Paste 2006 – R.J. Jewell, S. Lawson, P. Newman (eds)
© 2006 Australian Centre for Geomechanics, Perth, ISBN 0-9756756-5-6
https://papers.acg.uwa.edu.au/p/663_37_Chryss/

Turbulent Flow of Non-Newtonian Tailings in Self Formed Channels on Tailings Stacks

A.G. Chryss, T.G. Fitton, S.N. Bhattacharya *Rheology and Materials Processing Centre, RMIT University, Melbourne, Australia*

1 INTRODUCTION

One of the key requirements for estimating the storage capacity of tailings stacks is the ability to predict the stack profile or overall slope. As it has been observed (Williams and Meynick, 1986) that centrally discharged thickened tailings tend to confine themselves to self formed channels when transporting tailings down a beach, this provides strong clues that the channel slope may, in part, be dictating the final stack slope. Earlier work has pointed to the channel slope determining overall beach slope (Pirouz et al., 2005). The aim of this project is to develop a technique for estimating beach slope for non-segregating thickened tailings from laboratory size samples. This requires the development of a model of particle transport in self contained channels, and to further demonstrate what type of role the observed self formed channels play in beach slope formation.

2 METHODOLOGY

It has been observed that in a sub-aerial discharge of tailings slurry, the slurry typically flows from the point of discharge over the established beach in a relatively narrow self formed channel for some distance before it suddenly fans out into a wider, shallower sheet. The point at which this "break-out" occurs can vary from anywhere between the discharge point and the toe of the beach. The channel will then advance when sufficient depth of tailings has been deposited via sheet flow. This has led to the idea that the channel dictates the slope of the tailings beach.

It is necessary to first demonstrate experimentally that there is a relationship between a channel's equilibrium slope, where turbulence is just sufficient to have no net deposition or removal of particles, and the final stack slope.

2.1 Experimental apparatus

On site measurements were taken at two gold mines, Peak (Cobar, New South Wales, Australia) and Sunrise Dam (Western Australia). The flow behaviour of the naturally formed channels was modelled in a 10 metre long flume. This was constructed from a 0.4 m diameter half-pipe with a plunge box at the upstream end and a flow rate measuring box at the downstream end (see Figure 1). The dimensions of the flume were based on measurements taken of naturally formed extinct (dried) channels found on the stack at Peak Gold Mine in

Cobar. The shape could be approximated by a flattened parabola, or for convenience by a small arc of a large diameter circle, hence the use of a half pipe. The natural channel profiles with superimposed arcs of the pipe used can be seen in Figure 2. The length of 10 m was considered the minimum to achieve a steady state based on the work of Raju (Raju et al., 2000), and was confirmed on site with axial velocity measurements.

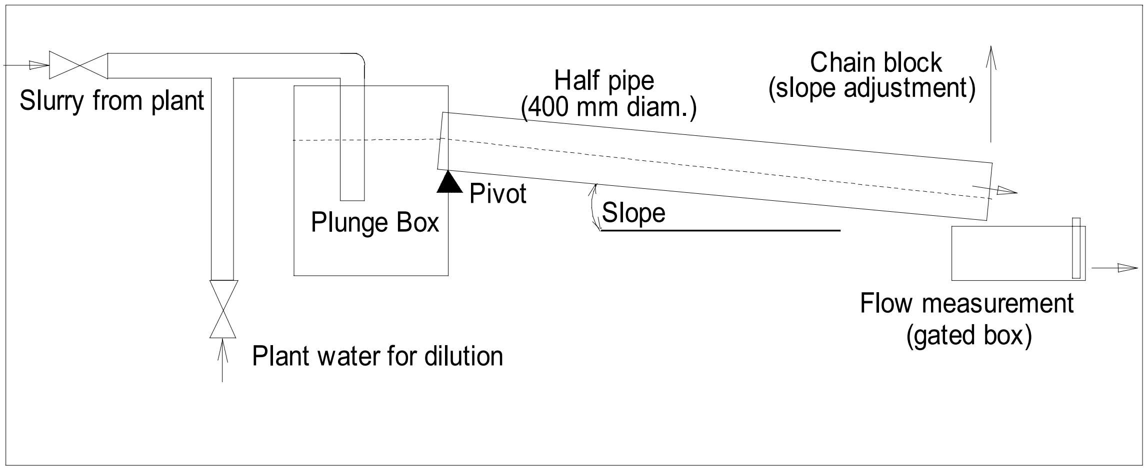

Figure 1 Diagram of experimental flume

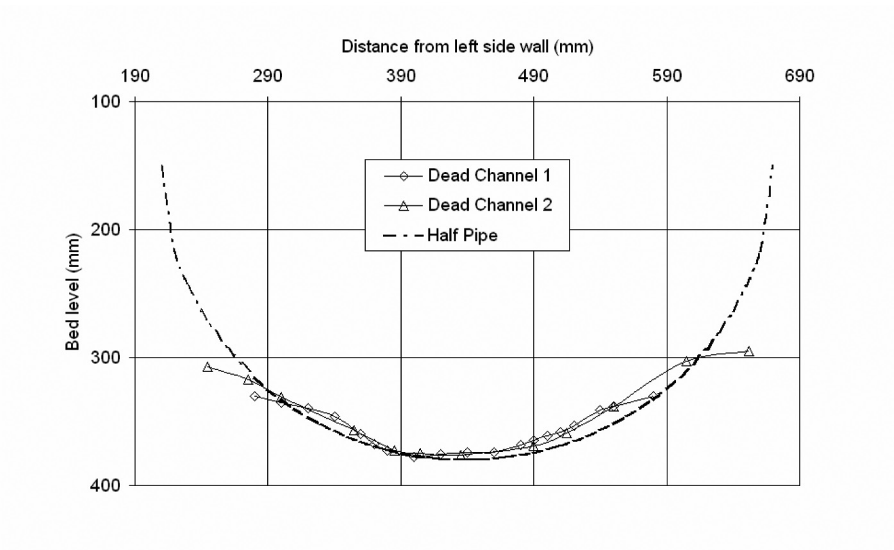

Figure 2 Diagram of experimental flume shape compared to channel shape

Tailings slurry was supplied to the plunge box direct from the thickener at flow rates up to 24 $l.s^{-1}$. Flow rate was controlled by an upstream diaphragm valve and concentration was varied by adding process water. The plunge box was used to dissipate energy before entering the channel. The half pipe was lined with coarse sand (≈ 1 mm) glued to the surface to trap tailings and to create a boundary surface of concentrated tailings similar to that found in natural channels on a tailings beach. The slope of the flume could be adjusted by a pivot at the upstream end and a chain block suspending the downstream end from an A-frame truss. The slope of the flume was measured with an automatic level.

The equilibrium slope condition was determined by two methods; for a fixed flow rate, concentration and slope the channel free surface was monitored for change in height, and then the channel wall was scraped to detect the level of build up.

To gather information on the velocity and turbulent fluctuations of the slurry flow the velocity and particle concentration were measured. Measurements of the velocity profile across the channel were made with a Delft E-30 velocity probe. This is inserted in the stream and measures the axial and either of the transverse velocity directions. An x-y traversing rig allowed repeatable positioning of the probe to within 1 mm. Similarly particle concentration within the channel was measured with a Delft Conductivity Concentration Meter (CCM), but this was only possible at Cobar due to high salinity at Sunrise Dam.

3 EXPERIMENTAL RESULTS

The results obtained from the flume can be seen in Figure 3. The relationship of increasing slope with decreasing flow rate can be clearly seen. There appears to be little or no effect of concentration on slope except for the weight concentrations below C_w 48%. This approximates to the “segregation threshold”, the concentration below which hydraulic sorting of particles by size is expected to occur. For the equilibrium slopes in the C_w >48% groups a Froude number of 1.3 (standard deviation 0.2) was observed.

Typical velocity profiles obtained for the channel centre line are shown in Figure 4. This follows the Prandtl universal log-law velocity distribution at low velocities. This relationship was developed for pipes but shown to be valid for wide channels (Vanoni, 1946) and used as an approximation for narrow channels (Faddick, 1986). For higher flow rates the effects of secondary flow due to channel dimensions becomes obvious as the velocity maximum drops below the surface. Figure 5 is a plot of particle concentration as a function of non-dimensional depth. Due to the small variation in concentration with depth, an extensive turbulent core, essential for particle transport, can be inferred.

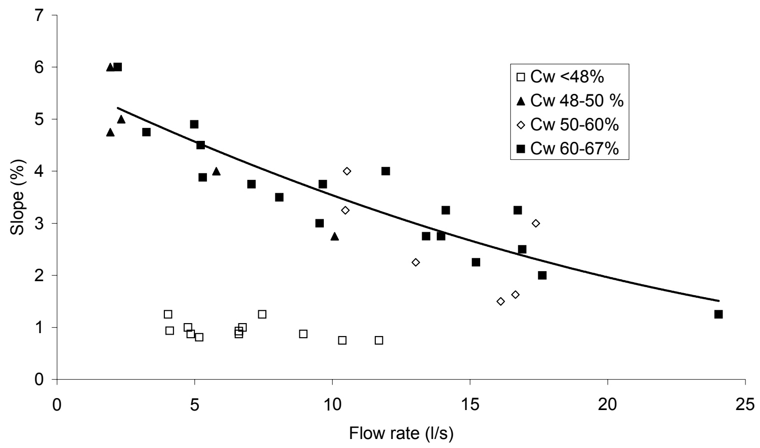

Figure 3 Experimental flume results from Sunrise Dam (solid line - best fit)

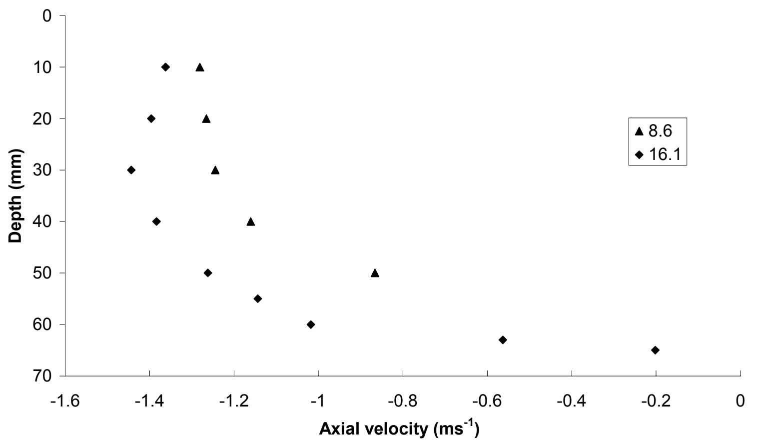

Figure 4 Axial velocity profiles from Sunrise Dam (two flow rates only). The effect of secondary flow is apparent for the higher flow rate

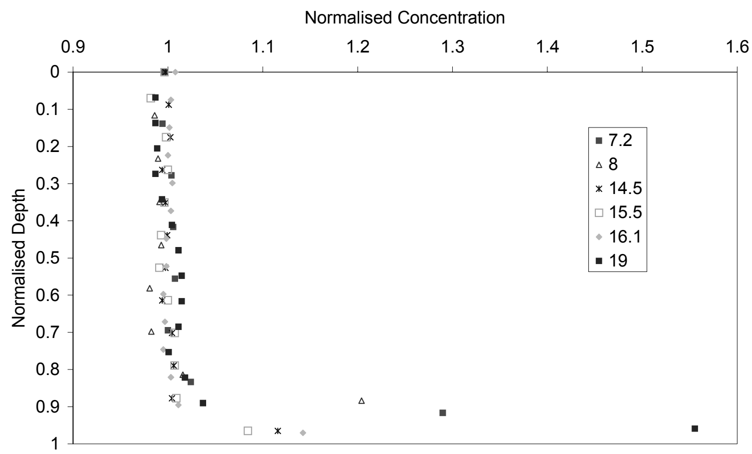

Figure 5 Normalised concentration compared to depth (Cobar). Flow rates are in ls^{-1}

4 A SIMPLE CHANNEL MODEL

To assist in making the results more general and to see which tests are appropriate for beach slope prediction a model of channel shape and slurry flow was derived. Although the channel slope can be estimated in the same fashion as for an industrial flume the major unknown is the hydraulic radius, which is a function of channel cross section. The model must therefore combine a velocity profile that is capable of suspending the coarsest particles present, with a channel shape derived from the properties of freshly deposited tailings (which the channel will flow through) and stable channel assumptions.

4.1 The channel shape

The stable channel approach as used for river modelling is taken as a first approximation. The approach of Lane (Henderson, 1966) uses stress vector addition at the channel wall, with wall shear stress and bed weight being reacted to by a resisting force (characterised by the angle of repose). As an angle of repose is not appropriate for the freshly deposited tailings, which behaves as a yield pseudo-plastic fluid, a yield stress is used in its place. Several simplifying assumptions are made. Assumptions of constant bed density (and therefore constant yield stress) and that the contribution to wall shear stress at any point is assumed to be due to the fluid directly above (a gross simplification) are used. Secondary flow is also ignored.

The mathematical manipulation is complex and will not be discussed further here. After integration the equation obtained in Cartesian co-ordinates is of the form:

$$x = y_0\,(h_0(y/y_0)^{0.5} + h_1(y/\,y_0)^{1.5} + h_2(y/\,y_0)^{2.5}) \tag{1}$$

where y_0 is the total depth and h_0 coefficients depend on the bed density, total depth and yield stress.

The yield stress values for settled tailings were derived from vane rheometry and are shown in Figure 6. The resulting shape for the channel for a settled concentration of C_w 68% is shown as an example in Figure 7. This is a good approximation to the channel shapes shown in Figure 2. The use of the constant bed density assumption produces an anomaly near the surface as the yield stress is greater than the wall shear stress and weight, this small region is approximated by vertical lines (Figure 7).

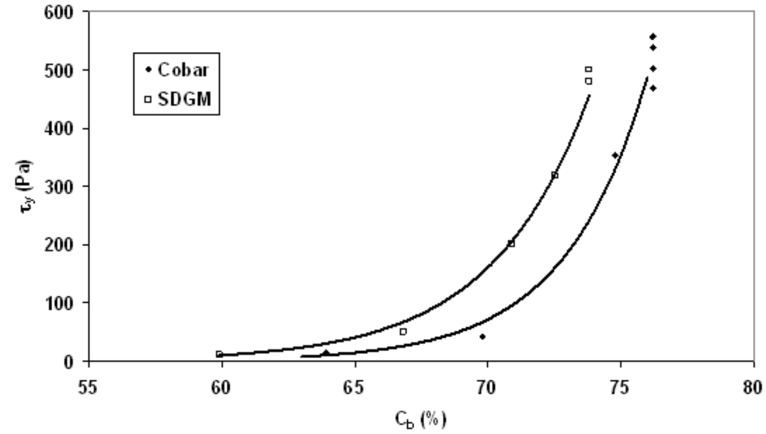

Figure 6 Yield stress measurement by vane rheometry for settled tailings

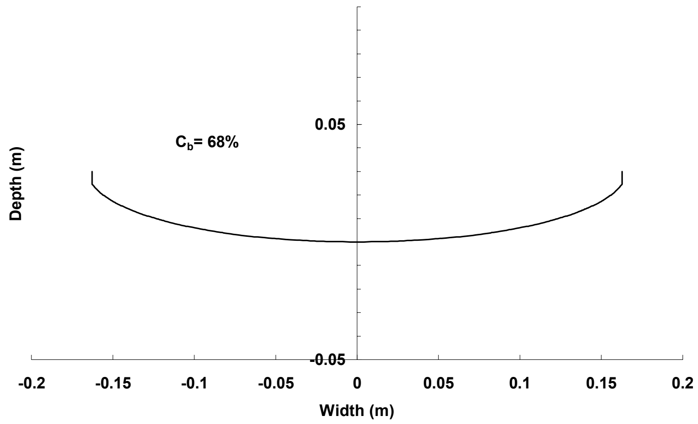

Figure 7 Calculated channel shape for bed concentration C_b 68%

4.2 Velocity profile

The velocity profile in the channel was approximated for one dimensional flow with the Prandtl universal log-law velocity distribution for turbulent flow. This is a good first approximation for the velocity profile for most of the channel, except where it was affected by secondary flow at high flow rates.

$$v(y)=V+1/\chi\ (g\ R_h\ S)^{1/2}\ (1+\ln(y/y_0)) \qquad (2)$$

Here y is the depth, V the mean axial velocity, χ is the Von Karman constant, g the gravitational constant, R_h the hydraulic radius, S is the slope and y_0 is the maximum depth. The value of χ used here is not the usual value of ≈0.4 which is derived experimentally for clear water in a pipe. Due to the non-Newtonian rheology of the tailings slurry an equivalent von Karman constant is determined by fitting to the experimental flume data as will be shown below. To estimate the magnitude of the velocities required to keep particles in suspension, comparisons were made to conditions reported for artificial channels in (Faddick 1986) where the limited field data suggest that for particle transport the velocity at 10% of the depth should equal 35 times the settling velocity of the largest particles. Although derived empirically, this condition is a simplified method of fixing Stokes Number at its maximum point in the channel. In this case the unhindered settling velocity is measured at 0.018 m.s^{-1} for the particles in the upper 3% of the particle size distribution. This implies the velocity at 10% of the depth should equal 0.63 m.s^{-1}, which compares well with Figure 4. Using this condition in equation 2 and solving simultaneously with well known Manning equation (Wilson, 1991 and Equation 3) for channel flow, values for χ and the Manning resistance coefficient, n could be derived from the experimental flume data:

$$V=R_h^{2/3}S^{1/2}/n \qquad (3)$$

The value of n was constant at 0.0081 m$^{-1/3}$ s., and the value of χ is plotted in Figure 8. The value is less than that of water and decreases with particle concentration, as is expected for a non-Newtonian suspension.

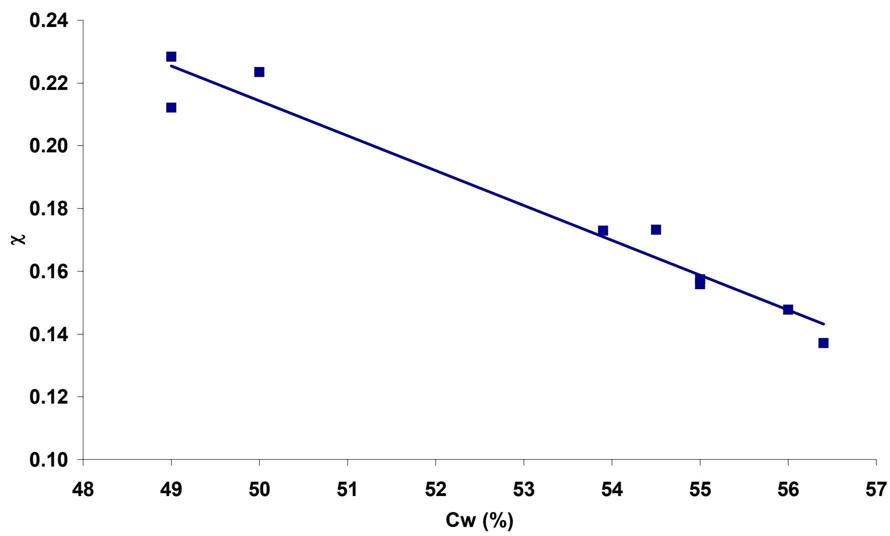

Figure 8 Equivalent von Karman constant for slurry in channel

5 DISCUSSION

To establish the validity of the argument that naturally formed channel slopes dictate the final stack slope it is necessary to compare the experimental flume values and site historical data. This is done in Figures 9 and 10 for the two different mine sites. Due to the concavity in the stacks the site data is broken into thirds. The calculated results are taken from the equilibrium slope that the experimental flume produced when running under the same conditions of flow rate and particle concentration for the stack discharge. The experimental channel data can be seen to compare well to the upper third of the stack. These results tie in with anecdotal evidence from site operation where splitting of discharge streams has produced steeper stacks. The possible causes of deviation in the lower thirds (concavity) is discussed in the next section.

The model of channel shape and velocity profile and the values of n and χ from the previous section are able to be used to predict how channel slope will vary under different conditions of the settled bed it flows through. Using typical values for settled concentration under different conditions of time and initial concentration the effect on channel slope can be calculated by solving Equations 1, 2 and 3 simultaneously for a given flow rate. This is shown in Figure 11, where an increase in settled bed concentration produces a decrease in slope. The implications of this will be discussed in the next section. This simple channel model can be used to predict the effect of changes to the stack slope produced by varying the nature of the tailings (eg. pH, particle size distribution etc) from a laboratory vane rheometry test.

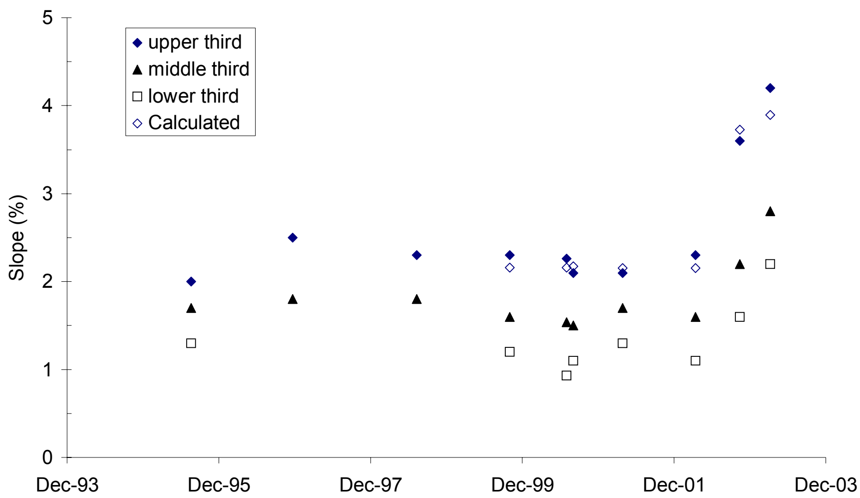

Figure 9 Peak (Cobar) historical data compared to flume data

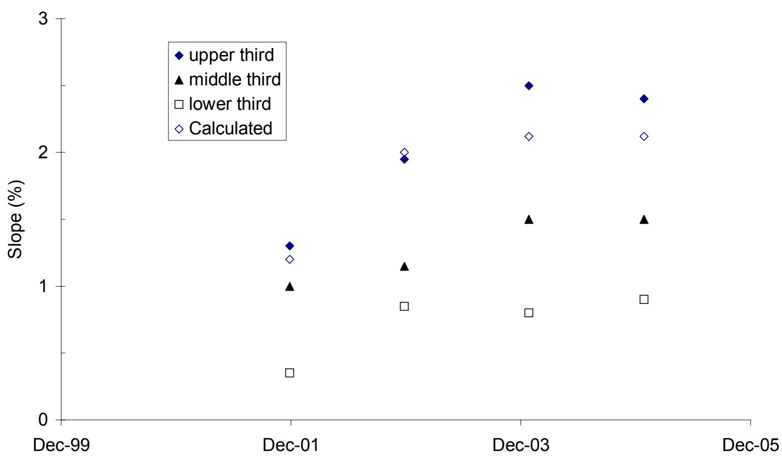

Figure 10 Sunrise Dam historical data compared to flume data

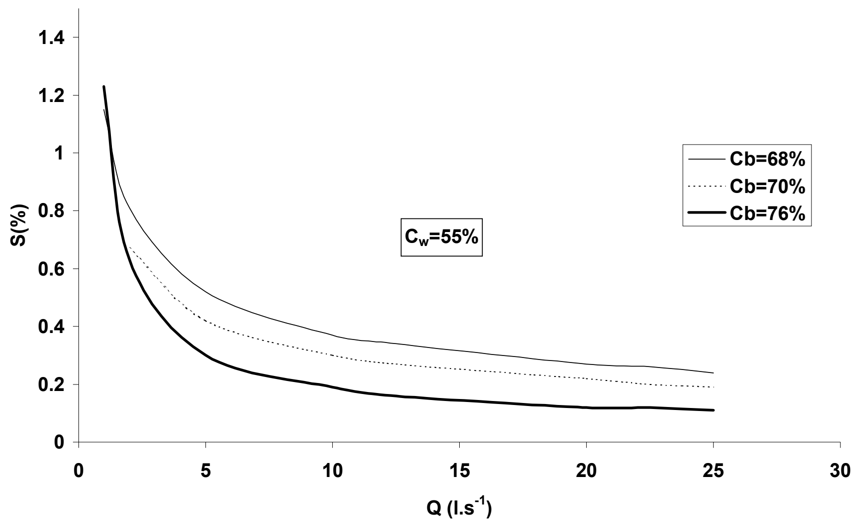

Figure 11 Calculated channel slope as a function of bed concentration

5.1 Beach slope concavity

In many cases the beaches formed by the sub-aerial discharge of a mineral slurry form a concave profile, rather than a purely conical stack. This is the case in both of the gold mines involved in these experiments (see Figures 9 and 10). The degree of concavity from one beach to another can vary considerably. The reasons for concavity presented in the literature (Morris, 2004 and Blight, 1994) is the segregation of the particles in the slurry occurring as the slurry runs down the beach, with the larger particles depositing a short distance from the spigot and the smaller ones going further down the beach. The larger particles are thought to form steeper beach slopes than smaller ones. This is not the case for the slurries examined here, which appear to be non-segregating at typical process concentrations.

A possible explanation for concavity with non-segregating slurries is a variation in channel shape due to differing bed concentrations. This is shown in Figure 11. If concentration increased toward the toe of the stack, a concave profile would be produced. This requires an additional, as yet unidentified, process to occur, possibly faster run off for the supernatant water. This remains to be determined.

6 CONCLUSIONS

The experimental data derived from a large scale flume on site measures an equilibrium slope for slurry transport that compares well to the upper third of a tailings stack beach slope. The use of a simple channel model to estimate beach slopes on stacked tailings provides a good basis for predicting how changes to the properties of the tailings slurry will affect the final stack slope. The model also has the potential to determine the reasons for beach slope concavity.

ACKNOWLEDGEMENTS

The authors wish to thank Anglo Gold Ashanti, Australian Tailings Consultants and The Australian Research Council for their sponsorship of this project, and Wheaton River Minerals for on site support.

REFERENCES

Blight, G.E. (1994) The master profile for hydraulic fill tailings beaches. Trans. Institution Civil Engineers, Geotechnical Engineering, 107, pp. 27-40

Faddick, R.F. (1986) Slurry flume design, Hydrotransport 10, 29-31 October, Innsbruck, Austria, pp. 143-147.

Henderson, F.M. (1966) Open Channel Flow, Macmillan, pp. 450-454

Morris, P.H. (2004) Mine waste beach profile and flow resistance equations, International Journal of surface mining, reclamation and environment. 18, 4, pp. 253-272

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

Raju, K.G.R., Asawa, G.L. and Mishra, H.K. (2000) Flow establishment length in rectangular channels and ducts, Journal of Hydraulic Engineering, 126, 7, pp. 533-539.

Vanoni, V. (1946) Transportation of suspended sediment by water. American Society of Civil Engineers, 3.

Wiliams, M.P.A. and Meynick, W.J.C. (1986) Tailings beach slopes. Workshop on mine tailings disposal, University of Queensland, Australia.

Wilson, K.C. (1991) Slurry transport in flumes. Slurry handling design of solid liquid systems. Brown, N.P and Heywood, N.I. (eds), Elsevier, London, pp. 167-179.