

An evaluation of cyclone performance to improve the quality of cyclone underflow material for tailings disposal

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Abstract

In any tailings disposal operation utilising cycloning for material separation, a crucial output contributing to the overall success of the operation is the quantity and quality of the cyclone underflow material produced. The cyclone underflow requirement for the tailings disposal solution is usually determined early on in the design stage for the mine and due to various constraints, is often based on limited investigations which very seldom allow for any actual cyclone performance testing. This means that excellent cyclone performance during operations is crucial in order to meet the design criteria in terms of the cyclone underflow material to ensure a safe and sustainable tailings disposal operation.

Through various onsite tests carried out on tailings dam being built utilising cyclones, the cyclone performance was evaluated based on various configurations and input parameters. Modifications to the cyclones were also tested and the impact on the cyclone underflow characteristics such as grading, water content and percentage split were reported on.

Configurations and modifications included the following:

- *Extensions to the cyclone assembly.*
- *Conversion of the cyclones to pressurised cyclones.*
- *Various spigot/vortex finder configurations.*
- *Pressure and slurry density effects.*

Key outputs measured from the test work and utilised in the operational plan for the tailings dam were:

- *Stackability of the cyclone underflow.*
- *Percentage split to underflow achieved.*
- *Particle size distribution of underflow material.*
- *Cyclone underflow water content.*

This paper provides details of the onsite tests carried out as well as an interpretation of the results, which provide invaluable information on evaluating and enhancing cyclone performance in their application towards tailings disposal. The approach in applying these outcomes towards successful design and operation of tailings disposal using cyclones, taking into account stability and water consumption will also be covered.

1 Introduction

The application of cyclones for tailings disposal is widely utilised throughout the world with a number of variations being applied in the method of placement and configuration of the underflow and overflow portions of the tailings produced by the cyclones. One of the common configurations is off dam cyclone plants with the underflow being placed either mechanically or hydraulically to raise the outer wall that contains the overflow.

In the South African context, the most common deposition method is that of on-wall cycloning whereby the full tailings is pumped directly from the processing plant to cyclones that are placed directly on the tailings dam perimeter. This has some distinct operational advantages but also poses challenges as the cyclones are not operating in a typical controlled process plant type environment, which they were originally designed to do. This paper covers test work carried out onsite to evaluate and improve the performance of cyclones in order to produce an underflow of sufficient quantity and of suitable quality to be able to build the tailings dam outer wall in such a way as to meet both operational and design criteria.

2 Design aspects relating to cyclone tailings storage facility

The shear strength of the tailings forming the outer wall of a tailings storage facility (TSF) and the location of the phreatic surface are the two most significant factors influencing the structural integrity of the facility. Where the full tailings does not satisfy design criteria with respect to shear strength or where the full tailings cannot be placed in such a way as to control the phreatic surface, cyclones are typically specified in order to classify the tailings stream into an underflow component meeting the design specification and an undifferentiated overflow component that is not required to meet any specific requirements. The coarse underflow is placed in such a way as to contain the finer low shear strength and often poorly consolidated overflow.

Once a design decision has been made to classify the tailings, the designer would assess whether the required volume of underflow can be produced to safely contain the overflow. The required volume is a function of the geometry of the minimum dimensions of the embankment prism, the height and the perimeter length over which the embankment is required.

2.1 Structural integrity

2.1.1 Shear strength

The typical specification for underflow with high shear strength and adequate drainage characteristics is a maximum of 15% passing the 75 micron (200 mesh) sieve size. For hard rock ores this specification will invariably guarantee an underflow that adequately meets shear strength requirements for an embankment for even the stringent conditions such as are encountered in areas with seismic activity. In order to resist significant deformation under seismic loading compaction of the underflow may be required.

2.1.2 Phreatic surface control

The second objective that is met by classification is to create a permeability contrast between the underflow forming the embankment prism and the overflow in the interior of the tailings facility. If a contrast of 100 can be achieved the phreatic surface will be guaranteed to be drawn down and maintained in a position just above the interface between the underflow and the overflow.

2.2 Geometric/volumetric details

The underflow specification driven by shear strength considerations clearly limits the maximum theoretical mass of underflow to the proportion of the total feed that exceeds 75 micron plus 15% thereof. As ores have been milled finer and finer to improve recovery efficiency so has the proportion of tailings that is available for underflow been reduced. As underflow becomes scarcer it becomes important to manage the cyclones and the placement of underflow more carefully to minimise the loss of coarse tailings to overflow and minimise inclusion of out of specification fines in the underflow. The split between underflow and overflow that determines the quantity of underflow as well as the stacking and drainage must be controlled in order to meet specifications.

2.2.1 *Managing split*

The practical maximum proportion of underflow that can be produced is not equal to the theoretical maximum owing to factors such as cyclone inefficiency, bypassing, pressure variations and variations in the tailings rheological properties. In practice, it is seldom possible to produce more than between 50% and 75% of the theoretical maximum underflow whilst meeting the specification. The most important factors influencing the actual split are the performance of the infrastructure (pumps, pipelines and cyclones) and the skill of the operators. Optimisation on a site-specific basis is always required to achieve the best performance.

2.2.2 *Stacking angle*

Any underflow that is placed outside the specified minimum dimensions of the embankment is effectively 'lost' and reduces the proportion of useful underflow produced. It is therefore also important to control the placement of the underflow carefully. The angle at which the underflow stacks is therefore important, and whilst being primarily a function of the solids, concentration of the underflow is also impacted by underflow rheology, particle size distribution and discharge rate. These parameters can, if not factored into design and operational considerations, further reduce the portion of useful underflow that is produced.

3 Cyclone design and configuration for TSFs

In order to achieve the criteria for the successful design and operations of a tailings dam using cyclones as listed in section 2, it is critical to achieve optimum cyclone performance in the field. Failure of the underflow to conform to specification in terms of shear strength, as well as permeability contrast to the overflow, can have a major impact on achieving the tailings dam design criteria. In addition, it can be very costly to modify the slurry delivery system and tailings dam infrastructure once it has been installed to accommodate an under-performing cyclone. There are however certain parameters that can be adjusted onsite to optimise cyclone performance.

Cyclone performance in relation to classification of tailings is best described in terms of the Tromp curve which has the following main aspects (Du Plessis and Bekker, 2010):

- The d_{50} , commonly referred to as the cut size, is defined as the size of particle that has a 50% (equal) probability of reporting to the overflow or underflow.
- The imperfection value defined as the gradient of the corrected Tromp curve.

3.1 Site factors contributing to performance

The onsite parameters which can be altered to improve cyclone performance include parameters such as pressure, spigot and vortex combinations and slurry density. The impacts these parameters have on performance are described below.

3.1.1 *Pressure*

Although most slurry delivery systems are designed to provide constant flow and pressure to the cyclones on the tailings dam, pressure fluctuations do occur. The higher the pressure, the higher the percentage mass split, with the associated lower cut size. Pressure is an indication of how much energy is available to drive fluid velocity in the cyclone, which in turn increases the centrifugal force in the cyclone. The drawback of increased pressure is higher power consumption and increased wear rates.

3.1.2 *Spigot/vortex finder combinations*

Changing the spigot and vortex finder sizes is the easiest and probably most effective way to adjust the properties of the underflow material produced from a cyclone, both in terms of quality and quantity. The larger the vortex finder diameter, the larger the flow going to the overflow and hence a coarser cut to the underflow.

The ratio of spigot to vortex finder size also plays an important role in the cut size of the cyclone. The larger the spigot is relative to the vortex finder, the lower the cut size and the less sharp the cut. This is due to an increase in water reporting to the underflow which results in a reduction in the cyclone's efficiency.

3.1.3 Slurry density

The feed slurry density influences the cyclone performance as it affects particle interference inside the cyclone. At a lower feed density, there is less particle interaction, resulting in the better cyclone performance and an improved cut. It must be noted that very fine particles follow the path of water and are not actually classified by the cyclone.

3.2 Cyclone modifications to improve performance

The optimal cyclone performance that can be achieved with various configurations of spigot/vortex finder, feed density and pressure settings are limited by each particular tailings dam's site constraints. Various onsite modifications to the cyclones that can further enhance cyclone performance have been recommended by Multotec, a cyclone manufacturer.

3.2.1 Barrel extension

Cyclones consist of an inlet, cone, and cone extension sections. Extending the barrel involves installing a lined pipe section of the same diameter as the inlet section between the inlet and the cone.

The theory behind extending the cyclone barrel is that it will allow more residual time for the material inside the cyclone and hence should produce a better cut, particularly for finer feed material. This results in a higher percentage split to the underflow at the same density.

3.2.2 Pressurised cyclone

Conversion of the cyclones to pressurised units consists of installing specialised vortex finders into the units with barrel extensions that convert the non-pressurised cyclones into pressurised units. A disadvantage of a pressurised cyclone is reduced throughput, but the density of the underflow is expected to be higher which improves the stackability (the slope of the beach away from the cyclone) of the underflow material used for on-wall cyclone dams.

4 Onsite cyclone test work

Fraser Alexander operates a number of cyclone tailings dams of which two are operated using self-propelled cyclone units (SPCUs). Each self-propelled cyclone unit is fitted with four 420 non-pressurised Multotec cyclones with the design throughput per SPCU being 300,000–350,000 t/month (approximately 10,000 t/day) dependant on the slurry feed density range. The SPCUs are fed via a slurry delivery system from a booster pump station situated at the base of the tailings dams.

In order to evaluate the effect on cyclone performance that various configurations and cyclone modifications would have, Fraser Alexander conducted onsite test work to determine optimum cyclone performance in terms of underflow quality and quantity.

4.1 Tailings dams test sites

The tests were carried out at the Kareerand and Brakpan tailings dams details of which are provided.

4.1.1 Kareerand TSF

The Kareerand tailings dam is situated in the Northwest Province of South Africa and is part of the Mine Waste Solutions site owned by Anglo Gold Ashanti. The tailings deposited is in the region of 1.7–2.0 million t/month (Mtpm) and is from reprocessing of gold tailings dams that have been re-mined hydraulically. An aerial view as well as the on-wall SPCU layout is shown in Figure 1.



Figure 1 Kareerand TSF

The typical grading of the tailings has between 75 and 85% passing 75 micron and an unusually high fine fraction that contains actual clay minerals. This increases the slurry viscosity and has led to significant challenges in producing sufficient underflow of a suitable quality. One of the reasons for the test work described in this paper was to determine the optimal configuration to achieve required performance in terms of percentage split to underflow as well as the related underflow material properties.

4.1.2 Brakpan TSF

The Brakpan tailings dam is situated in the Gauteng Province of South Africa and is owned by DRD Gold Ergo. The tailings are deposited at a rate of 2.1 Mtpm also from reprocessing of gold tailings dams that have been re-mined hydraulically. An aerial view of the tailings dam that has a footprint of 1,400 hectares as well as the on-wall SPCU layout is shown in Figure 2.



Figure 2 Brakpan TSF

The grading of the cyclone feed material at the Brakpan TSF has 65–70% passing 75 micron with the fine portion of the tailings being relatively coarse for gold tailings.

4.2 Objectives of test

Besides the requirement of a permeability contrast of 100 between underflow and overflow, one of the quality criteria for the underflow is that it needs to stack at a slope of 1:4 in order to contain the underflow within the design prism and to form the slope of the outer wall without mechanical intervention. In addition, the geometric design of the upstream raised prism dictates the volume of underflow required which in terms of cyclone performance translates into the percentage split.

The objectives of the various onsite tests to determine the optimum cyclone configuration to improve performance have been based on meeting three main design criteria:

- percentage split to underflow
- stackability of underflow material
- particle size distribution of underflow material.

4.3 Site test methodology

Tests were carried out on operational self-propelled cyclone units with various configurations and modifications to the cyclones. Table 1 indicates the various configurations that were tested.

Table 1 Summary of test configurations

Test parameter	Configuration
Vortex finder/spigot combination	135/35, 135/45, 135/55, 135/65
Feed pressure	120–200 kPa
Cyclone barrel extensions	0, 1 and 2 extensions
Pressurised cyclone	Non-pressurised/pressurised

For each test configuration, density measurements were taken using an electronic Marcy scale for the feed, overflow and underflow respectively and these were used to calculate percentage split as well as solids concentration for the underflow. The stackability of the underflow was recorded based on a visual assessment. The typical site test unit setup is shown in Figure 3.



Figure 3 Site test unit

4.3.1 Barrel extension/pressurised cyclones

The test units were initially tested with no modifications to record baseline performance and were then incrementally modified with barrel extensions and conversion to pressurised cyclones to assess any improvement in performance.

Figure 4 shows the track cyclone unit with the two outer cyclones with barrel extensions installed as well as the installation of the specialised vortex finder to convert the cyclone into a pressurised cyclone.



Figure 4 Barrel extensions/pressurised cyclone

4.3.2 Underflow pumping system

Another variation that was utilised was the implementation of a cyclone underflow pumping system that was used to construct the pool wall of the tailings dam. This consisted of 10 cyclones mounted to discharge into a feeder box on the outer perimeter of the tailings dam. The underflow was then pumped along the pool wall and placed in paddocks as shown in Figure 5.



Figure 5 Cyclone pumping into paddock

5 Results of test work

In total, 900 tests were carried out on the two sites with the various cyclone configurations and modifications. The resultant data set has provided a significant amount of information for evaluation of cyclone performance under actual site conditions.

5.1 Barrel extension test results

The cyclones were tested with a combination of 300 mm barrel extension initially with a 135/35 and 135/65 vortex finder/spigot ratios to determine the impact the barrel extension would have on the percentage split to underflow. In terms of stackability, operational experience onsite had shown that the 135/35 combination produced an underflow which would stack at a suitable angle to allow for wall building, whereas for the 135/65 combination, the underflow density is too low to allow stacking.

The feed pressure was varied between 120 kPa and 200 kPa for the tests in order to evaluate the influence pressure had on the split. Table 2 shows the average percentage split results for all these tests.

Table 2 Barrel extension results

135/35				135/65			
Pressure (kPa)	No. of barrel extensions			Pressure (kPa)	No. of barrel extensions		
	0	1	2		0	1	2
	% mass split to underflow				% mass split to underflow		
120	3.5%	6.7%	7.5%	120	14.1%	16.2%	13.4%
140	6.9%	6.1%	7.1%	140	12.3%	17.7%	16.5%
160	4.0%	4.8%	9.0%	160	12.7%	17.2%	17.2%
180	6.4%	6.9%	11.0%	180	13.7%	15.8%	17.3%
200	8.7%	11.3%	7.9%	200	15.5%	15.4%	17.3%

Since the operating pressure onsite is in the range of 160–200 kPa; Figure 6 shows the graphical representation of the results for the test at 180 kPa which is within the actual operational range.

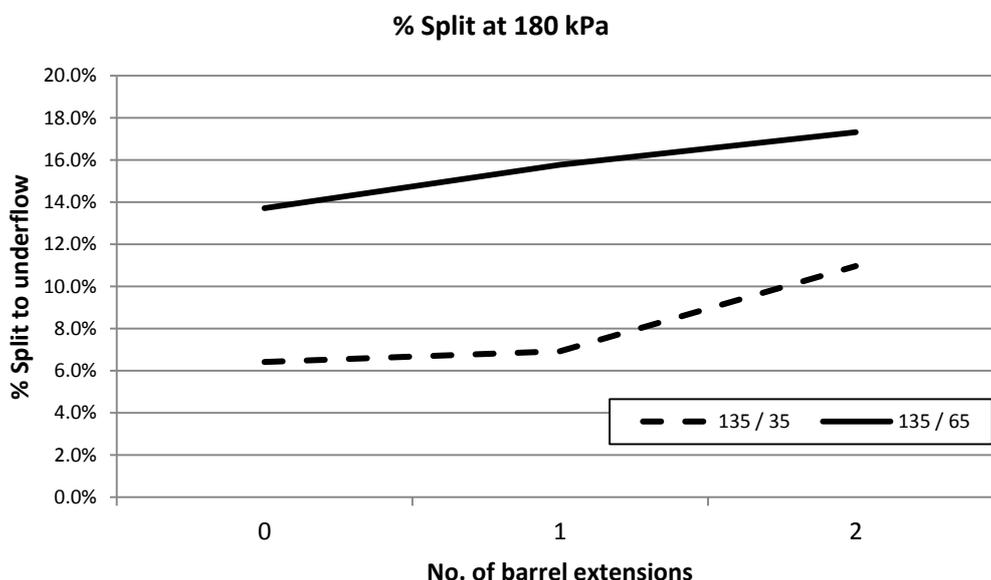


Figure 6 Percentage split versus barrel extensions

From an evaluation of all test data related to the improvement in split as a result of adding the barrel extensions, it was shown that the barrel extension improved the split in the order of magnitude of 15–20%. The constraint however is that for on-wall cycloning the underflow material must stack in order to be able to build the outer wall of the TSF. The percentage split for the 135/65 achieved is in the region of 17%, but the underflow material produced did not stack at the required minimum angle. Conversely the 135/35 combination produced an underflow which stacked but at a lower percentage split in the region of 11%, which is not sufficient for the geometric requirements of the TSF design.

In order to determine the highest percentage split for a material that would have a suitable stacking angle, a second set of tests was done with a 45 and 55 spigot. This test was done with the cyclone unit already fitted with barrel extensions and the results comparing all the spigot sizes tested is shown in Figure 7.

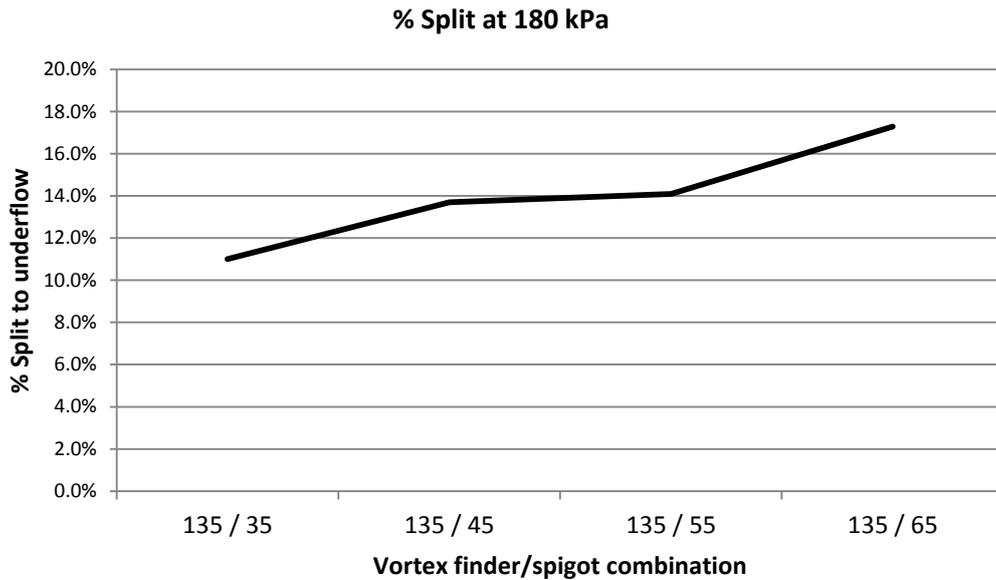


Figure 7 Percentage split versus spigot size

The increase in split achieved for the larger spigots is as predicted from cyclone theory, but it was found that the underflow material produced with the 55 and 65 spigot did not stack at the required minimum slope angle. Figure 8 shows the cyclone test unit on the left with variable density underflow from each of the four cyclones. The image on the left is an operational unit showing suitable stacking of the underflow.



Figure 8 Cyclone underflow stacking

5.2 Pressurised cyclone tests

The theory indicated that converting the cyclones to pressurised units would increase the underflow density for the same cut point (percentage split for a uniform grading). This would obviously be advantageous as the higher the underflow density, the greater its yield stress and hence improved ability to stack. The pressurised cyclone test was carried out on cyclones that had barrel extension pieces fitted. The range of the test work was limited to the spigot and pressure configurations that gave the best results during the first phase of testing. Figure 9 shows the improvement in split achieved with the pressurised cyclone compared to the standard cyclone (fitted with two barrel extensions).

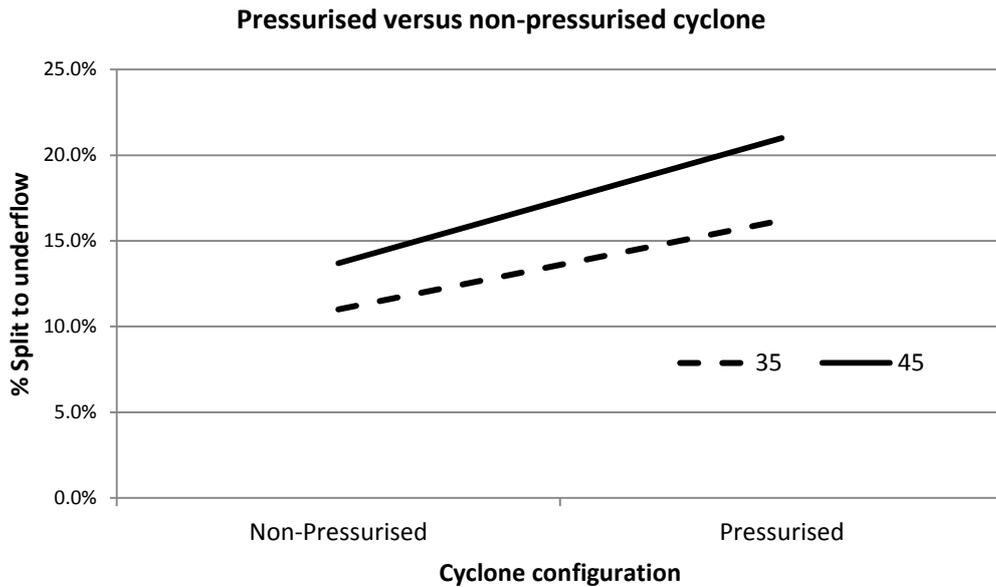


Figure 9 Percentage split for pressurised and non-pressurised cyclones

One practical aspect that must be noted is that for the non-pressurised cyclones, we use an extension pipe which has been aptly named an ‘elephant trunk’ to assist with placing of the underflow. With the pressurised cyclone however, the energy inside the cyclone is increased significantly and the material did not stack. However, if we removed the elephant trunk the energy dissipated due to the cyclone flaring allowing stacking of the underflow. Figure 10 shows the deposition technique with and without elephant trunk with the image on the left showing the underflow flaring for a pressurised cyclone configuration.



Figure 10 Pressurised versus non-pressurised cyclone

5.3 Relationship between percentage split and underflow density

Although for the onsite test work the measure of stackability of the underflow was based purely on whether we could build the outer wall, the test data set did provide the opportunity to evaluate the theoretically inverse relationship between percentage split and stackability. Although the yield stress of the underflow was not measured, it is known from practical experience that the underflow density essentially determines whether the underflow will stack or not with the cut-off point being around 1.8 t/m³ bulk density. A comparison of the percentage split versus the underflow density was done for all the test data in order to see if some correlation could be determined. Figure 11 shows the results for all of the 900 tests carried out.

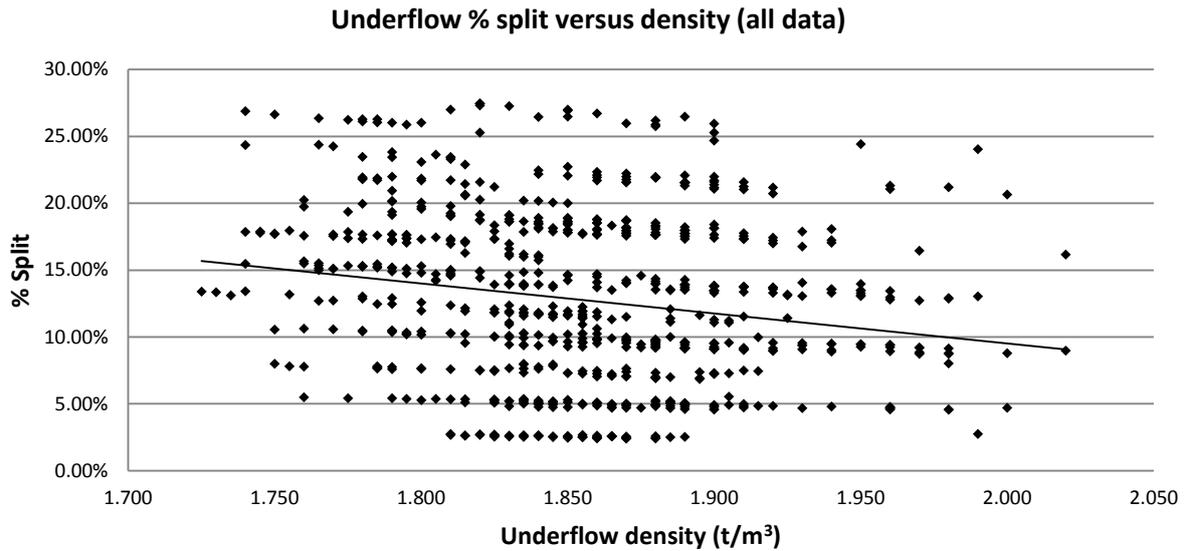


Figure 11 Underflow percentage split versus density

The results presented in Figure 11 do not show a distinctive relationship between percentage split and density, but it must be noted that these results represent a number of test configurations in terms of input parameters such as pressure and cyclone setups (barrel extensions, spigot and vortex size).

Figure 12 shows the same relationship for the cyclone tested with two barrel extensions at a constant pressure of 180 kPa. The only variable altered for this test was the spigot size.

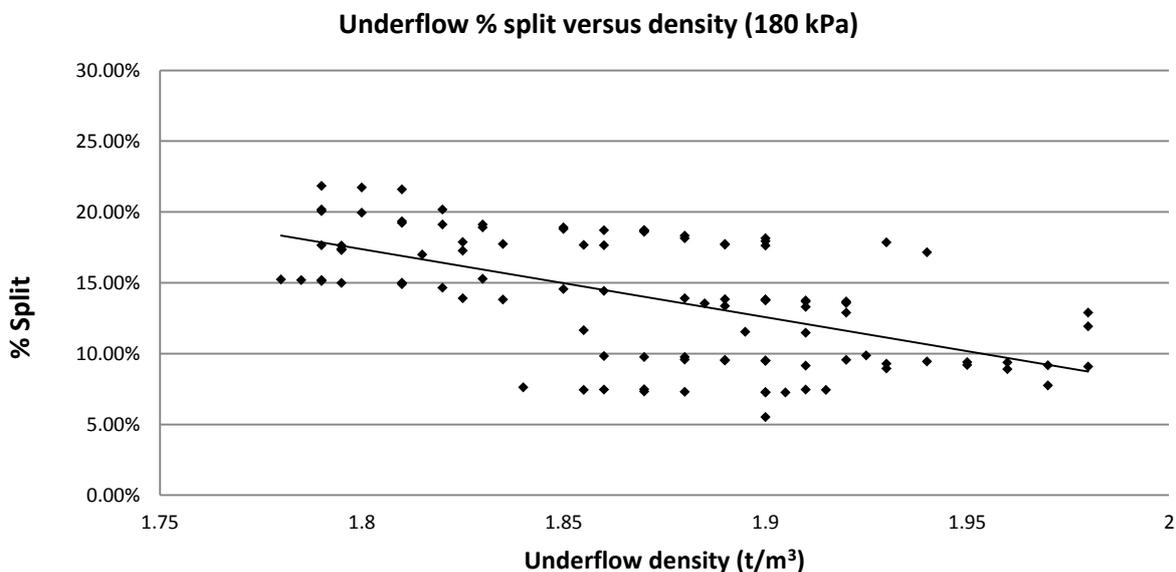


Figure 12 Underflow percentage split versus density

Although there is still some scatter in the results, the trend between the percentage split and underflow density for the tests with reduced number of variables does show the expected correlation between percentage split and underflow density.

The degree of scatter does however indicate that the variability in the yield stress of the underflow is significant and this is the main criteria influencing stackability.

5.4 Comparison of underflow particle size distribution

The test work was focussed on the practical options to improve split whilst maintaining the required stacking angle and hence focused on a significant number of test readings of the various slurry stream densities in order to calculate percentage split to underflow. However as mentioned in section 2, the phreatic surface control is also an important requirement and this is directly related to the grading achieved for the underflow material. Inadvertently, the building of the pool wall on the Kareerand TSF was being done using a different system to the outer walls as described in section 4.1.3. Since the pool wall does not form part of the outer wall of the tailings dam, the constraint on grading and permeability does not come into play, and the adoption of this method was chosen for its operational benefits.

This gave us the opportunity to compare the underflow grading from the standard SPCU operation where we are focussed on achieving a suitable grading, and the pool wall system where the underflow density is the determining factor, based on the pumping system constraints used to transport it to the paddocks.

Figure 13 provides the comparative grading curves for the underflow produced through the pumping system which produced a split in the region of 30% compared to the grading of the underflow produce with the SPCUs using a 135 / 35 vortex spigot combination that produced a split of approximately 11%.

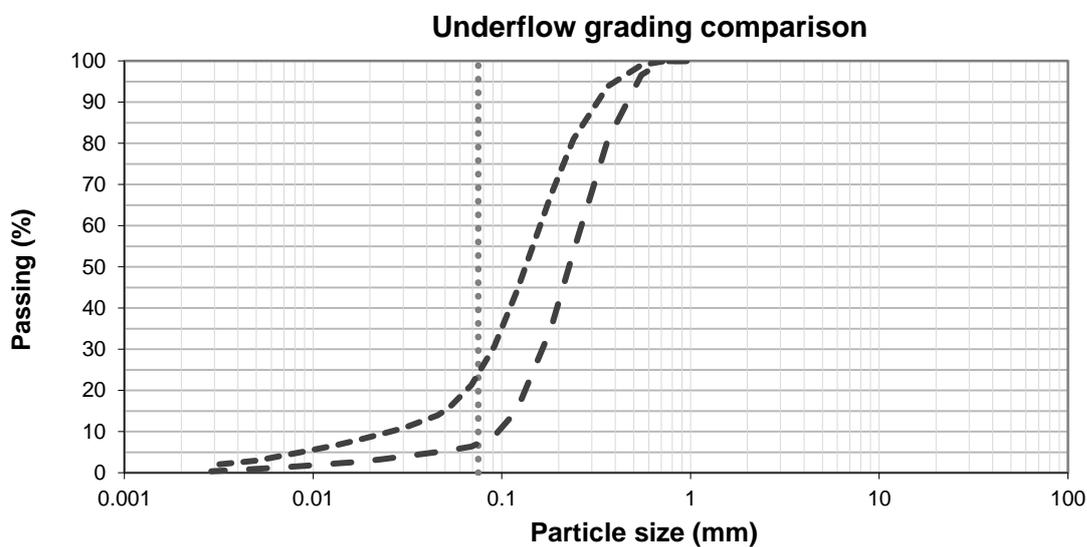


Figure 13 Comparison of underflow particle size distributions (PSD)

The underflow grading from the pumping system has 24% passing 75 micron compared to the SPCU underflow which has only 8% passing 75 micron. This further illustrates the inverse relationship between underflow quality and quantity. At the higher split, the underflow is finer, which is not suitable in terms of stacking angle or permeability for building the outer wall of the tailings dam.

6 Opportunities to enhance tailings management using cyclones

The benefits of using cyclones to manufacture underflow from which a stable embankment can be constructed in a downstream, centreline or upstream configuration have already been well established in practice. With the advent of finer grinding of tailings for a variety of commodities the viability of traditionally spigotted and paddocked tailings facilities has shifted. The finer tailings no longer segregates and hence the beach slopes on which spigotted platinum and copper tailings facilities depended to achieve freeboard can no longer be achieved except on large dams with long beaches. Paddocking can be considered as an alternative and has been implemented by Fraser Alexander on some facilities in Africa but for some cases this does not represent the best alternative and cycloning can be more attractive. The high

percentage of fines however precludes achievement of a high split and hence the cycloning option is only viable where the split requirements are low such as for a valley fill.

Water scarcity has also driven a review of the impact that the depositional scheme and rate of rise of a tailings dam has on water consumption. The paper by Knight et al., (2012) practically illustrated how cycloning can reduce water consumption when compared with a conventionally paddocked gold tailings dam, and Lyell et al., (2008) demonstrated how increasing rate of rise can reduce water consumption.

The two trends referred to above are changing the drivers of the selection of the deposition scheme for a particular setting and justify some of the conventional thinking around the selection process.

6.1 Geotechnical properties and split

The conventional approach to specification of cyclone underflow is to restrict the percentage passing the 75 micron sieve size to no more than 15%. Since the shear strength, drainage and desiccation characteristic of tailings with considerably higher proportions of fines passing the 75 micron size can readily meet the geotechnical criteria for forming a stable outer wall, a review of the conventional specification for underflow is justified. It may therefore be possible and clearly advantageous to construct the outer wall of a facility requiring a much higher split to underflow than would be achievable whilst meeting the conventional specification. Clearly as the specification is relaxed the margin for error will decrease and the need for reliable control and management of the cyclones will increase.

6.2 Water balance and water recovery

The result illustrated in the paper by Knight et al., (2012) indicates that significant reductions in water consumption could be achieved by introducing cyclones. The benefit of splitting the tailings into a coarse and a fine fraction is derived by the following:

- Reducing the water retained within the tailings.
- Reducing the surface area that is maintained in a wet or saturated state for a significant proportion of the total time.
- Reducing the permeability of the tailings underlying the permanent water pond and thereby reducing seepage.
- Potentially reducing the area of the permanent water pond.

The advantages outlined above justify comparison of the alternative deposition schemes on the basis of water consumption criteria whenever considering a greenfields project. Furthermore, the conversion of existing facilities such as No 5 dam at Chemwes described by Knight et al., (2012) should be considered where water needs to be saved and where increasing rate of rise may be undermining the geotechnical integrity of a facility.

7 Conclusions

Cycloning provides an effective means for classifying tailings to ensure a safe and sustainable tailings disposal operation, especially with the current approach towards finer grinding of tailings.

There are a number of modifications and changes to the configuration of cyclones that can enhance performance which can include extending cyclone barrels or conversion to pressurised cyclones. Notwithstanding any modifications, ongoing measurement of cyclone performance is crucial to a successful operation to ensure that the design criteria of the tailings dam are met.

The quality and quantity of the underflow material are the overriding criteria for success in a cyclone tailings dam and this paper provided an understanding of the relationships between the percentage split, stackability and grading of the underflow.

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