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Mine fines dewatering trials using amphibious vehicles at the Tronox KZN Sands Fairbreeze Mine

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Abstract

The Tronox KZN Sands Fairbreeze Mine is located in Zululand, south of Mtunzini on the east coast of South Africa. Mining activities commenced in 2015 and the declared life of the mine is 15 years.

Fairbreeze Mine is beneficiating an orebody that is part of the Berea Red dune system and the fines content is known to approach 30% in some areas of the deposit. The definition of 'fines' in the mineral sands industry is classified as any particle passing 75 µm and consists predominantly of clays and some traces of silica particles of silt size.

Historically, the mining industry has made use of sub-aerial deposition to dewater fines that do not drain freely. The only tools available to the processing facilities using the sub-aerial deposition dewatering method, has been:

1. *Depositing the fines at a yield stress as high as possible to achieve steeper beaches to facilitate higher water removal rates by means of bleed.*
2. *Increasing the sub-aerial area available for optimal evaporative drying, thus decreasing the rate of rise.*

In order to minimise the risk and to reduce the sterilisation of large tracts of land, mining companies are being forced to consider alternative dewatering techniques.

The use of amphibious vehicles, or mud-crawlers, is a well-documented alternative in the alumina industry but little is known about the performance of amphibious scrollers on mineral sands fines residue. This paper investigates the effects of mechanical scrolling performed by mud-crawlers on the dewatering and the ultimate final dry density of Fairbreeze fines. The investigation looks at ways that mud-crawlers can be applied as a financially viable alternative to sub-aerial deposition.

Keywords: *amphibious vehicle, mud-crawler, bleed, fines, disposal, residue, dewatering, sub-aerial deposition, mud-crawler, ridge, scroll, mineral sands*

1 Introduction

Tronox KZN Sands has been mining on the east coast of South Africa since 2001. Hillendale Mine was commissioned first and depleted in 2013. Rehabilitation activities continue both on the mined areas and the residue storage facility (RSF).

The Hillendale Mine made use of 133 hectares (ha) to dispose of fines using the sub-aerial fines deposition method, on a 21-day rotation cycle. The design assumed that the deposition cycling would result in an annual rise rate of 1 m.

Using the learning from Hillendale, the Fairbreeze Mine was commissioned in 2016, making use of a 250 ha open surface provided by the Mega-Sabeka residue storage facility (MSRSF). The sub-aerial deposition process was duplicated at Fairbreeze and is the current fines disposal method. The MSRSF is also set to rise at 1 m per annum at design mining throughput.

Li et al. (2014) defined the different stages of dewatering of fines as the following:

- Sedimentation is the process in which solid particles settle out of the suspending water medium without touching, and thus there are no effective inter-particulate stresses built up.
- Consolidation is where particles start to interact with each other and excess pore water is squeezed out of the residue by means of pressures exerted due to overburden, loads and seepage forces.
- Desiccation is the process where water is removed from the residue by means of evaporative processes. The evaporative process is separated into two further sub-phases. The initial phase takes place under saturated conditions where water is drawn out of the material until it reaches its desaturation point. Beyond the desaturation point, evaporation rates drop considerably and are largely dependent on the permeability of the material as well as the suction in the unsaturated zone.

In sub-aerial deposition, sedimentation and consolidation processes take place naturally and are defined as the release of free water in the form of 'bleed'.

Bauxite processing operations make extensive use of amphibious vehicles to promote the bleed process of caustic solution from the iron and alumina rich red mud residues. Munro and Smirk (2012) made mention of the added challenge of the formation of caustic crusting, which retards the natural bleed and evaporation processes. Amphibious vehicles have been found effective in breaking this crust formation and reinstating the dewatering release of the economically valuable caustic solution.

The KZN Sands fines do not display the same crusting behaviour but it is postulated that the action of the amphibious vehicles will still promote the removal of water.

The intention of this paper is to record the dewatering effects of the mud-crawlers on the deposited clay fines and to quantify the effect that these machines have on the bulleted variables discussed previously.

2 Methodology

The research methodology was undertaken in the context of an operational disposal facility. The test work is underpinned by a complete sampling campaign that is also intended to define the geotechnical, physical and structural characteristics of the Fairbreeze fines. The test work campaign was broken into phases that would allow for a robust financial justification for the continuation of the mechanical dewatering initiative.

Phase 1 comprised exploratory work and was intended to prove that there was a statistically dependable dewatering improvement when using mud-crawlers on Fairbreeze fines.

Phase 2 comprised consolidation trials similar to those performed by Munro and Smirk (2012) using marked wooden gauge poles. The findings and observations will be explained in the results section.

2.1 Phase 1: Exploratory work

In the first phase of the trial, it had to be established that mechanical scrolling could achieve significant dewatering performance when compared to undisturbed control areas. Initially, RSF modelling and life-of-mine calculations targeted a final dry density of 0.95 t/m^3 that had to be achieved on the existing facility, to ensure that the final fines volumes could be reduced enough to negate the need for capital-intensive deposition infrastructure in the future.

It was also hypothesised that there would be differences between moisture content in the scroll depressions and on the scroll ridges. An example of the scroll ridges and depressions is shown in Figure 1.

The scroll depressions and ridges were sampled independently and compared to the moistures of the control areas, to determine whether there were significant differences in moisture content.

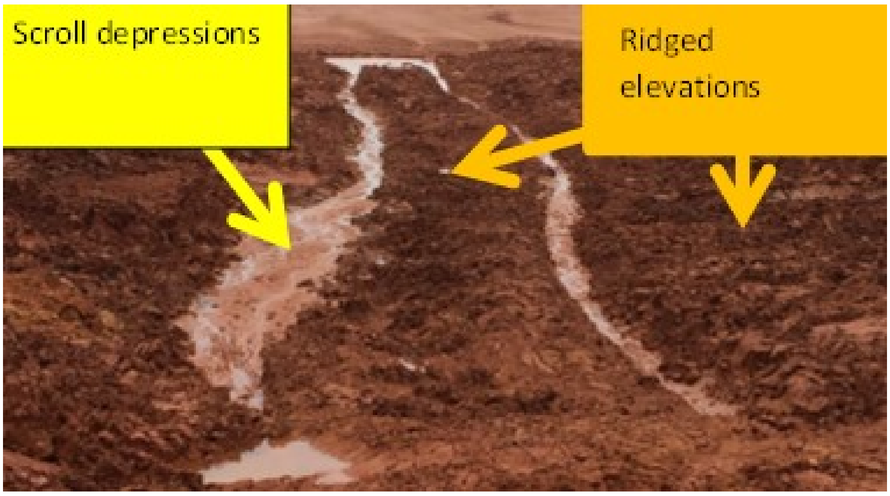

Figure 1 Showing the two distinct rolled regions that were sampled

The ability to deposit in evenly distributed layers on a level surface was initially challenging due to undulating topography. This improved as the underlying layers filled in depressions, and could be used as a consistent base in the later tests.

It was found that the heterogeneity of the bulk material, both in the control and rolled areas, required repeated campaign iterations to generate a body of data that could establish statistical certainty of a dewatering effect. The student t-test was applied to the data generated from samples from both the 'rolled' and 'unrolled/control' paddocks in order to assess whether a statistical difference existed or not.

After initially establishing that the sample variance was too high to prove significant differences in the trials versus the control (due to the low number of paddock samples), the number of samples (n) had to be increased to prove significant difference. The samples (n_c) per control plot were increased from seven to 10 and the number of samples (n_r) per scrolled plot were increased from seven to 15.

2.2 Emulation of Munro and Smirk (2012) consolidation trials

Two consolidation trials were developed in line with those indicated in Munro and Smirk (2012), and the hypothesis to be tested was slightly different for each.

The intent of the consolidation trials was to discover the consolidation and bleed behaviour of the deposited fines and how it releases moisture in reaction to mechanical scrolling by the mud-crawler. The use of graded wooden gauge poles was a novel way of understanding volume changes as a function of water bleed removal in certain cross-sections of the paddock.

Paddock 1 was a rectangular paddock constructed in a sufficiently dewatered and accessible section of the RSF, with dimensions described in the sketched diagram of Figure 2. The main hypothesis tested was whether there was an improvement in fines dewatering because of consolidation enhanced by the mechanical movement of the mud-crawler rolled along the contour.

Details of the trial setup:

1. Two rows of gauge poles spaced at 2 m intervals were placed in the rolled clay fines on the MSRSF.
2. The two parallel rows are spaced 10 m from each other.
3. The filling point is 27 m and 37 m from the two rows of gauge poles, indicated by an arrow in the bottom corner of the sketch.
4. Bund walls were constructed around the trial paddock to retain the fines as it was pumped from the Primary Wet Plant's positive displacement pumps.

5. Slurry feed from the dewatering thickeners was sampled as it exited the pipe to quantify the initial solids and water mass composition and particle size distribution of the deposited material.
6. The gauge poles were surveyed with a theodolite to ensure that the tops of each peg was at the same horizontal level.
7. Each gauge pole was marked at 5 cm intervals using nails to allow the paddock surface level to be ascertained.
8. Due to the undulating initial floor height, the vertical height of each gauge pole above the ground was recorded, to allow for overall volume changes in the deposited layers.
9. The gauge pole height was recorded after each slurry fill event and then used as a datum, against which the % volume change of the fines was calculated, as a result of moisture bleed losses with time.
10. Bund walls were periodically broken in sections to remove surface bleed water and were repaired before each fill cycle to retain the next cycle of deposited fines material.
11. The trial was started on 1 June 2018 (low solar radiation and evaporative conditions).

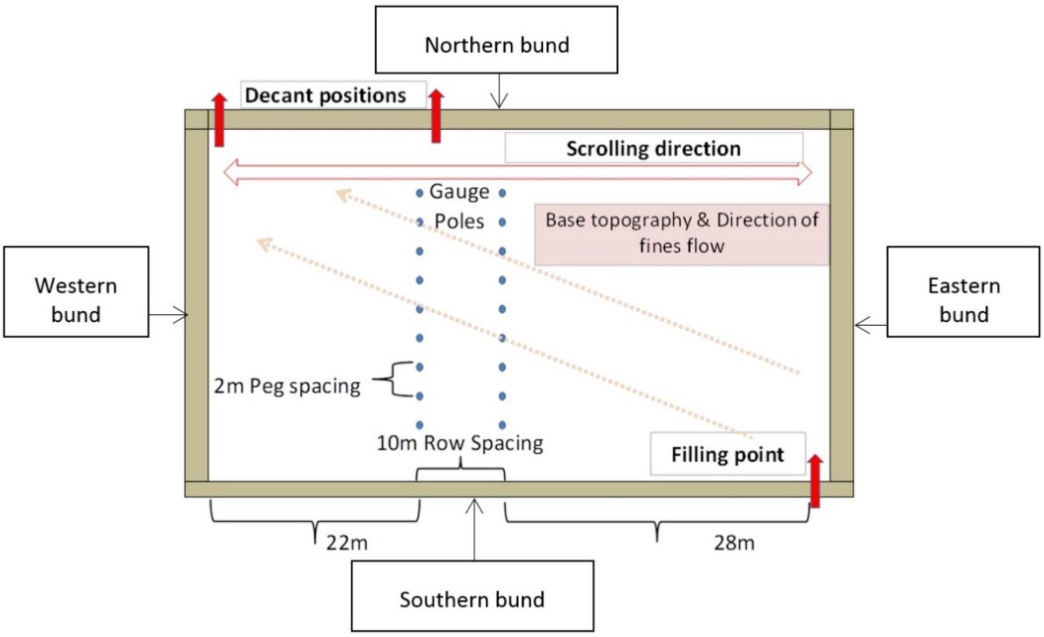

Figure 2 Sketch showing the setup of the first consolidation trial paddock

Paddock 2 was constructed in a similar way adjacent to paddock 1, but with perpendicular gauge pole rows intersecting to form a cross. The intention was to test the effects of scrolling perpendicular on the beach profile of the material.

A secondary part to the test was to quantify the size and reach of the 'displacement' ridges observed in the first paddock trials. It was theorised that the elevated displacement ridges would be used to increase the bleed rate of water due to its raised phreatic surface. The size of the displacement ridge and horizontal reach would allow for the calculation of the required roll spacing, to achieve maximum dewatering effect with minimal effort.

The mud-crawler was made to scroll parallel to row 1 and to intersect row 2 on either side of the middle gauge pole line. The middle gauge pole line (row 1) would provide information on the beach slope angle and the perpendicular line would give an indication as to the cross-sectional profile of the material as a result of the formation of the displacement ridges and scroll depressions. The gauge pole spacing was 4 m on the 'perpendicular' gauge pole line (row 2) and 2 m on the 'parallel' gauge pole line (row 1), to provide granularity (Figure 3).

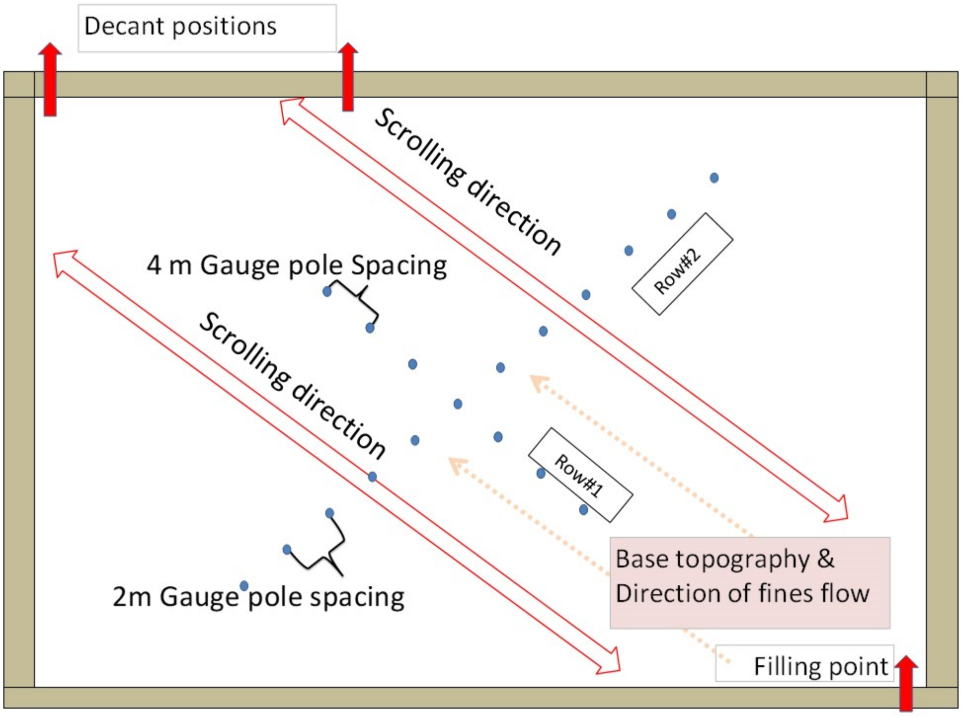

Figure 3 Paddock 2 consolidation trial

2.3 Sampling methodology

Core sampling of the exploratory rolling trials was performed on the surface of the rolled and control paddocks using a gouge sampler, with dimensions of 1 × 1 × 30 cm inserted 10 cm below the surface and delivered directly into sealed plastic sample packets. Each position was sampled three times to generate enough sample mass for laboratory analysis. The closed packet samples were delivered to the laboratory within three to four hours for immediate analysis.

Slurry samples taken from thickeners and on the RSF thickened tailings discharge points were collected in closed plastic buckets or sample bottles (depending on sample mass requirement).

The consolidation trial paddocks were sampled from the surface, using an extendable sample scoop, which allowed sampling away from the paddock boundaries to remove wall effects. Samples were taken according to visual surface observations, (i.e. 'dull', 'rough', 'water-logged'/'shiny', 'cracks appearing') in an attempt to be representative of the paddock according to appearance.

3 Results

3.1 Physical characteristics

Using results from Feng and Yang (2010), Poulos et al. (1985) and Ribeiro et al. (2011), typical red mud size distributions from Canada, China and Brazil are plotted against the Fairbreeze fines. Figure 4 indicates the comparison of Fairbreeze fines plotted against red mud, but also shows the comparison between de-flocculated hydrometer (geotechnical definitions) and the Malvern analysis of the same Fairbreeze fines sample.

It was intended with this comparison to understand the referenced materials and to understand the potential behaviour differences between red mud and Fairbreeze fines.

There are several differences between the dispersed hydrometer fines determination method and the Malvern Mastersizer, which are not explored in this article. The main reasons for differences are that the hydrometer method makes use of dispersant to break up the flocculated agglomerates into individual particles whereas the Malvern method analyses the agglomerates as individual particles. This explains the shift in d_{50} = 2 µm for hydrometer analysis and d_{50} = 10 µm for the Malvern analyser.

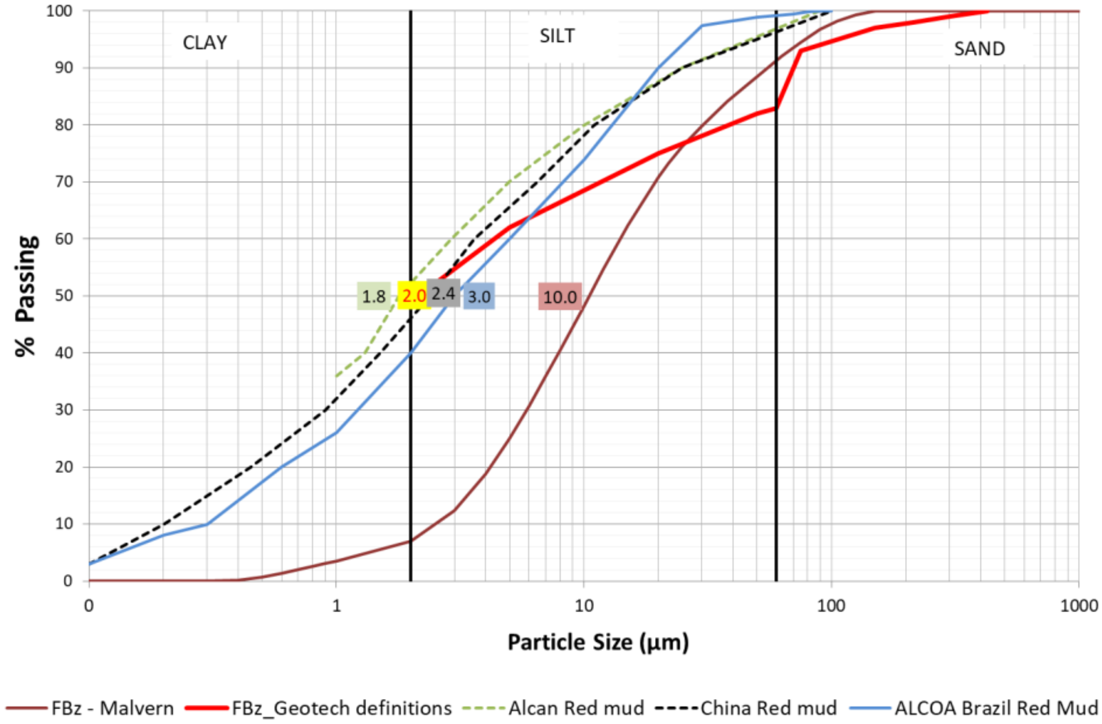

Figure 4 Particle size distribution comparison between Fairbreeze fines and typical bauxite red mud analysed using the hydrometer/screening combination and the Malvern Mastersizer

Due to quick turnaround time and ease of use, the Malvern Mastersizer was used in these trials, to account for the +75 µm sand content in the samples. The presence of oversize sand alters the % solids dependent behaviours of the samples.

3.2 Dewatering effects of the exploratory trials

The results in Figure 5 are a comparison between the scroll depression (sample taken from the bottom of the scroll depressions, just above the saturated zone) and ridge samples (sample taken from the raised displacement ridges formed between the scrolls) taken from the initial paddock trials. Unfortunately, due to the high variability and the number of replications taken per paddock (n = 7), it was not possible to prove statistically significant relationships between scroll depressions, unscrolled areas and scroll ridges.

It was decided to increase the number of samples, 'n', for control and scrolled/ridged paddocks to n_c = 10 and n_r = 15 respectively. This allowed for a greater degree of certainty and could prove statistical significance within the 95% confidence limits.

With increased sample population sizes, it was possible to prove statistically significant effects of mechanical fines handling on the removal of free water from Fairbreeze fines.

Once it was established that larger sample populations were needed, the deposition and scrolling cycle was repeated in the trial area, and the scrolled areas and unscrolled control areas were sampled to establish the effects of scrolling on the dewatering rate of deposited fines.

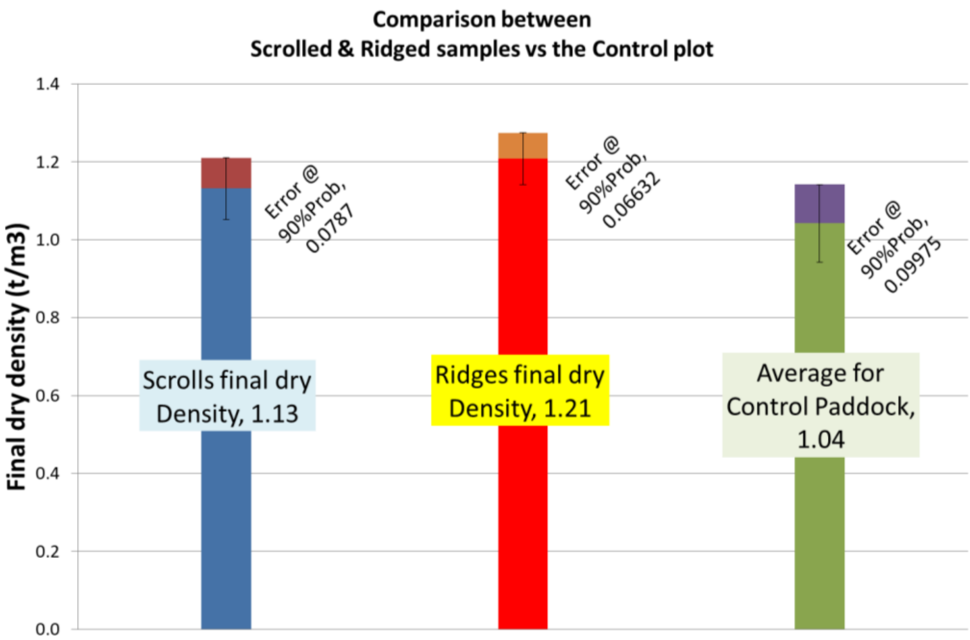

Figure 5 Plot of final dry density for scroll depressions, raised ridges and unrolled control paddocks

The comparative results in Figure 6 showing the scrolled and unscrolled control final dry density results indicate that there is a significant effect when amphibious scrollers are used to mechanically dewater deposited fines at Fairbreeze.

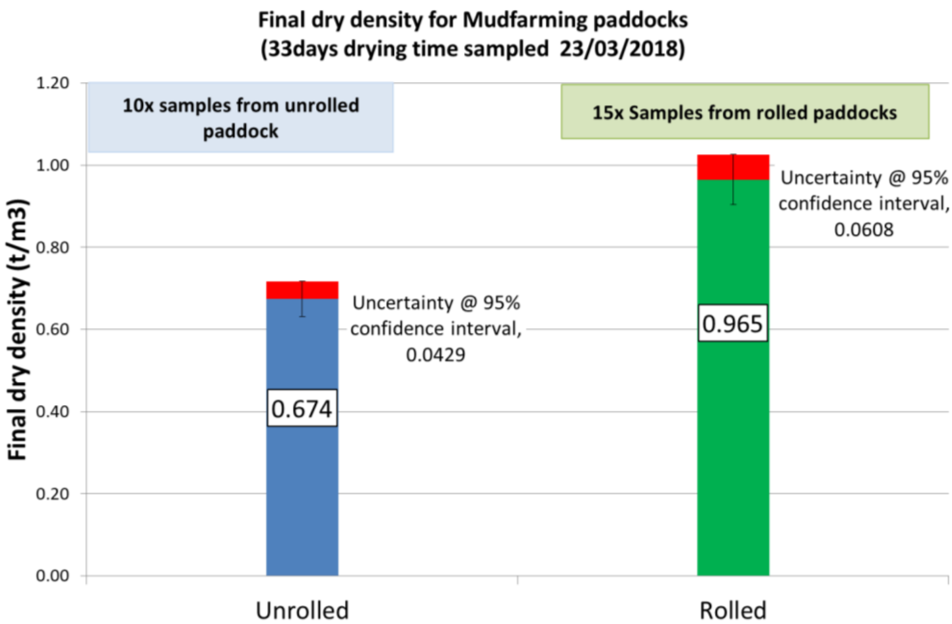

Figure 6 Effect of mechanical mud farming on the final dry density achieved on Fairbreeze fines

3.3 Results – Munro and Smirk (2012) emulation trials

3.3.1 Paddock 1 consolidation results

Initially it was found that the consolidation of the deposited material was being affected by the underlying base layers deposited previously, and the uneven consolidation was causing the formation of pools of bleed water in certain areas of the trial paddocks. The first paddock also experienced water pooling due to the nature of its design where the scrolling occurred along the contours and not cross contour. This pooling observation informed the change in paddock design and led to the creation of the second paddock.

The effects of the pooling of free water are shown in Figure 7. The change in paddock elevation at points indicated by A, B and C shows how the removal of water off the paddock surface accelerated the paddock dewatering and consolidation process by as much as 2–5%.

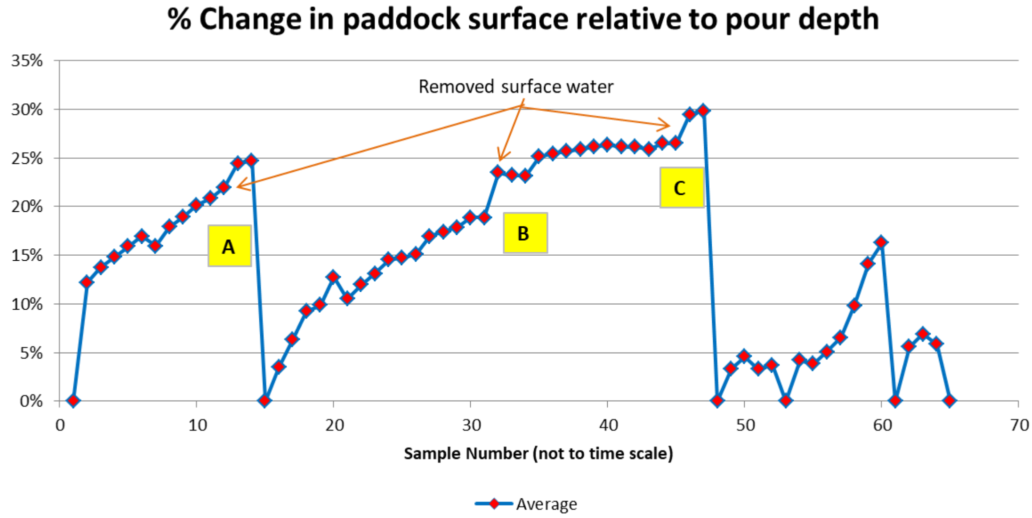

Figure 7 Effect of removal of free bleed water on the subsequent consolidation of deposited clay fines

The initial settling observations then informed the way in which the future paddocks were scrolled and managed. A decision was made to roll at a slight angle (changed from 'on contour' to slightly 'cross contour'), to ensure that there was free-draining bleed water from the paddocks, thus preventing the formation of pooled water.

Another observation was the formation of a displacement ridge when scrolling. Figure 8 indicates the displacement ridge at a distance of between 5 and 8 m from the scroll lines. The elevated displacement ridge also shows visible signs of bleed escaping at the toe of the ridge (between gauge poles 4 and 5 numbered from the right).

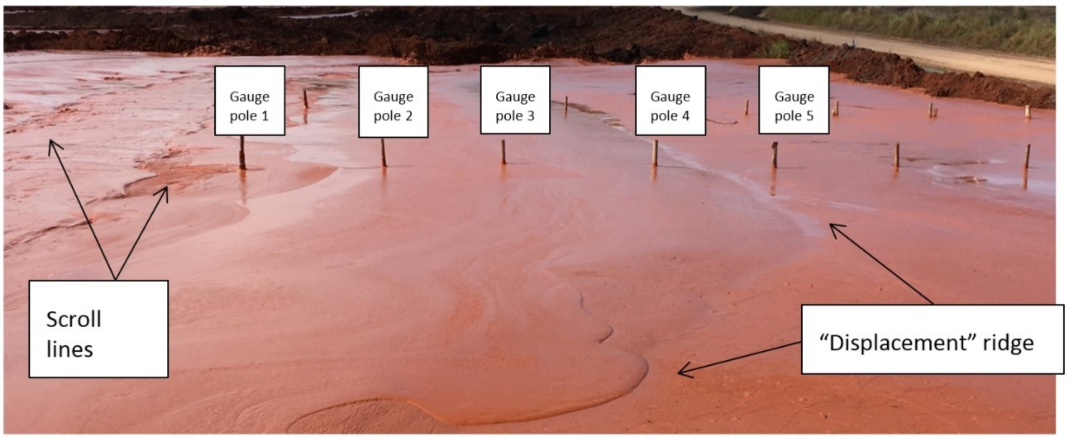

Figure 8 Recently rolled paddock indicating an elevated displacement ridge

The displacement ridge size seemed to be larger when the material was rolled within 3–5 days of deposition, (probably due to its low yield stress). Some of the displacement ridges that formed during rolling later in the drying cycle were only 3–4 m.

Figure 9 gives the paddock surface contours indicated by the gauge pole heights measured in metres from the gauge pole closest to the scroll depression. It indicates the paddock sloping gently to the left, and the displacement ridge is evident at its peak at about 4 m from the start of the gauge poles and about 5 m from the edge of the scroll depression.

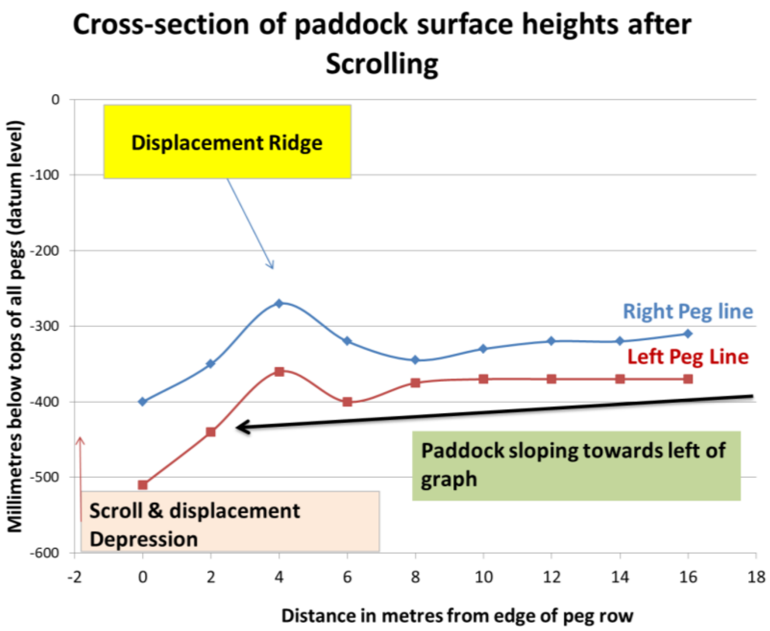

Figure 9 Gauge pole heights measured below datum indicating Paddock 1 just after scrolling

The second trial paddock was then designed to quantify the extent and height of the displacement ridge, to allow for modelling of the rolling intensity required on the entire RSF.

3.3.2 Paddock 2 consolidation results

The consolidation behaviour of the material in the second paddock is indicated in Figure 10. The construction of paddock 2 (Figure 3) and the allowance for free drainage perpendicular to the slope contour meant that the scrolling direction was almost parallel to the mud slope. This prevented accumulation of surface water and facilitated free bleed water drainage.

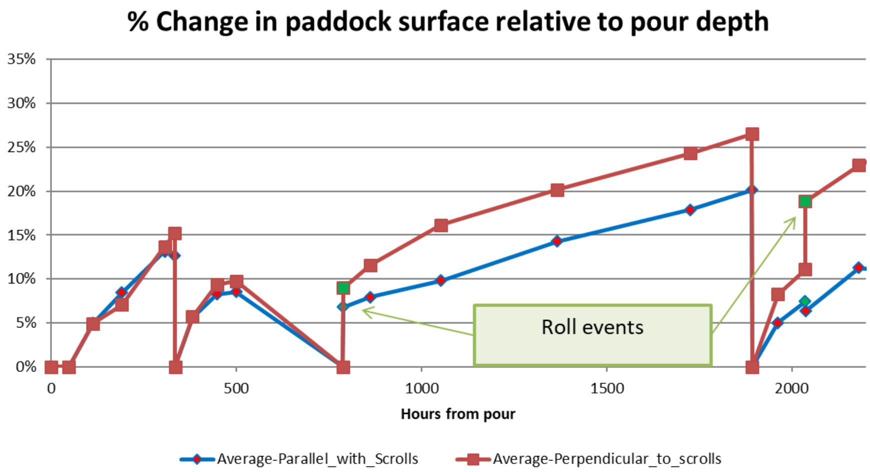

Figure 10 Consolidation results from Paddock 2 indicating the effect of a displacement ridge on the parallel gauge pole line compared to the perpendicular gauge pole line

Between hours 1000 and 1800 of the trial, the series labelled 'Average-Perpendicular_to_Scrolls' shows a 5% settlement offset relative to the 'Average-Parallel_with_Scrolls' height. This offset shows the effect of the displacement ridge on the two sections. The apparent rise in the 'Perpendicular' and drop in the 'Parallel' series at hour 2000 indicates that material was displaced in the second scrolling process.

Figure 11 shows the cross-sectional height of the paddock surface post a rolling intervention. The diagram clearly indicates the scroll depressions, inter-scroll ridges and the displacement ridges generated by the moving machine.

The undulating surface depicted in Figure 11 facilitates more rapid bleed of water due to decreased horizontal paths of travel and the removal of water pooling from the fines surface.

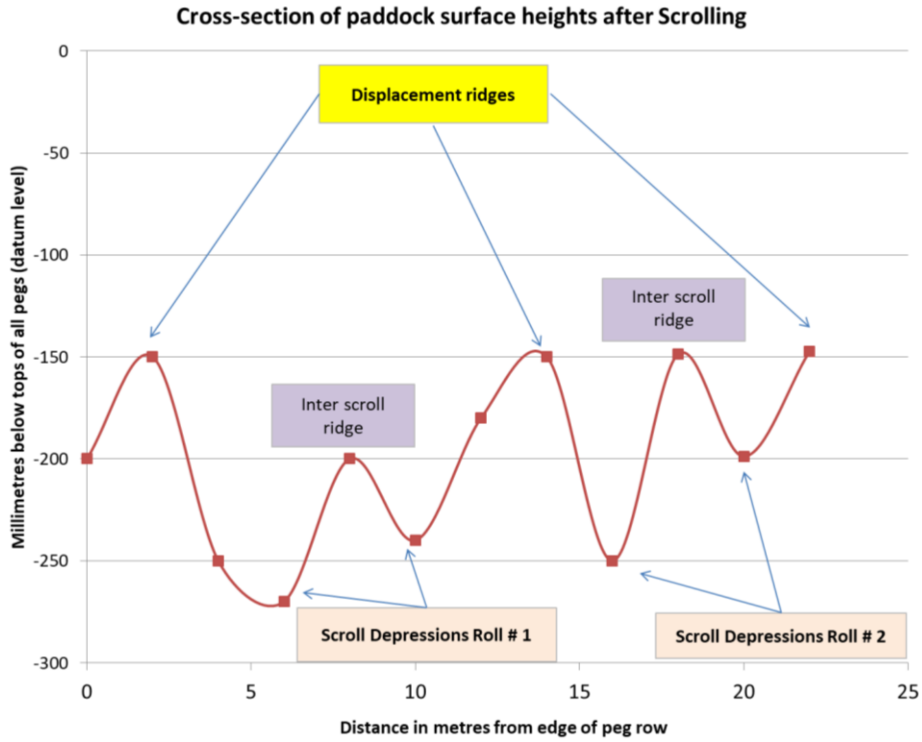

Figure 11 Gauge pole heights measured below datum indicating Paddock 2 just after scrolling

3.4 Trafficability challenges

A critical parameter that has the most influence on the success of the mud-crawler dewatering intervention would be the ability of the vehicles to travel and cover the 257 ha RSF surface within a specific time frame. The mud-crawler's travelling speed is the key to determining the number of machines required and will ultimately determine the operating costs.

The difficulties experienced by the Fairbreeze amphibious scrollers to propel themselves without competent underfoot conditions are confirmed in Munro and Smirk (2012) where it was concluded that as the disposal layer depth increases beyond their observed optimum of 1.2 m, the mud-crawler travel rate is severely inhibited.

At Fairbreeze, the movement of the mud-crawlers in deeper fines areas (in excess of 900 mm) was partly facilitated by means of an excavator arm that was operated as a 'paddle' to facilitate the dragging of the chassis through the thickened material. This method and the chassis dragging can be seen in Figure 12.

Munro and Smirk (2012) also stated that "The availability of a competent and suitable underfoot surface is critical to the optimal operation of the mud-crawlers".

The reduced clearance between the bottom of the crawler chassis was also found to introduce extra bottom drag resistance, retarding the progress of the vehicle through the mud.

Figure 12 Mud-crawler moving through clay fines indicating bottom drag on chassis

To increase the clearance of the chassis above the mud surface and to reduce the bottom drag effects, the machine manufacturer has implemented a solution to increase the length of the scroll support arms and scroll diameters to improve buoyancy and reduce the submerged effective area for drag.

The improved scroll machine has indicated a significant improvement in travel speed with a noticeable reduction in bottom drag as well as elimination of the need to make use of the excavator arm to propel itself.

Figure 12 clearly shows the build-up of fines on the scroll surfaces. This accumulation of 'sticky' material onto the scroll surface was noticed as being a major retardant in the ability of the crawlers to travel effectively in the lower yield stress areas of the RSF.

This inter-flight build-up has not been as marked on the improved vehicle and the improved scrolls have been able to self-clean in the event of travel through sticky material.

An active mud farming contracting company has also ventured into mud farming on phosphate clay fines, and states on their website (Phibion Tailings Management – Case Studies (Phibion 2018)) that:

> *"Phosphate tailings represent a dewatering challenge due to their high clay content, limited drainage and low density."*

and

> *"In situ management of the tailings is difficult due to the propensity of the materials to stick to metal surfaces as well as the uncertain strength available to support safe operations".*

Similar physical properties have been experienced with amphibious scrolling equipment on trial at Fairbreeze.

3.4.1 Results of travel speed trials

The travel rates of the amphibious scrollers were determined using the Intelli-IQ global positioning system which logs the distance travelled and machine hours at specific points.

The highest 10% of the travel distances achieved in a sampled time period were selected to calculate the undisturbed speed of travel in the low yield stress areas. This ensured that the data selected excluded periods where the mud-crawlers were constructing bund walls, building ridges or performing stationary tasks using their excavator buckets, thus simulating the continuous scrolling operations described in the numerous literatures.

The average ‘unrestricted’ travel speed achieved with the original (chassis dragging) amphibious scrollers was calculated to be 0.1 km/hr in the low yield stress fines. This value has improved to around 0.16 km/hr in low yield areas, with the better clearance provided by the larger scrolls of the modified machine and the reduced fines build-up on the scrolls.

The competent underfoot conditions, which are expected to improve as the machines reclaim softer areas with regular scrolling activity, allowed the machines to achieve travel speeds of up to 0.8 km/hr.

An average travel speed attainment of 0.43 km/hr has been used to perform scroller coverage calculations.

Table 1 indicates the important variables that are used in the amphibious scroller scrolling intensity calculations and the expected surface coverage on the current facility. A short explanation for each value is given in the right-hand column.

Table 1 Critical amphibious scroller performance variables used in the financial feasibility study

Variable	Units	Comments
12 hr	hrs per day (1 shift system)	Day shift only
0.43 km/hr	km/h of operation	Upgraded machine travel rate
9.3 hrs	Effective scrolling time (hrs)	Excluding refuelling, travel time and inspections
3.6 km	km travelled per day per scroller	–
14.62 m	Scroll intensity	Centre-to-centre distance between consecutive parallel scroll sets
684 m	Distance to be covered per hectare	At the calculated scroll spacing/intensity
1500 ha	hectares covered per year per machine	1 machine operating as a scroller continuously
257 ha	Area to be scrolled	Open area excluding pool of MSRSF
12 cycles/yr	Rotation cycles for two machines	Machines operating in fines material

Table 1 indicates that the current RSF sub-aerial deposition working surface can be scrolled at least once per month with a fleet of two amphibious scrollers, affecting a 1 m deep fines layer.

Increased effective scrolling time per shift and the use of a 24-hour shift system would also increase the mud-crawler coverage and the average depth affected, thus improving dewatering effectiveness.

4 Conclusion

With unlimited access to scroller resources, it can be expected that the final dry density of Fairbreeze fines can be improved by 43% from 0.674 t/m^3 to 0.965 t/m^3 in a 30-day deposition cycle, with the use of mud-crawling equipment.

When operating in low yield stress fines, the displacement of fines by the amphibious scroller creates a displacement ridge that can extend between 5 and 8 m from the scroll edges. Measurements from the trials indicate this displacement ridge to be in the region of 30–50 mm above the original beach. The displacement wave pushes the settled fines above the surrounding beach elevation, thus creating an enhanced hydraulic gradient that facilitates faster drainage.

By manipulating the scroll spacing intensity, the displacement ridges can be optimised to bleed material into the parallel scroll depressions and ensure a row spacing of 14.62 m between parallel scroll lines, while still affecting the settling and dewatering of the entire MSRSF facility. This spacing will allow a pair of upgraded amphibious scrollers to cover the 257 ha MSRSF area at least once a month, with scope for optimisation and improvement.

The consolidation trials indicate a marked benefit of 2–5% consolidation increases immediately after the removal of surface bleed water from the consolidating fines surface.

The behaviour of the Fairbreeze fines and its tendency to stick onto the steel scrolls is similar to the observations in the phosphate industry and will have to be understood and managed so as not to retard future amphibious scroller progress.

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