve the stability of the TSF whilst allowing the TSF to be developed at a higher rate of rise thereby reducing the required overall footprint.

Two different cyclone methodologies are indicated in the following figures. Figure 1 shows 250 mm diameter cyclones which are used on TSFs with multiple cyclones operating simultaneously.

**Figure 1 Multiple 250 mm cyclones**

Figure 2 shows a self-propelled cyclone unit (SPCU), comprised of four 430 mm diameter cyclones mounted on a tracked undercarriage developed for deposition rates exceeding two million tons per month.

**Figure 2 Self-propelled cyclone unit**

Constructing a TSF utilising cyclones is relatively complex with several factors requiring consideration. The design profile, including the outer wall slope, underflow wedge width and freeboard requirements, needs to be managed to ensure legal and design compliance. An additional factor, not often considered, is the limitations of the cyclones themselves. Design specifications include the required mass of underflow (percentage split) and the quality of the underflow in terms of permeability and fines content. Cyclones are highly sensitive to the consistency of the feed slurry, particularly flow rates, pressures and particle size distribution. Although the cyclone and internal configuration can be designed to suit specific tailings, the variation in underflow quantity and quality can be significant due to changes in the feed properties.

The cyclone underflow is deposited to form a prism within the outer wall zone. To maintain the design prism, the slope of the upstream and downstream sides of the prism needs to be constant. The slopes of the actual prism achieved however is dependent on the cyclone performance in terms of the underflow stacking angle.

Should the average slope achieved be steeper than the design slope, the overall slope can be maintained relatively easily by means of setting out the cyclones at the design centreline and, if necessary, evening out the slopes manually as part of the operation.

If the actual slope is flatter than the design slope however, it is not possible to maintain the design slope without some form of mechanical intervention which raises the cost of the operation. Following the design centreline will result in underflow being deposited outside of the prism, thereby potentially exceeding the permitted footprint of the TSF. Should the cyclones be positioned at the stacking angle, the resultant flatter overall side slope will result in a reduction in storage capacity of the TSF and/or an increase in the final rate of rise due to the smaller surface area.

The slurry properties defining the stacking angle of the underflow need to be better understood to provide a more accurate prediction of the outer slope during the design phase as well as for ongoing monitoring of the achieved side slopes. The cyclone underflow behaves as a relatively coarse cohesionless thickened tailings. It is hypothesised that the stacking angle is a function of the yield stress of the underflow, similar to that of a thickened tailings operation. A thickened tailings operation is indicated in Figure 3 where it has been proven that no segregation takes place on deposition and hence the beach slope is a result of the yield stress of the tailings and not gravitational sorting of particles as with a conventional density operation (Cooper & Smith 2011).

**Figure 3 Beach slope on a thickened tailings operation**

To test the hypotheses, a study was conducted on a cycloned platinum TSF where the life of the facility is of concern as the side slope is flatter than the design slope. This paper describes the selected operation, the ideal outer wall profile to be attained by a cyclone operation, the study methodology and a summary of the study results and proposals for further studies.

## 2 Selected site

The site selected for the study is an upstream platinum cyclone operation. The TSF is a ring dyke with the current maximum height in the order of 40 m and a final design height of 50 m. The average rate of rise is currently in the order of 5.0 m/yr with the final maximum rate of rise set at 6.0 m/yr. Deposition is by means of multiple 250 mm diameter cyclones with up to eight cyclones operating at any one time. A single vertical gravity penstock decant system is provided near the centre of the basin. The volume of water on the facility is kept to a minimum by decanting to a return water dam.

The intermediate slopes are designed at 1(v):2(h) with benches provided at regular intervals to achieve an overall slope of 1(v):3(h). The outer wall is flatter than that specified by the design with the intermediate slopes varying between 1(h):2.2(v) and 1(h):2.5(h) and an average overall slope in the region of 1(h):3.5(v). The reason for non-conformance to the design specifications is that the intermediate slopes are constructed at the stacking angle of the cyclone underflow. The comparison of the design and actual slopes is shown in Figure 4.

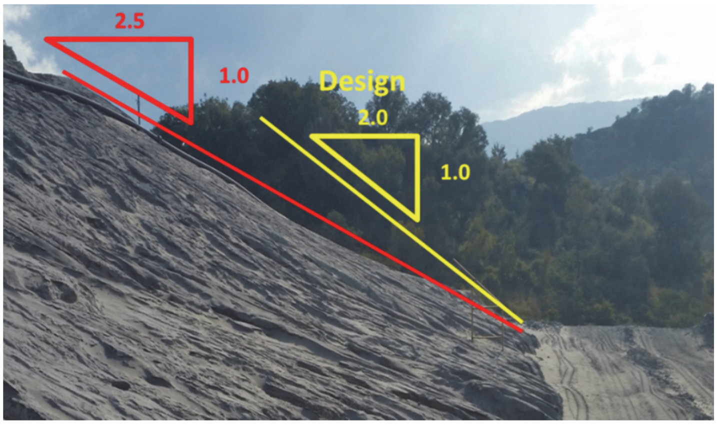


**Figure 4 Actual versus design slopes**

The flatter slopes have resulted in a higher rate of rise than predicted with the life of the TSF potentially limited by the maximum rate of rise to below the design life. As a result, construction of the new TSF had to be accelerated to ensure the rate of rise of the current TSF will remain below the specified maximum.

Attempts have been made to steepen the intermediate slopes by setting out the cyclones at the upstream design centreline. This however resulted in a portion of the underflow being deposited in the downstream direction thereby reducing the effective underflow volume placed in the design prism as well as extending the footprint. This is demonstrated in Figure 5.

**Figure 5 Loss of underflow in downstream direction**

The demand on the cyclone underflow is relatively high because of the relative size of the basin and length of the perimeter wall. Feed, underflow and overflow slurry densities are recorded manually on an hourly basis to ensure the cyclones are performing optimally to provide a split to underflow of at least 20% to maintain the underflow width and freeboard. The reduction in effective underflow placed also impacts the development of the wall with a negative impact on freeboard. Design data relevant to the study is summarised in Table 1.

**Table 1 Design data**

| | |
|---|---|
| Specific gravity | 3.0 |
| Angle of friction | 34° |
| Slurry feed density | 1,500 t/m$^3$ |
| Deposition rate per cyclone | 30,000 t/month |
| Percentage split by mass | 20% |

# 3 Ideal outer slope

An ideal design profile for a cycloned TSF is shown in Figure 6. The sketch indicates a side slope which provides a less intrusive aesthetic profile with concave intermediate slopes forming a final scalloped slope with an overall slope of 1(v):4(h) to aid rehabilitation and reduce erosion. Figure 7 indicates the actual side slopes achieved on the selected site, demonstrating that the ideal slope can be achieved relatively easily depending on the design profile and stacking angle of the underflow.

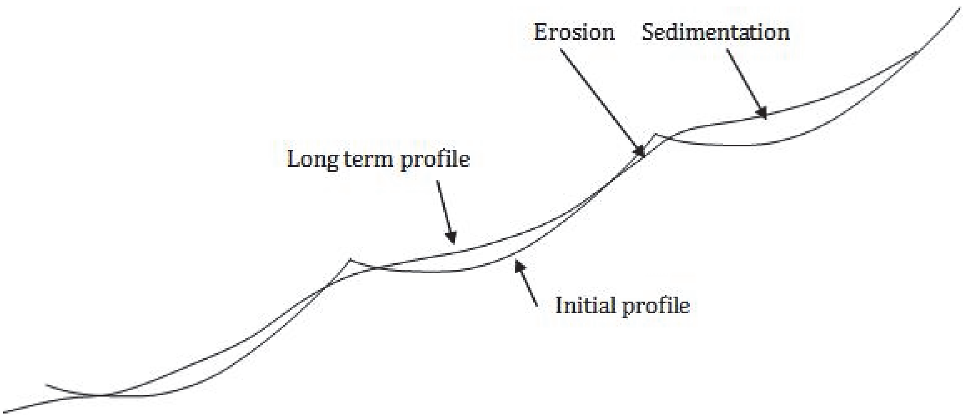


**Figure 6 Ideal profile**

**Figure 7 Achieved side slope (uppermost intermediate slope)**

# 4 Methodology

A quick estimate of the yield stress of thickened tailings can be obtained using the '50 Cent Rheometer' (Pashias & Boger 1996). The method is derived from the concrete industry which uses a slump test to measure the workability of fresh concrete. The theory behind the method is that during the test, the tailings will flow until the cross-sectional area has increased to a point when the stress required to support the weight is reduced to the shear stress. The method has been shown to provide reliable results and obviates the need for expensive equipment to be utilised onsite. The rheometer is simply comprised of a 3 mm thick stainless steel cylinder 75 mm high by 75 mm wide. The test involves placing the cylinder on a horizontal board, filling the cylinder with a fresh sample of underflow tailings, slowly raising the cylinder and measuring the resultant slump of the underflow. The yield stress is then calculated as a function of the slump and underflow density. A schematic of the slump test is given in Figure 8.

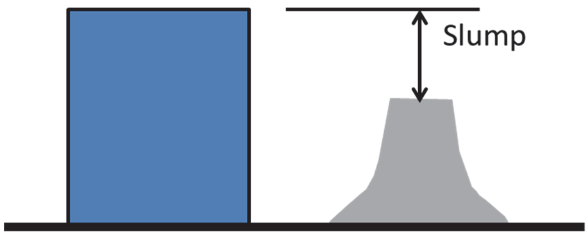


**Figure 8 Slump test**

Measurements of underflow density and slump were taken from two adjacent cyclones operating concurrently on an hourly basis during day shift for a period of seven days. A sample of underflow was first extracted directly from the cyclone spigot, the density measured using a digital scale and then placed immediately into the 50 cent rheometer, levelled off and the slump test done as quickly as practical to limit the effect of drainage of additional water from the underflow. The data was used to estimate the underflow yield stress and then analysed to determine consistency and potential correlations between the underflow density, yield stress and stacking angle.

# 5 Results

Yield stress was calculated based on the slump measurements (Pashias & Boger 1996). Considering the limited variance in feed density, the data indicated a larger than expected variance in underflow density. Data from the results is summarised in Tables 2 and 3. The variance is also evident in Figure 9.

Table 2 Data summary: Cyclone A

| Cyclone A | Average | Standard deviation | Standard deviation/average |
|---|---|---|---|
| Feed density (t/m$^3$) | 1,490 | 24.7 | 1.7% |
| Underflow density (t/m$^3$) | 2,285 | 125.7 | 5.5% |
| Slump (mm) | 60.4 | 4.7 | 7.8% |
| Yield stress (Pa) | 41.7 | 16.8 | 40.4% |
| Stacking angle (degrees) | 20.5 | 3.6 | 17.3% |
| % underflow by mass | 25.4% | 2.0% | 7.9% |

Table 3 Data summary: Cyclone B

| Cyclone B | Average | Standard deviation | Standard deviation/average |
|---|---|---|---|
| Feed density | 1,505 | 19.5 | 1.3% |
| Underflow density | 2,278 | 104.9 | 4.6% |
| Slump (mm) | 60.53 | 4.4 | 7.3% |
| Yield stress (Pa) | 41.1 | 15.5 | 37.7% |
| Stacking angle (degrees) | 21.25 | 3.0 | 14.3% |
| % underflow by mass | 25.1% | 1.8% | 7.3% |

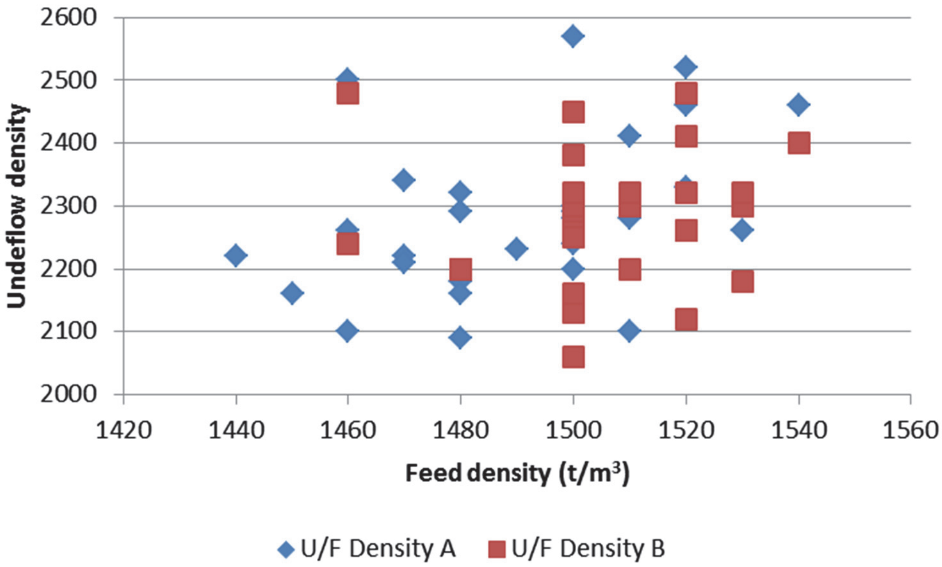


Figure 9 Underflow versus feed density

Figure 10 shows the variance in stacking angles of underflow deposited at different times.

Figure 10 Variable stacking angles

## 5.1 Yield stress verification

A high-level analysis was undertaken to confirm the validity of utilising the 50 cent rheometer to estimate the yield stress in terms of the consistency achieved in the calculations due to the high scatter in underflow densities. This was undertaken by means of analysing the overall trends.

As discussed previously, there was an unexpected inconsistency between the feed and underflow densities as shown by the difference in standard deviation and the data scatter in Figure 11. The general trend is fairly constant for both cyclones with a gradual increase in yield stress with decreasing density, opposite to what one would expect.

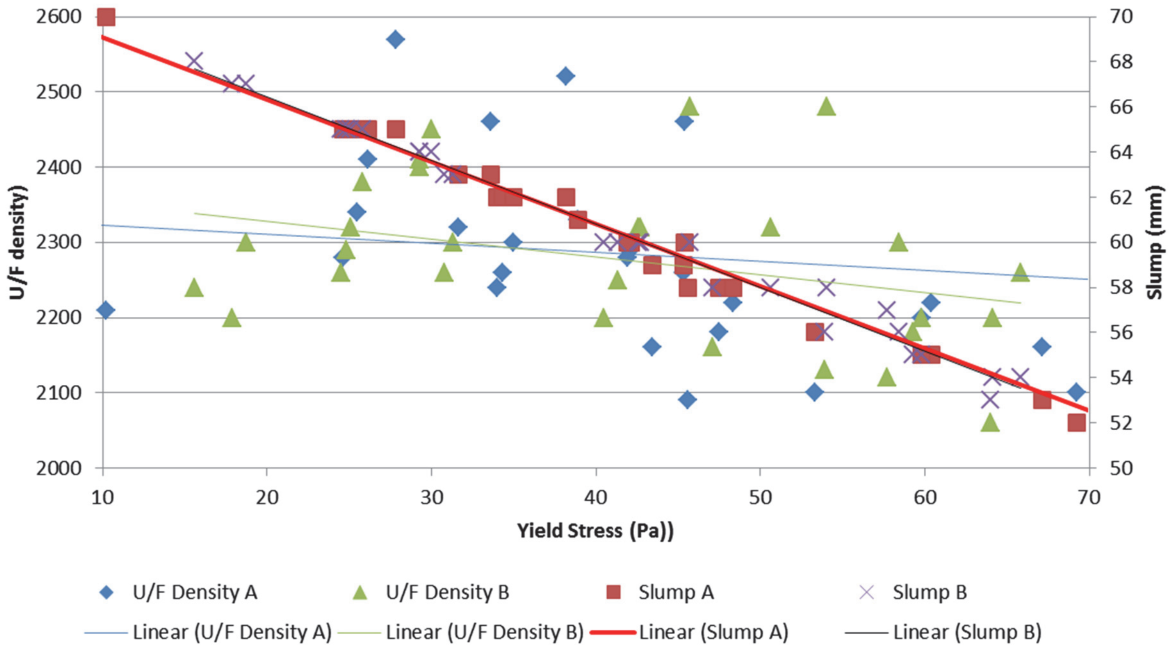


Figure 11 Slump and underflow density versus yield stress

There is, however, a straight-line correlation between slump and yield stress with increasing yield stress and decreasing slump. The scatter of slump and yield stress is significantly less than that of the underflow density. The data therefore shows that the calculation of yield stress is weighted towards the slump value with limited effect of the variation in underflow density.

## 5.2 Stacking angle

The stacking angle was measured by laying a 3 m long straight edge on the slope and measuring the angle using an angle finder.

Plots of the calculated yield stress, percentage solids of the underflow and underflow density are presented against the stacking angle in Figure 12. The data is presented separately for the two cyclones due to the unexpected relationship between underflow density and slump.

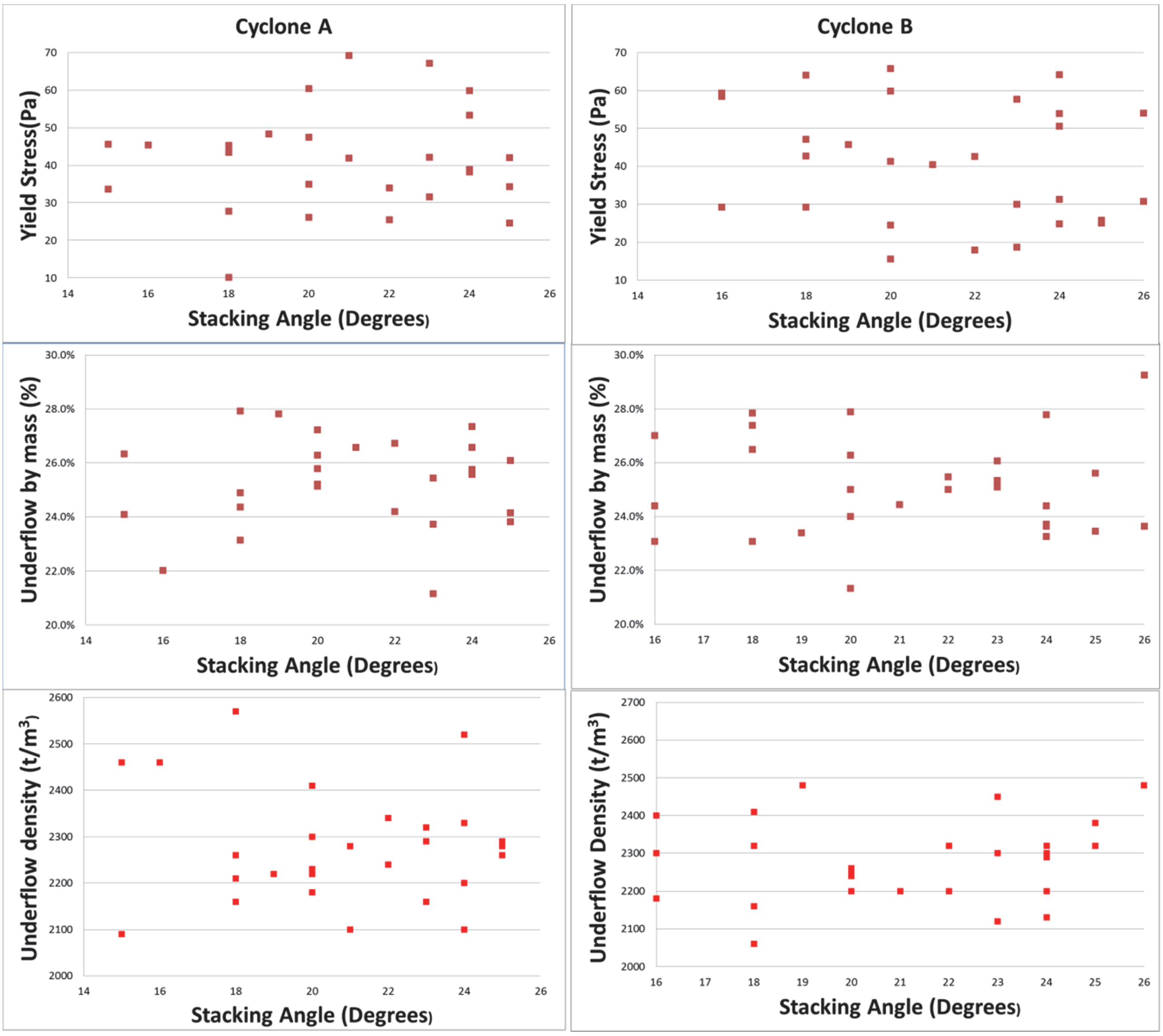


Figure 12 Stacking angle calibration

# 6 Conclusions and recommendations

Although the testing was considered reasonably rigorous, the data indicates a fair amount of scatter with some anomalies and hence no direct relationship between the yield stress and stacking angle could be found.

The high degree of scatter of underflow density to feed density is probably a result of the sampling process and sensitivity of the properties of the feed to cyclone performance.

The relationship between percentage underflow by mass and yield stress will be influenced by the volume of fines in the underflow which was not measured.

The study was undertaken as a preliminary study to determine firstly whether the hypothesis is true and if so, what further work is required. Although it was not possible to prove the hypothesis, the study has shown that it will be worthwhile extending the study but including the analysis of additional geotechnical properties that may have an influence, especially the fines content of the underflow.

The following additional work is recommended:

- Extension of the dataset including gold, ferrochrome and chrome cyclone facilities.
- Calibration of the yield stress obtained by means of the 50 cent rheometer for the various ore types by means of laboratory or field testing utilising an appropriate rheometer.
- Particle size analysis to evaluate the effect of varying fines content in the underflow.
- Underflow permeability.
- Confirmation of the discrepancy between underflow density and slump.
- More accurate calculation of the percentage underflow by undertaking surveys of the resultant prism.
- Calculation of the effective percentage underflow, i.e. the mass of underflow correctly placed in the design prism rather than the total percentage.
- Measurement of feed pressure to the cyclone to monitor performance of the cyclone.
- Measurement of flow rates and the effect of the energy on deposition on the stacking angle.

# References

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