Slurry Flow in Self-Formed Channels on Tailings Beaches

Andrew Chryss, Lachlan Graham and Krishna Mohanarangam
CSIRO, Australia

ABSTRACT

Most of the more appealing models for predicting beach slopes of sub-aerially deposited tailings rely in some way on the existence of a small, self-formed channel of slurry flowing through recently deposited and settled tailings. The models are loosely based on fluid dynamics and often borrow from established correlations developed for pipeline flow and large scale channel or river flows. To close the models, various limiting assumptions are made. These include assumptions of Newtonian fluid behavior, either overtly or as a consequence of using correlations that require constant viscosity behavior. The ability of these channel-based beach slope models to predict long-term beach profile has never been established quantitatively, but based on the available literature and anecdotally, it would seem to be poor, largely due to the limited understanding of fluid behavior in small channels. Literature speculation on the nature of flows in self-formed channels is often unsupported by measurement, leading to some curious descriptions.

As part of a tailings management research project, physical modeling of self-formed channels was conducted using a 20 m long variable slope channel. The channel was instrumented for measurement of flowrate, velocity profile, concentration distribution and depth. The flow behavior of a tailings analogue (carbopol solution and graded sand) was characterized with the aim of determining the necessary conditions for maintaining the solid phase in suspension. High viscosity fluids could not suspend the solid phase for any great distance, and only lower viscosity carrier fluids were able to generate sufficient turbulence to transport it. The presence of a bed of fast moving solids was a novel finding for small channels. This is a major influence in the channel's behavior and is directly related to the difficulty in applying consistent modeling.

INTRODUCTION

TSF footprint affects the viability of any tailings management operation through the economic consequences of large scale earthworks, the uncertainty arising from storage of large quantities of potentially hazardous fluid and how it limits the number of sites that can efficiently be used as a TSF. The application of various thickening technologies may reduce footprint, but is practical only if a sufficiently stable beach slope is generated. Beach slope prediction is a vexed problem that is frequently addressed in mineral resources literature, but with little consensus or demonstrated accuracy. Steeper slopes provide greater storage volume, but require special, upstream processing to achieve.

It has been observed (Williams and Meynink, 1986) that centrally discharged thickened tailings tend to confine themselves to self-formed channels when transported down a beach, and this provides strong clues that the channel slope may, in part, be dictating the final stack slope. Other work has pointed to the channel slope determining overall beach slope (Pirouz et al, 2005). To improve thickened tailings beach slope predictability, the existing channelized tailings model needs to be further developed and revisited from a more fundamental foundation. This assumes that the conditions of the discharged tailings in a self-formed channel dictate the beaching angle and therefore the stack growth. This channelized tailings model has been shown to be a promising method to predict beach slope, but is based in part on the heterogeneous flow of solids in Newtonian fluids. The use of empirical descriptions of large channels are also adapted for channelized tailings model without allowing for the secondary flow effects that become significant for narrower channels. Greater understanding of high concentration flows is necessary for the development of the model to include the motion of solids in non-Newtonian carriers. If the complex behavior of solids in non-Newtonian carriers flowing in small channels can be described and applied appropriately, it will form the next step in improving the modeling of beach slopes and consequently increase the application and efficacy of thickened tailings TSF's .

Recent presentations at tailings conferences (Pirouz *et al*, 2014, amongst others) discussing the nature of the flow regime in self-formed open channels highlight some major issues in the understanding of particle transport in open channel flows. As the total transport of solids is necessary for a long beach, and coarse solids cannot be transported a great distance in laminar flow, the degree of turbulence necessary to transport solids is a vital question. In addition, the nature of the transport regime is important, i.e. are solids fully suspended, pseudo-homogeneous flow, or part of a rolling or sliding bed, or other form of heterogeneous flow? The speculation in parts of the tailings literature that channels with central un-sheared plugs are laminar (Fitton & Slatter 2013) or not necessarily laminar (Pirouz *et al* 2014) and provide a mechanism for particle transport needs to be examined experimentally. Replacing the current broad assumptions in beach slope modeling requires better measurement and more involved analysis. The need for velocity profiling and concentration profiling to model behavior instead of the simpler gross parameters of volumetric flowrate and slope is due to the complex nature of channel flow. Unlike pipelines, open channels do not have rotational symmetry and a simple shear stress field. Due to the type of materials usually transported by flumes and channels, the majority of studies have been for wide channels carrying dilute slurries (e.g. Abulnaga 2002). Wide channels have the advantage of approximating constant velocity with depth behavior in the transverse direction. Open channels with non-Newtonian fluids in laminar flow have been studied by Haldenwang (2003), Burger, J., Haldenwang, R., & Alderman (2010) and Sanders (2002), while the transport of solids in wide channels has been investigated by Sanders (2002) and Spelay (2007). The relevant area for describing flow on a TSF is the transport of coarse particles by turbulent flow of non-Newtonian slurries in small open channels, which is unpopulated in the literature.

Trials with a tailings analogue, comprising a non-Newtonian carrier fluid and suspended coarse particles, are described in this paper. They were conducted to determine the conditions governing the minimum conveying angle. This is the smallest angle at which a channel will convey all the solids present for a given flow rate, rheology, particle size and density. In the channelized tailings description of beach slope formation, the minimum conveying angle is also the angle that a stable self-formed channel will operate, and consequently the slope that a beach will develop. A key question to be answered will be what rheological conditions will allow transport of course materials and which will not? Any possible transport in laminar flow requires that the settled solids must slide or flow over the top of any existing deposit to be transported across the TSF, requiring a highly viscous carrier fluid. To transport the solids as turbulent suspensions in self-formed channels requires a carrier fluid that is sufficiently viscous to reduce the settling velocity of the solids, but is not so viscous that the required degree of turbulence to suspend solids cannot be achieved for the given TSF slopes. This implies that only slurries with carrier rheological conditions that allow for some degree of turbulence will be able to convey coarse solids, and determining what these conditions are will have implications for upstream processes.

EXPERIMENTAL PROCEDURE

Equipment

To examine the flow in self-formed channels on the TSF, an inclinable, rough-surfaced, channel test facility was built, a schematic of which is shown in Figure 1. The design allows for an artificial, representative channel to be created under steady-state or transient conditions and then monitored for velocity and particle distribution, which is not possible on a TSF. The channel is established by operating a 20 m long, 300 NB pipe in slack flow. The fixed shape of the channel represent a typical self-formed channel as described in Chryss *et al*, 2006. A rough-walled channel was used to better reproduce the flow conditions on a TSF. The surface roughness of the channel wall will change the particle-wall friction and if the roughness is greater than the boundary layer it will increase the degree of turbulence for the same flowrate compared to a smooth wall channel. The test facility is instrumented with a magnetic flow meter, variable speed pump, inclinometers, dual ultrasonic depth gauges and an ultrasonic Doppler velocity profiler (UDVP) and cross-correlation bed velocity/deposition probes. It is capable of being positioned to any angle or grade, but was restricted to a maximum of 4° for these experiments.

Using the UDVP probe measurement technique, a two dimensional mapping of velocity can be made. The orientation of the transducers can be seen in Figure 2, and an example of the velocity profiles is also shown in Figure 2. The transducer inserted from above the free surface is to improve near wall measurements, however, the disturbed flow around the probe has meant these results are not representative and were discarded.

The deposition of solids was detected via two techniques. The ultrasonic depth gauges were placed at approximately 10 and 15 m along the channel. Any deposition (usually starting upstream and working down the channel) was detected as a difference in free surface levels between the two depth gauges. A more rapid response was derived from the deposition probes. These are pairs of electrodes (two-hole ceramic tube, 4 mm OD with electrode diameter 1 mm) embedded in the channel wall that detect movement of solids in the region close to the wall. The signal response differs depending on whether solids are settling or sliding along the wall (see **Figure 3**). The pairs of signals can also be cross correlated to measure bed velocity (**Figure 3**).

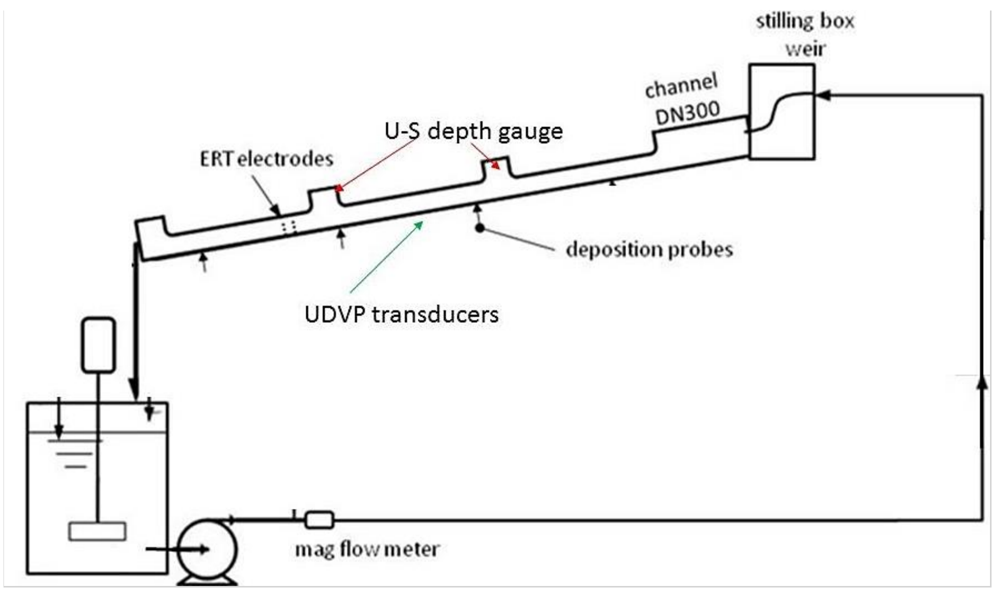


Figure 1 Schematic of the 300 mm diameter, 20 m long inclinable flume test facility

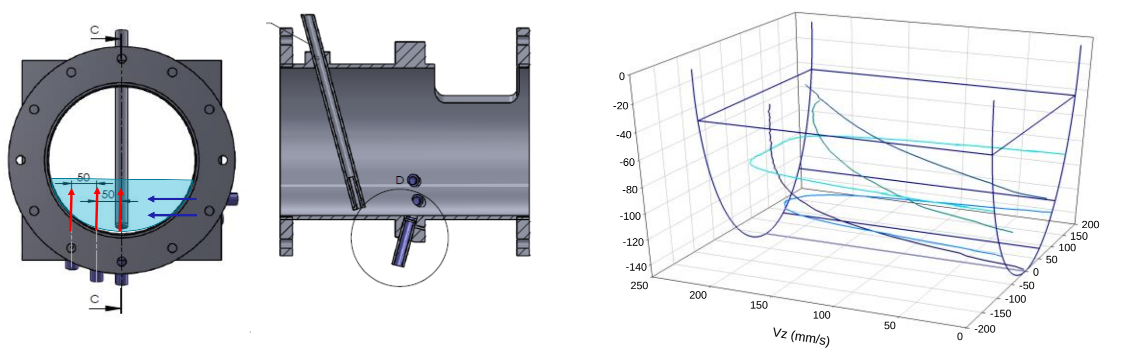


Figure 2 (left) Sectioned view of the UDVP probe module. Arrows indicate location of measured velocity profile. (right) UDVP velocity profiles from 5 transducers (F1, 247 L.min-1, slope 0.5°)

Fluid rheology was measured in a profiled concentric cylinder geometry. A Haake Rheostress RS1 rheometer was used throughout. Temperature control was maintained via a recirculating water bath, with test temperature variation of ± 0.1 °C. Temperatures were matched to the channel test conditions. The upper range of the measurements in the concentric cylinder geometry was limited due to the inaccuracies caused by the onset of Taylor-Couette eddies, a secondary flow effect at high shear rates. In the unaffected region, the correct shear rate (allowing for the non-Newtonian fluid effect) was obtained by using an integration approach for the Couette inverse problem. This method is generally more successful than a differential approach due to the inevitable noise present in real data.

Materials

All experiments were conducted with a fluid analogue of a thickened tailings stream. The use of an analogue allows for greater control of the fluid and particle properties, minimizing uncontrolled variations. The analogue consists of a carrier phase and a solid phase. The carrier fluid represents the water and such particles that either colloidal or readily suspended (nominally <20 μm) and the solid phase consists of particles that are too large to be rheologically active. This type of analogue has been used successfully in earlier work (e.g. Pullum *et al* 2006). The carrier fluid was a carbopol solution with its rheology varied via dilution or salt addition. The solid phase was a washed sand (Sibelco Incast 70) with a d_{50} of 0.18 mm. The sand was added at a volume fraction of 0.1 C_v.

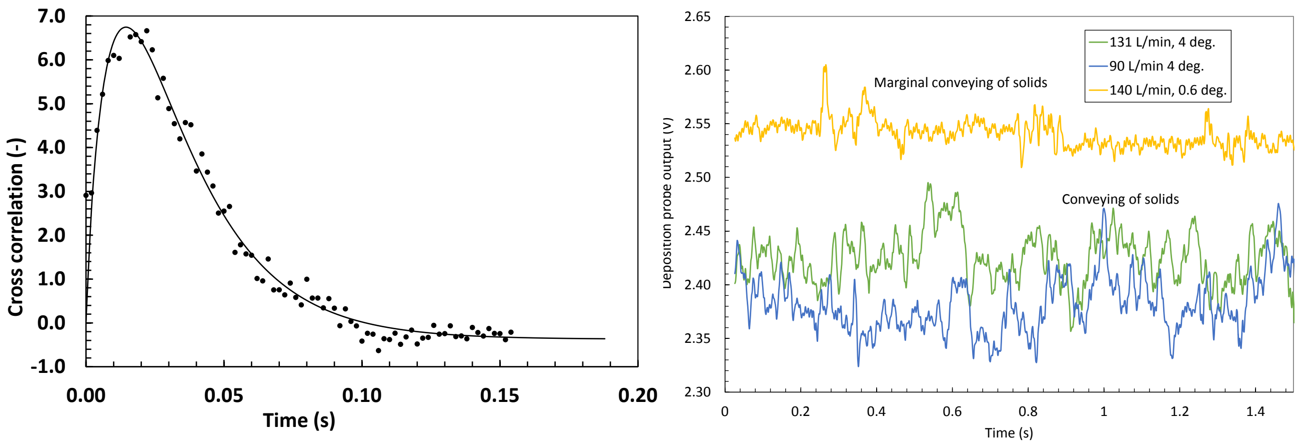
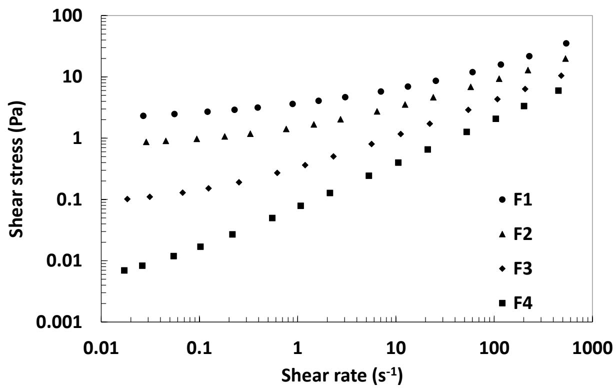


Figure 3 (left) Deposition probe output at varying flow conditions. (right) Sample cross correlation output. Peak time is converted to velocity using the distance between probes

RESULTS OF CHANNEL EXPERIMENTS

Runs were conducted with four different sets of rheology characteristics (see Figure 4) and two solids loadings (0 and 0.1 C_v). The velocity profiles from the runs without solids are shown in Figure 5; only the centerline profiles are shown for clarity. The progressive change in velocity profiles goes from fluid F1 (with a Reynolds number <1) to the lowest viscosity fluid F4 (Reynolds number >2300). Reynolds number for this work is calculated using a wall viscosity based on mean wall shear stress. The vertical profile for F1 close to the surface is an effect of the yield stress which creates an un-sheared plug in the channel center. This was confirmed by observation and is a similar phenomenon to that observed in Pirouz (2014) in trials at Chuquicamata. The decreasing yield stress in fluids F2-F4 sees the disappearance of this plug, but the lower viscosity fluids, F3 and F4, begin to achieve the type of vertical profile that is associated with one-dimensional turbulent flow over a surface as is typically used to model channel flow. It will be noted that fluids F1 and F2 have point velocities that exceed the mean axial flow, however, F3 and F4 do not as they have a greater degree of mixing due to rising turbulence and non-axial secondary flows. As a further indication of turbulent behavior, the normalized velocity fluctuations for F4 are shown in Figure 5.



Fluid	τ_y	k	n
F1	2.10	1.48	0.47
F2	0.75	0.77	0.51
F3	0.08	0.26	0.60
F4	0.00	0.01	0.72

Figure 4 (left) Rheogram of Carbopol solutions used as carrier fluid in channel trials. (right) Herschel Bulkley model parameters for test fluids

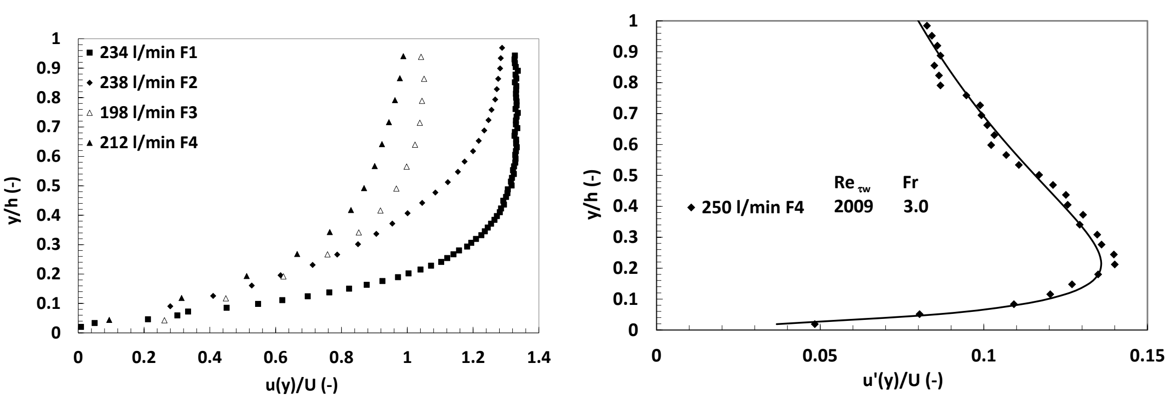


Figure 5 UDVP centerline axial velocities for particle free runs 2° slope. Velocities with depth, *u(y)*, are normalized over mean axial velocity U. Distance above invert, y, is normalized over depth, *h*

A series of runs were subsequently conducted with 0.1 C_v coarse solids added. Output from level sensors, deposition probes and visual observation all indicated that the fluids F1 to F3 were unable to transport coarse solids under any conditions tested. This included flow rates up to 400 $L.min^{-1}$ and angles up to 4° (equivalent to 7% gradient). In most cases, increasing flow rate led to a faster rate of silting in the channel. The F4 fluid was able to convey solids in a stable channel. A selection of the velocity profiles for these runs can be seen in Figure 6. The results shown are for a constant slope and increasing flowrate. When the shape of the profile is compared to Figure 5 where the F4 fluid has no solids, a distinct local velocity maximum can be seen at approximately 2 mm above the invert. This can be attributed to a density current of solid particles, that is, a moving bed along the bottom of the channel. Under no circumstances was the flowrate sufficiently high to maintain an homogeneous distribution of the coarse fraction at all depths.

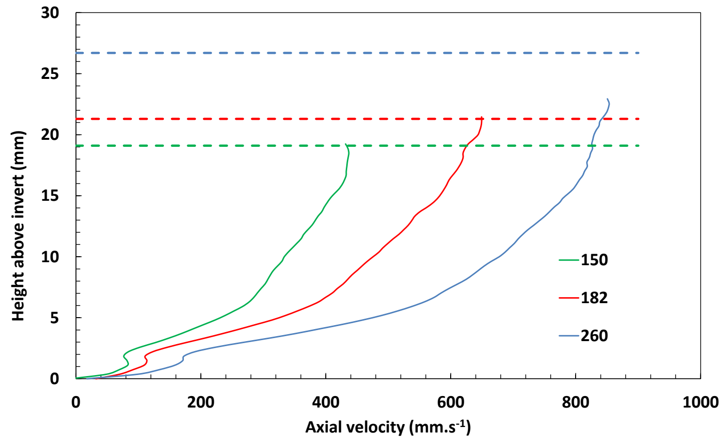


Figure 6 Velocity profile measured by UDVP for channel centerline (F4 fluid, 2° slope) free surface shown by broken line. Legend in L.min-1

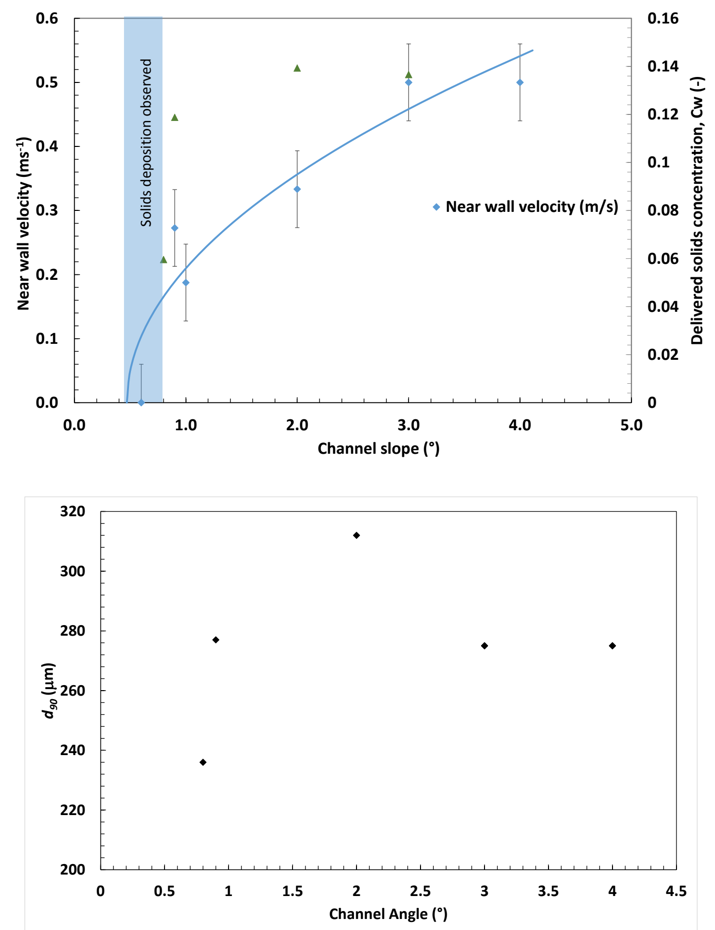


Figure 7 (above) Near wall velocity in open channel measured by deposition probe for constant flow rate (140 L/min). Delivered solids concentration are shown on the right hand axis. (below) d_{90} of delivered solids

Cross-correlation of the deposition probes provided velocities of coarse particles near the invert. These are shown for a constant flow rate and varying slope in Figure 7. It can be seen that as the slope decreases the near wall velocity decreases, as does the delivered solids concentration (i.e. greater hold up in the channel). Under these conditions of flowrate, rheology and particle characteristics, the channel stopped conveying at a slope of 0.6°. A similar indication is given by the decrease in d_{90} with decreasing angle shown in Figure 7, where the peak at 2° is due to the increased hold up (which is biased to larger sizes). Delivered concentration and PSD were measured off-line. The decline in channel stability and solids conveying capacity can be seen to decrease with decreasing slope as expected, first detected via solids size segregation, secondly by a decrease in near wall particle velocity then a decrease in delivered concentration, and finally by a failure to suspend solids altogether.

DISCUSSION AND CONCLUSIONS

Different velocity profiles were observed for the different rheology fluids tested and turbulent behaviour could be claimed only for the lower viscosity, low or zero yield stress fluids. The un-yielded plug (Pirouz *et al* 2014) was present in the velocity profile for the very high viscosity fluids (and was matched by visual observation). When solids were added to the carrier there was clear evidence that high viscosity laminar flows could not transport coarse solids for any great distance, and transitional-turbulent flow was necessary. Comparison can be made cautiously to the results from Fitton *et al* (2009) measuring minimum conveying angle from the Sunrise Dam copper/gold process in a similar fixed channel (it should be noted that the channel rig in Fitton *et al* is 10 m long and detects height differences manually). The rheology of the range of tailings samples is comparable to the F4 fluid in the low-to-medium concentration range. In the Sunrise Dam case, minimum conveying angle was seen to increase with increasing wt.% solids (both coarse and fine) without limit. The current study implies that this increase would be bounded by a reduction in turbulence at the higher concentrations, perhaps beyond those measured on site.

These results imply there are three potential flow scenarios for discharged tailings;

- Non-settling suspension, either through high viscosity or small solids, would not produce channelized flow. In the case of the self-formed channels on tailings stacks, the substrate (or wall) is the recently deposited tailings that have partly drained or desiccated and are at a higher solids concentration. This makes a substrate that can be considered as a high yield stress material. The variations in rate of seepage and particle characteristics will therefore alter the channel shape, accounting for some of the variation in beach slope between different ore types, deposits and processing methods. As no settling occurs in the deposited layer to create the necessary denser wall material, no channel can be formed. This lack of differentiation creates sheet-flow or paste-like behavior.
- A viscous carrier with coarse solids. There would be insufficient turbulence for a suspension to prevent coarse particles dropping out. Channels may form and over a short distance laminar flow can convey solids, deposition near discharge point is likely. A temporary central plug may be formed with high yield stress suspensions.

- A low viscosity carrier with coarse solids. There may be sufficient turbulence for coarse solids to be fully suspended. In the case of only the lighter fraction being suspended, a density current or sliding bed may also be present.

From Figure 5 it is apparent that there is little commonality between fluid responses to similar channel conditions. The variation from laminar to transitional turbulent flow and the different degrees of mixing at different flow rates and channel slopes serve to illustrate the points made above about small channel flow generally. When combined with the observation of the density current, this work highlights the complexity of modeling small self-formed channels and consequently beach slope prediction and demonstrates why many of the methods currently used will be limited in their predictive ability. This is due to the many simplifying assumptions used which miss the subtleties of small channel behavior. Further analysis of the experimental data and further experimentation with different particle characteristics will assist in defining a flow regime that is capable of conveying solids of a given set of fluid and particle properties. Although not a complete description of small channel flow behaviour on a TSF beach, the above description identifies many of the shortfalls of current models and indicates the areas where further development is needed for predictions to be as adaptable as necessary.

ACKNOWLEDGEMENTS

The financial support of Anglo Operations, BASF, Freeport McMoran, Gold Fields, Nalco, Newmont, Outotec, Shell Canada Energy, and Total E&P Canada through the AMIRA P1087 project is gratefully acknowledged, along with the support from CSIRO Minerals Resources. The authors are also grateful for the assistance with the rig set up of Dean Harris, Greg short and Paul Bowditch of CSIRO.

REFERENCES

Abulnaga, B.E. (2002). *Slurry systems handbook*. New York: McGraw-Hill.

Burger, J., Haldenwang, R., Alderman, N. (2010). *Experimental database for non-Newtonian flow in four channel shapes*. Journal of Hydraulic Research, 48(3), 363-370.

Chryss, A., Fitton, T., Bhattacharya S.N. (2006) *Turbulent Flow of non-Newtonian Tailings in Self Formed Channels on Tailings Stacks*, Paste 2006 Limerick, Ireland, 429.

Fitton, T., Chryss, A., Bhattacharya, S.N. (2006) *Tailings beach slope prediction: a new rheological method*. International Journal of Mining, Reclamation and Environment, 20(3), 181-202.

Fitton, T.G., and Slatter, P.T., (2013) *A tailings beach model featuring plug flow*, Paste 2013 Belo Horizonte, Brazil, 493-503

Haldenwang, R. (2003) *Flow on Non-Newtonian Fluids in Open-Channels*, Doctor Technologiae Thesis, Dept. of Civil Engineering, Cape Technikon, South Africa.

Pirouz, B., Kavianpour, M.R., Williams M.P.A. (2005) *Thickened tailings beach deposition*. Field observations and full-scale flume testing. Paste 2005. April 20-22, Santiago, Chile.

Pirouz, B. Javadi, S., Seddon, K., Williams, M.P.A. (2014) *Modified Beach Slope Model for non-Segregating Thickened Tailings*, Paste 2014, Vancouver Canada.

Pullum,L., Graham, L., Rudman, M., Hamilton, R. (2006) *High concentration suspension pumping*, Minerals Engineering, 19(5), 471-477.

Sanders, R.S., Schaan, J., Gillies, R.G., McKibben, M.J., Sun, R., and Shook, C.A. (2002) *Solids transport in laminar open-channel flow of non-Newtonian slurries*, Hydrotransport 15, Banff, AB, v.2, 597-612.

Spelay, R.B. (2007) *Solids transport in laminar, open channel flow of non-Newtonian slurries* (Doctoral dissertation, The University of Saskatchewan).

Williams, M.P.A., Meynink, W.J.C. (1986) *Tailings beach slopes.* Workshop on mine tailings disposal, University of Queensland, Australia.