# Beach Profile Modeling at Centinela Mine, Chile

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## ABSTRACT

Since 2012, pilot, semi-industrial and industrial tests have been carried out to design a new and improved distribution and discharge system and generate a steeper beach profile on the Minera Centinela tailings facility. Spigot flow rates from 0.3 to 200 $m^3$/hr were originally tested followed by a large-scale trial of 20 simultaneous independent discharges of equal flow spaced at 60m centers. In 2014, the large-scale trial was implemented and has now been operating for approximately two and a half years and constitutes the "new spigot system" and is being operated at more than 90,000 tons per day.

Prior to the implementation of the new spigot system, the tailings were "stacked" using small, stepped, paddocks requiring the full time use of several excavators to construct confining embankments. Beach slopes within the paddocks were less than 1 %. During the commissioning period of the spigot system, deposition in these paddocks was slowly phased out as they were progressively covered by the continuous beach formed by the new system.

Over this period, there have been opportunities to review the topography of the tailings facility, update the rheology through additional tests at the laboratory and pilot scale level, and carry out calibrations based on the actual measurements of the beach profile and discharge conditions. Progressive increases in the concentration of solids of the tailings have further contributed to an increase in the generated beach slopes.

From the calibrations made to date, only minor adjustments to the rheology estimates made at the laboratory level have been necessary. These adjustments are in line with both mineralogical and operational variability of any concentrator plant and are within the range of variability and uncertainty associated with beach modeling.

This paper describes the development of the discharge system, its implementation and experiences, and the calibrations.

## INTRODUCTION

Beach profile prediction at Minera Centinela is particularly important since this determines the timing and elevation of construction of confining embankments as well as the timing of pump installations. The mine produces tailings at a nominal rate of 105,000 tpd so deposition planning is vital and key to this is confidence in beach profile prediction.

However, beach profile prediction methods are not settled science. A range of methods exist all with promise but the problem of verification comes down to comparisons of predictions with actual beaches which take several years to develop.

The issue of beach profile prediction became a focus issue for Minera Centinela in 2012 when it was clear that their existing methods of deposition and slurry generation were not sustainable. At that stage Minera Centinela embarked on a program of paste thickener construction to increase the percent solids in the tailings slurry. In tandem with this was a program of beaching related rheological testing, beach prediction and beaching trials. The paste thickeners were commissioned in 2015 and, inevitably, since they were the largest of their kind worldwide, Minera Centinela experienced problems with reliability. As these problems have been progressively addressed the slurry percent solids levels have steadily increased from 62 % solids by weight to close to 64 % solids. Since the end of 2016 to date the solids discharged to the tailings deposit have averaged more than 65 % solids with a continuing progressive increase.

During this time slurry discharge headers have been commissioned and beaches have been developed over the temporary paddocks formed using continuous construction techniques necessary to enable a degree of stacking of the tailings to limit the elevations of confining embankments. The headers have been regarded as full scale trials for proving up discharge designs and beach predictions and have provided an essential platform for the comparison of predictions with actual beaches.

The issue of beach prediction and beach development is not simply a matter of the beach modeling method. All the current prediction methods, understandably, rely on the application of representative rheological parameters which, during design, need to be estimated using laboratory and pilot scale testing methods. There are issues with representative sampling of the tailings which is affected by variations in the ore mineralogy and processing plant reliability. The laboratory testing methods are subject to issues of settling out and segregation during testing which affects the validity of the results. And then there are other external issues that affect the beaching characteristics such as operational practices in terms of thickener control, as well as discharge management on the Tailing Storage Facility (TSF).

This paper presents the chronology of beach prediction, comparison and calibration at Minera Centinela over the period from 2012 to August 2016 and provides an indication of the relative reliability of the modeling and the testing methods employed, as well as the calibrations carried out to improve prediction reliability.

## 2012 TO 2013

As noted in the introduction issues with slurry percent solids and discharge methods came to a head in 2012 by which stage the TSF comprised a series of small paddocks formed using the tailings themselves together with intermediate confining embankments constructed of mine waste rock. These are evident in Figure 1.


**Figure 1** Aerial photo of TSF in 2012

In parallel with thickener assessments a program of beaching-related rheological testing at a range of percent solids from 57 % to 69 % was carried out entailing:

- Rotary viscometer testing
- Vane rheometer testing
- Small scale flume testing (200mm wide, 2m long flume)
- Pilot-scale beach testing (3m wide by 10m long paddock).

The objective of the small-scale flume testing (McPhail, 2008, 2014) was to enable the measurement of points on the slurry flow curve at shear rates of below 20 $s^{-1}$ below which rotary viscometer test results are of poor reliability due to settling out of the slurry in the cup. Beach modeling using the stream-power entropy method (McPhail 1995, Charlebois et al, 2013) and the rheological parameters from the above testing indicated that a flow rate of 130 $m^3/h$ per discharge (flow stream down the beach) would significantly improve the beach slope.

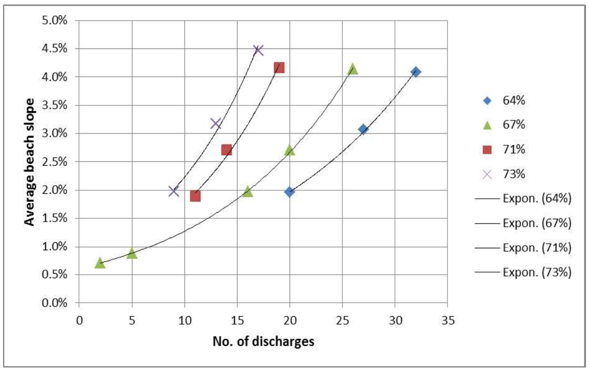


**Figure 2** Plots showing predicted average beach slope vs number of discharges over a range of solids concentrations

Based on the above predictions Minera Centinela constructed and commissioned a semi-industrial-scale trial deposition into a paddock approximately 100m square to receive discharge at 45m$^3$/h at two locations operated independently (Gaete and Bello et al, 2014). The paddock and a discharge are indicated in Figure 3.

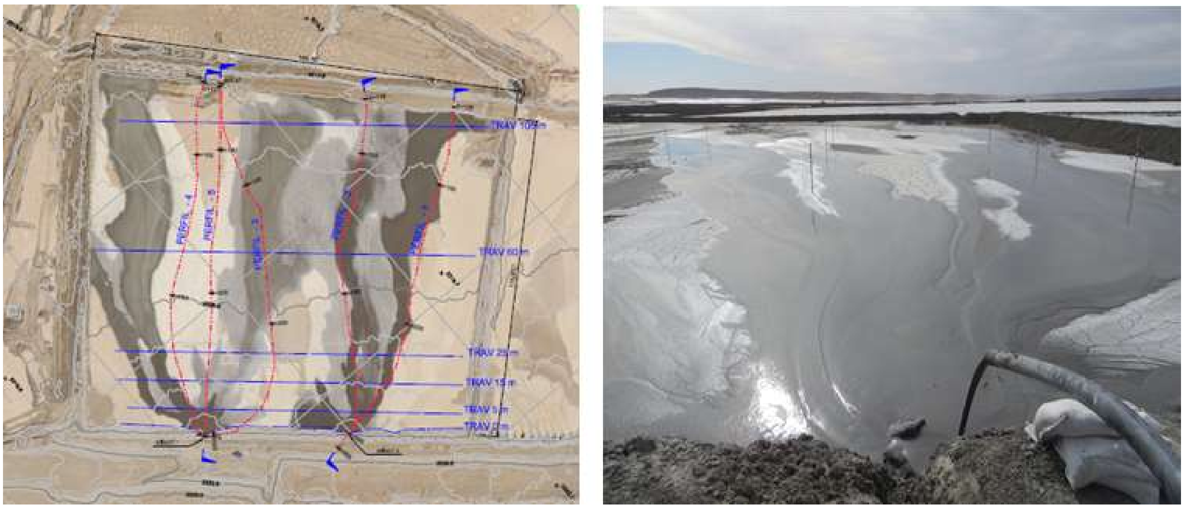

**Figure 3** Semi-industrial-scale trial paddock

**Table 1** shows the average beach slopes before, during and after the trial. Beach slopes developed to values higher than 2.75 % and trended to 3 %, up from 1 % to 2 % before the trial. A comparison with the beach predictions for the semi-industrial scale deposition indicated that the predicted beaches slightly under-estimated the actual beach; the predicted beach was 2.6 % for the flow rate and paddock dimensions compared with approximately 3 %. Part of this difference could potentially be ascribed to the representativeness of the lab samples on which the predictions were based given the variability in the slurry rheology measured on samples taken during the semi-industrial scale trial. This rheology is indicated in

**Table 2** and results from grind, mineralogical and thickener variability. But part of the difference can be accounted for by taking into account the meandering nature of the flow streams and the effective lengthening of the beach length. This can be effected by multiplying the direct beach length by the square root of 2 (McPhail, 2015).

**Table 1** Beach slopes in trial paddock

| | Average Beach Slope % | | |
|---|---|---|---|
| | **Before Trials** | **Mid-October 2013** | **End of Trials (Early November 2013)** |
| Profile 1 | 1.07% | 2.48% | 2.75% |
| Profile 2 | 0.98% | 2.55% | 2.96% |
| Profile 3 | 1.82% | 2.37% | 2.82% |
| Profile 4 | 1.82% | 2.86% | 2.93% |
| Profile 5 | 1.89% | 2.91% | 3.11% |

**Table 2** Variability of measured rheology during the deposition trials

| | **% Solids (% w/w)** | **Viscosity (Pa.s)** | **Bingham Yield Stress (Pa)** | **$P_{80}$ (µm)** | **S.G Solids ($t/m^3$)** | **Spigot Flow Rate ($m^3/hr$)** |
|---|---|---|---|---|---|---|
| Minimum | 59.7 | 0.0213 | 10.0 | 119 | 2.67 | 34.1 |
| Maximum | 64.8 | 0.0540 | 34.0 | 170 | 2.84 | 53.2 |
| Average | 62.6 | 0.0379 | 21.4 | 139 | 2.75 | 44.9 |

By this stage beaching-related rheology had been estimated using a number of methods at a range of flow rates all based on stream-power entropy modelling, lab and pilot scale testing and back analysis from the semi-industrial scale trial (Gaete and Bello et al, 2014). A summary of the flow rates is provided in **Table 3**.

**Table 3** Range of flow rates and scales used to derive rheological parameters

| | **Laboratory** | **Pilot** | **Semi-Industrial** |
|---|---|---|---|
| Trial Area (width x length) | 0.2 m x 2.0 m | 3.5 m x 10 m | 120 m x 100 m |
| Discharge Flow Rate | 0.2 l/s | 3.5 l/s | 12.5 l/s |
| Volume of Tailings Deposited (pulp) | ~0.02 $m^3$ | ~3.7 $m^3$ | 9,613 $m^{3\,*}$ |

It was concluded that:

- The lab and small scale flume testing provided reasonable estimates of beaching-related rheology.
- The stream-power entropy modeling approach provided reasonable estimates of the average beach slope.

The results gave Minera Centinela the confidence to commission the design of the full-scale system as well as commission a full scale temporary system for training purposes. This temporary system, referred to as Peineta Corto Plazo (PCP), was designed to discharge for an operational discharge range from 88,000 to 105,000 tpd through 20 spigots spaced at 60 m to reduce the probability of the flow streams combining (McPhail, 2015).

## 2014 TO 2015

The PCP system was commissioned in July 2014. By February 2015 approximately 200m of beach had been developed over the paddocks as a result of discharge from the PCP system. This provided an opportunity to calibrate the beaching predictions. Figure 4 shows an aerial photo of the deposited beach from the PCP as at February 2015. Sections A and B were suitable for beach calibration passed through an emergency storage area and was irregular). September 2015

shows rheological parameters derived from small-scale flume and rotary viscometer testing carried out in March 2014. Herschel-Bulkley parameters are indicated. Parameters from the small-scale flume are applied at shear rates lower than 20 $s^{-1}$ to 50 $s^{-1}$ and parameters from the rotary viscometer are applied at shear rates above this range. Figure 5 and Figure 6 show the beach model predictions using the rheological parameters in September 2015

and actual percent solids measurements and discharge rates recorded in the period preceding each calibration model. Over the period from July 2014 to February 2015 the average slurry percent solids was 62.4 %. It is of interest to note that the stream-power entropy method requires that the total distance over which the stream power is lost be used as the beach length which accounts for the extrapolation of the beach profile beyond the initial 200m. In the actual beach there is a step down to a lower paddock at this distance with the flow stream drawn through to the lower level as well as subsequent levels through decanting pipes.

It is evident from Figure 5 and Figure 6 that the beach modeling shows promise in predicting the full-scale beach profile. It was recognized, however, that it will be important to take into account settling out in the flow stream which result in a higher concentration at the bed face. The higher concentration of solids implies higher rheology.

**Table 4** Results of rheological testing carried out in June 2014

| | | **Flume** | | | **Rotary viscometer** | |
|---|---|---|---|---|---|---|
| Text | 62 % | 64 % | 67 % | 62 % | 64 % | 67 % |
| Yield stress (Pa) | 0 | 0 | 0 | 7.9 | 10.6 | 27.7 |
| k | 1.8 | 0.845 | 9.3 | 0.036 | 0.042 | 0.072 |
| n | 0.62 | 0.98 | 0.37 | 1 | 1 | 1 |

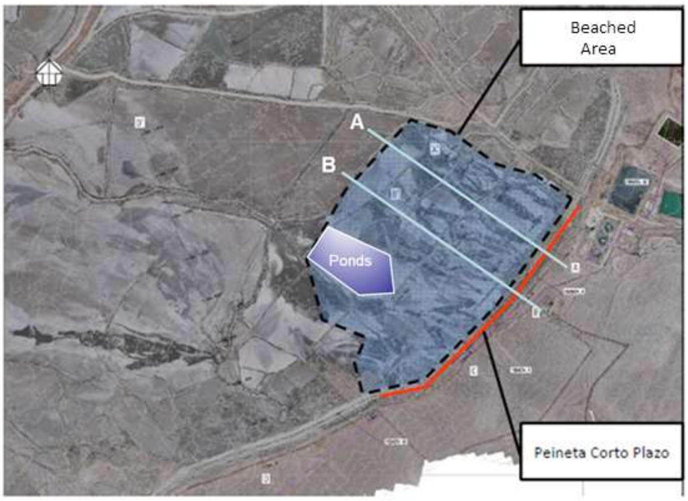


**Figure 4** Aerial photo of the PCP deposition as at September 2015

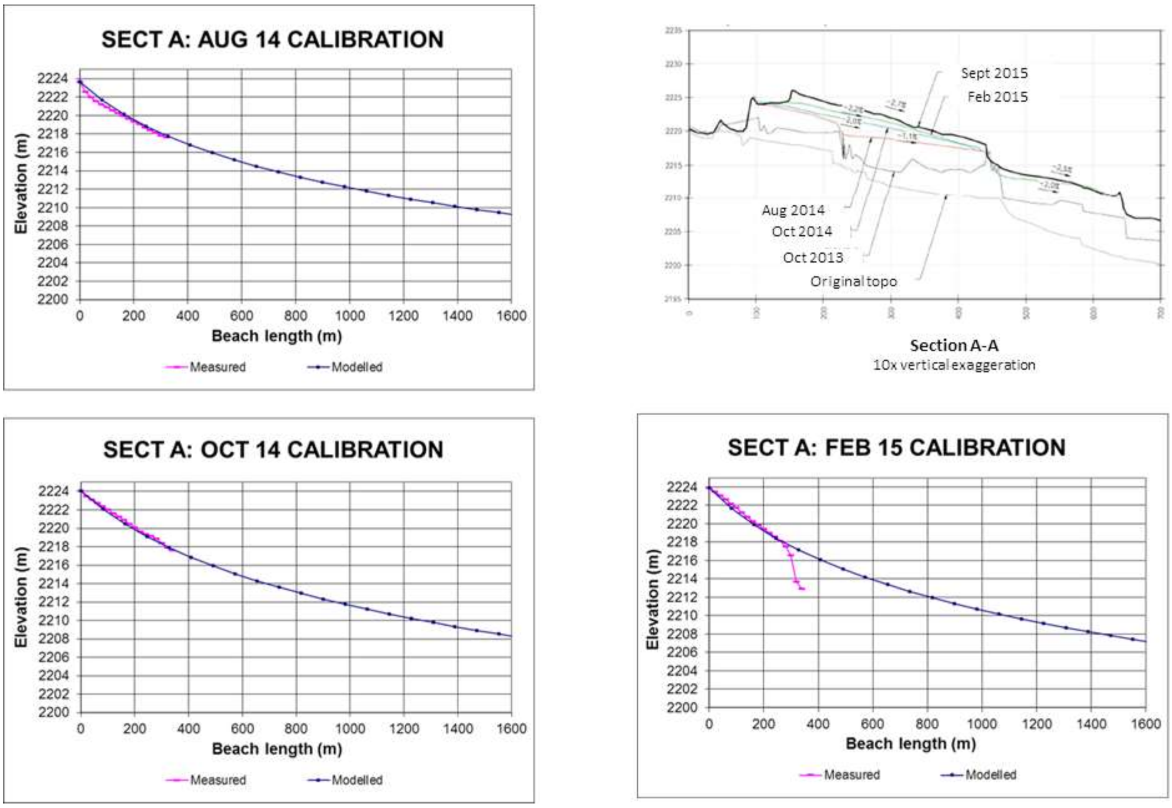


**Figure 5** Comparison of predicted vs actual beach for Section A

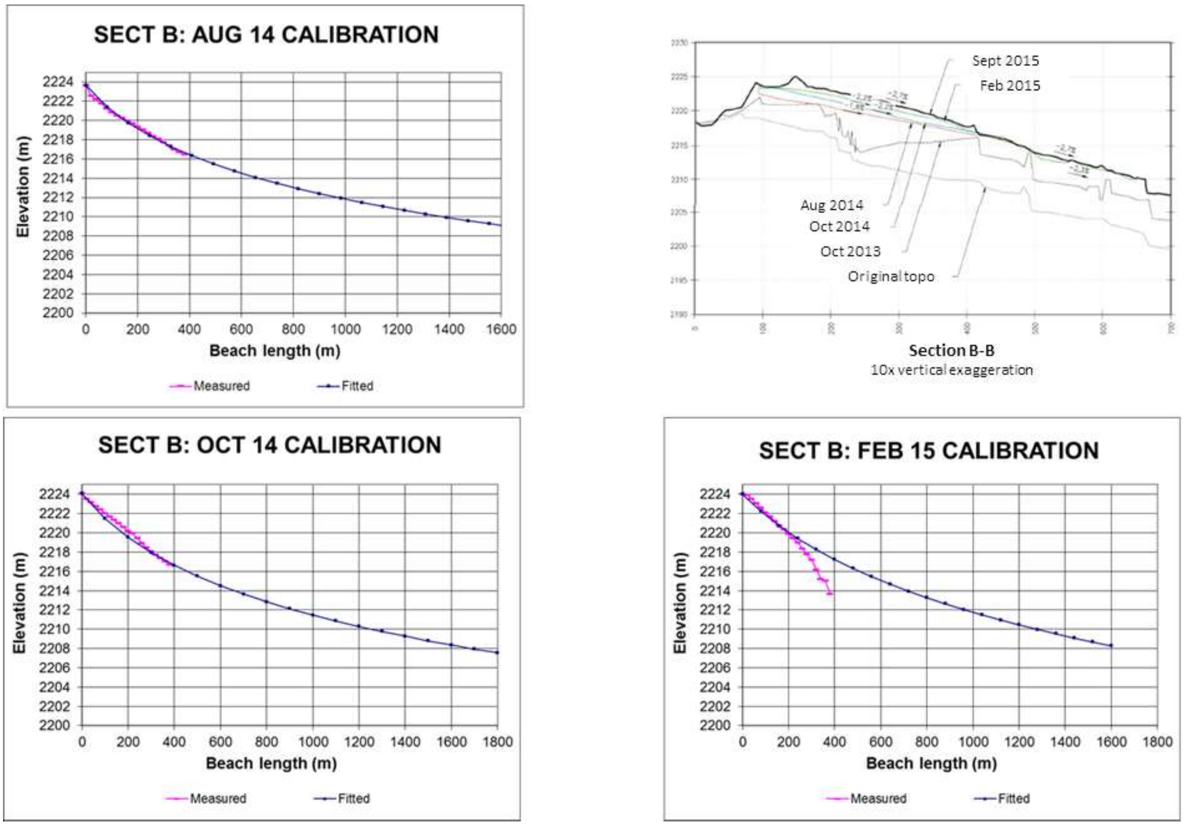


**Figure 6** Comparison of predicted vs actual beach for Section B

**2016**

A calibration using the parameters in September 2015

was carried out in 2016. During this time thickener performance had increased with the average percent solids being discharged from the PCP being 63.3 % with excursions up to 64.5 % solids and production had increased to 105,000 tpd.
Figure 7 shows a satellite photo of the TSF as at August 2016. A notable feature of this photo is the fact that the flow streams from the spigots, which are spaced at 60 m centers, remain independent ie do not combine over the beach length of almost 2 km.

Figure 8 shows the contours down the beaches and the locations of three sections used to compare modeled and measured beaches. Also indicated are the locations of steps in the beach that are residual from past paddock operation.

Calibration modeling was carried out to generate the best fit to Section 2 which is relatively free of residual steps from the old paddocks and then applying these parameters to Sections 1 and 3. This is also the longest of the three beaches at nearly 2,000 m.

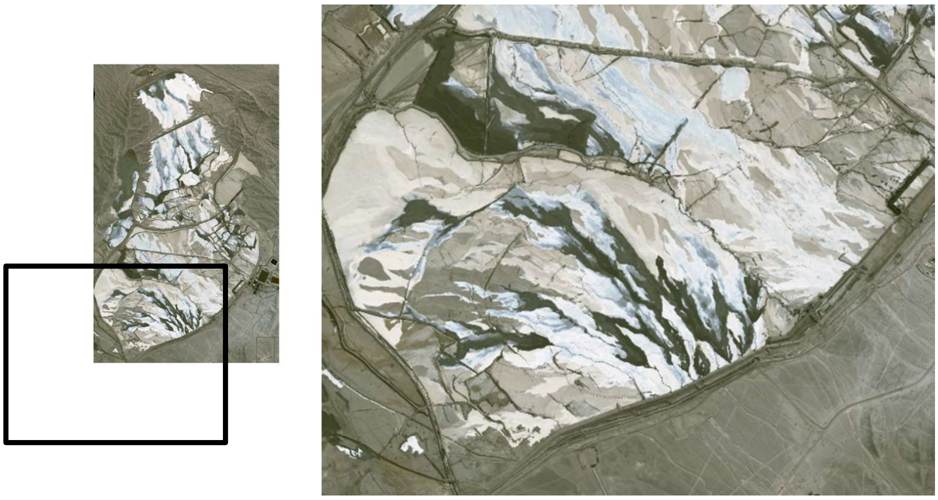

**Figure 7** Aerial photo of the PCP beach as at August 2016

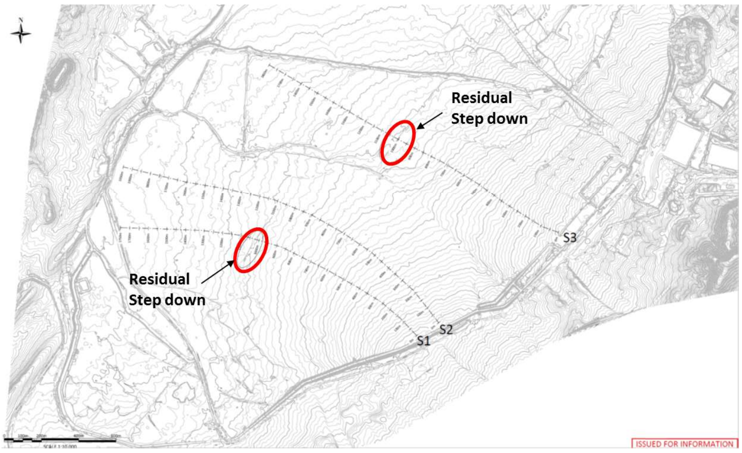


**Figure 8** Plan showing beach contours from discharge from the PCP

The calibration incorporated modeling of the settling out of solids within the tailings stream such as is observed in pipe flow when flow velocities are close to the settling velocity. This gradient means that the concentration of solids at the depositing bed face in the flow stream is higher than the average concentration which means that the rheology at the bed face will be higher. Also, since the solids that are deposited at the bed face have a higher concentration than the average, the water entrained during deposition will be lower than the average in the flow stream. This means that the concentration in the flow stream will be reducing with distance down the beach.

To model this effect a fluidized bed column test was developed (McPhail et al 2016) in which the slurry is pumped up a 2m column and recirculated to establish equilibrium. The column enables simulation of the reduction in stream power which would normally occur in the full scale because of viscous and friction forces by using gravity thereby enabling a long beach to be simulated in a relatively short column. Column tests conducted in 2016 on tailings mineralogically similar to those at Centinela produced the results indicated in Figure 7 which shows the change in percent solids of the flow stream with change in stream power.

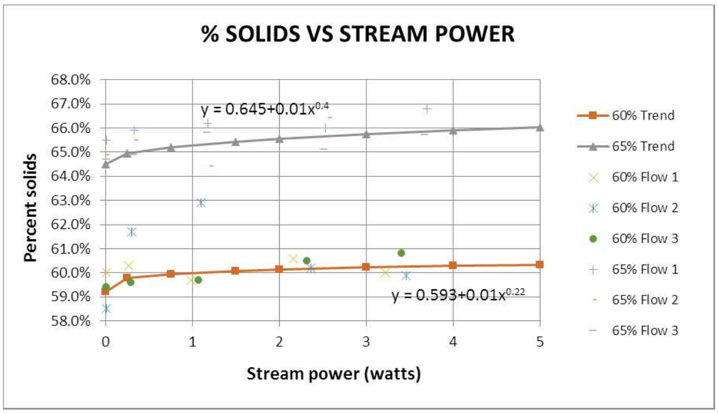


**Figure 9** Fluidized bed column results showing change in percent solids with change in stream power (after McPhail et al, 2016)

Calibration was effected by:

- Applying the lab and small scale rheological data from September 2015
- .
- Applying production rates and solids concentrations as recorded by Minera Centinela as part of their deposition monitoring protocol.
- Lengthening the flow path of the flow stream by multiplying by the square root of 2 to take into account the meandering nature of flow down the beach.
- Varying the parameters that define the concentration of the slurry at the depositing bed face.

Figure 10 shows a comparison of the measured and calibrated beach for Sections 2.

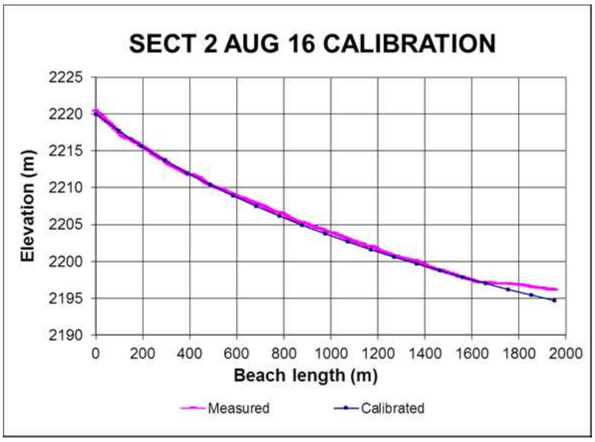


**Figure 10** Calibration on Section 2

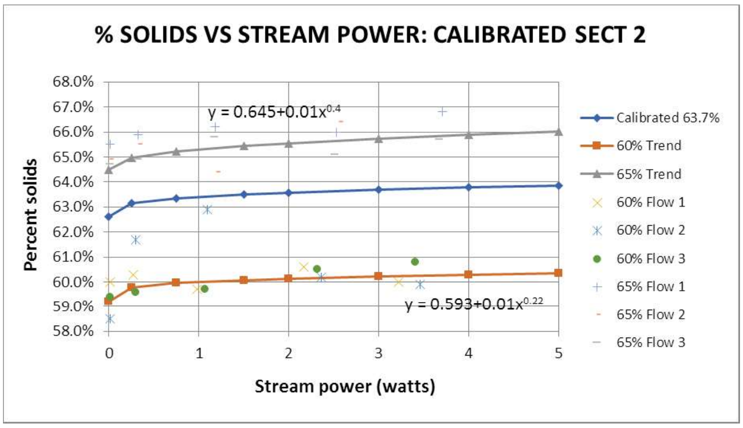


**Figure 11** Calibration on Section 2

Figure 12 shows the modelled beaches based on the calibrated parameters from Section 2 when applied to Section 1 and Section 3. The impact of the residual steps from the days of paddock operation on the beach profile is evident for Section 1 and Section 3 in Figure 12

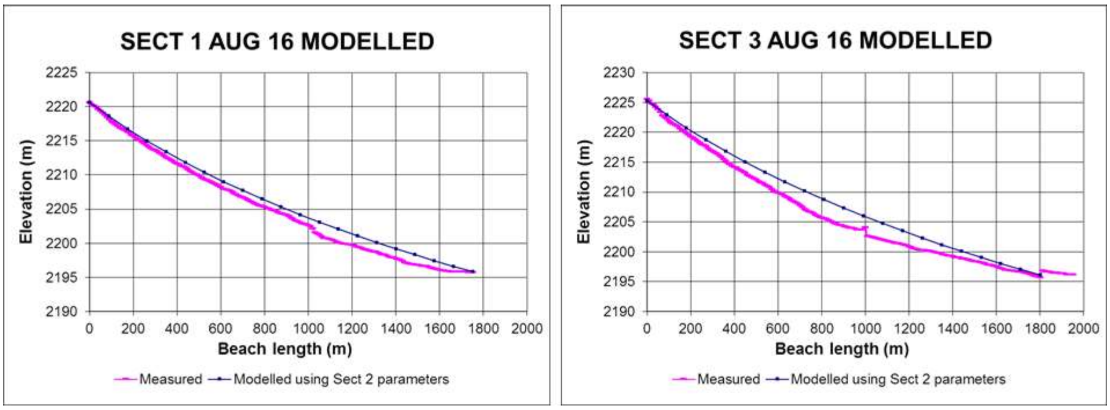


**Figure 12** Modeling results for Sections 1 and 3

## SUMMARY AND CONCLUSIONS

This paper has described the chronology of testing, analysis, modeling and calibration of beaches at Centinela through the deposition of pilot, industrial scale and full scale deposition trials and finally calibration of a fully developed beach almost 2 km long with an average beach slopes ranging from 1.3 % to 1.7 %.

At the time of design of the discharge system for Minera Centinela, specific consideration was given to the spacing of the discharges since beach slopes will be improved if flow streams do not combine down the beach. A spacing of 60 m was selected for trial.

Beach calibrations against deposited profiles in 2014 and 2015 following the development of some 200 m of beach showed that the beach model had promise. It was concluded, however, that it would be important to bring into account settling in the flow stream as a result of which the rheology at the depositing bed face is elevated. To assess this, a fluidized bed column test was developed during 2015 and tailings similar to those at Minera Centinela were tested (McPhail et al, 2016).

The 2016 beach survey indicated that flow streams remain essentially independent over the 2 km beach which means that the 60 m spacing between discharges is adequate for ensuring independent flow.

The 2016 beach calibration and modeling shows that the stream power entropy modeling method based on rheology from laboratory and small scale flume testing, as well as fluidized bed column testing, has promise even at production rates in excess of 100,000 tons per day. In applying the stream-power entropy model it is essential to consider the longer beach length generated by the meandering nature of the flow path.

## ACKNOWLEDGEMENTS

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