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Surface Disposal of Paste and Thickened Tailings — A Brief History and Current Confronting Issues

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Abstract

The concept of thickened tailings "stacking" as a means of surface disposal of mine tailings, first introduced by Eli Robinsky in the mid 1970s as an alternative to storing tailings in impoundments behind embankments, has come a long way. Australia has been the leader in research and development of the method, and a significant number of operating schemes are in Australia. The application of the technique world-wide has accelerated since 1995. The authors have identified a number of issues that confront the technique – beach slope prediction, pipeline design, seepage to groundwater, seismic stability and rehabilitation – and discuss each in turn.

1 Introduction

The most common form of tailings storage/disposal remains surface disposal into engineered facilities. This is despite the advent of underground paste backfill, and the perceived attractiveness in some regulatory and environmental circles of open pit backfilling.

The concept of "stacking" thickened tailings in a low conical pile on flat ground, referred to in this paper as central thickened discharge (CTD), was introduced to the mining industry by Eli Robinsky in Canada in the 1970s at Kidd Creek at Timmins in Ontario. This operation is still in production. Implementation of the idea was slow over the next 15-20 years but its acceptance is now much more widespread. The paper will present a brief history of the applications to date that the authors, at least, are aware of.

A number of themes are apparent from this history:

- Early schemes were based on a given thickener performance. Improvements in thickener design introduced design choices in this department.
- There is a clear move towards "system" design that fully integrates tailings disposal into the whole mine plan and looks for the best fit and lowest cost and seeks a match between thickening, pumping, stacking, operating and water costs.
- There has been a significant increase in the emphasis on water recovery and minimising water usage.
- There has been an increased emphasis on closure and rehabilitation.

Notwithstanding this more widespread understanding and acceptance, there are many technical issues that still confront the technique, for example:

- Prediction of beach slope.
- Pipeline transport.
- Seepage to groundwater.
- Beach stability under static and earthquake loading.
- Closure strategies and long-term behaviour.

The list highlights the essential difference between "stacked" tailings surface disposal and impoundment storage. With the latter, the tailings are contained within an impoundment created by an embankment. The design issues focus on the integrity and stability of the embankment. With the former, containment of the tailings is either absent or is minimal. This is an advantage since the very long-term integrity of embankments can be problematic. But relying on unconstrained "stacked" tailings to stay where they are put, both during the mining operation and after closure, places the focus entirely on the behaviour and properties of the tailings themselves. This is a very different challenge.

2 Segregation

The most important property of a thickened tailings slurry to permit the "stacking" of tailings, either in a CTD configuration or down-valley discharge (DVD), is that it must be non-segregating, i.e. there must not be hydraulic sorting on the beach. The deposited tailings must have the same in situ particle size distribution at the head of the beach as at the toe. If this is not so, the coarse fraction will deposit as a relatively steep cone at the discharge point and the fine fraction (the slimes) will fan out over a wide area at an increasingly flat slope at the toe. The storage characteristics – volume versus height versus area covered – will be poor for such a highly concave profile.

Non-segregating tailings on the other hand, for a constant slurry density (percent solids) and flow rate, will form a planar beach slope – the same slope throughout, and the storage characteristic will be at an optimum. In practice, even non-segregating tailings will form a concave beach profile due to variability in thickener performance (Fitton et al., 2007) but the degree of concavity and hence the loss of capacity will be a lot less severe.

The results of particle size distribution tests, expressed as percent minus 75 microns, versus distance down the beach for three cases, are presented in Figure 1 as an example. The Elura data are very consistent. For Peak there is scatter but no overall trend of decreasing particle size with distance. The Bougainville trial was relatively small scale. Some coarse material appears to have dropped out very close to the discharge but thereafter segregation is substantially absent.

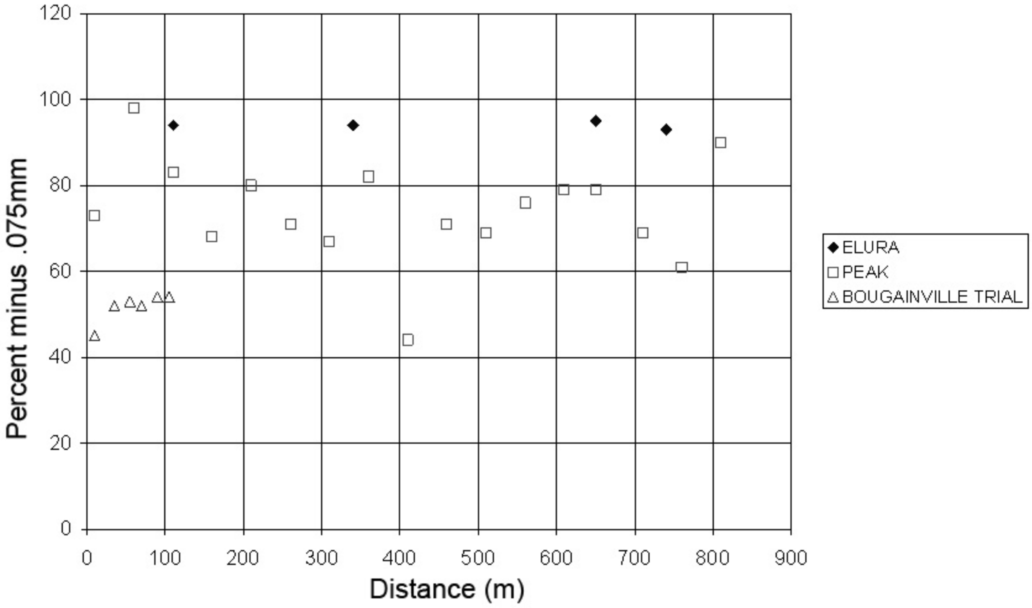

Figure 1 Particle size distribution versus distance from discharge (Williams, 2000)

3 What’s in a name?

The authors would like to emphasise that there is a continuum of variance in tailings slurry properties with increasing percent solids. There is some misconception that there is a step change in tailings properties and behaviour between *thickened tailings* and *paste*. This is not so. The continuum is nowhere better illustrated than in the plot on Figure 2, which is taken directly from Jewell and Fourie, “Paste and Thickened Tailings – A Guide (2006)”.

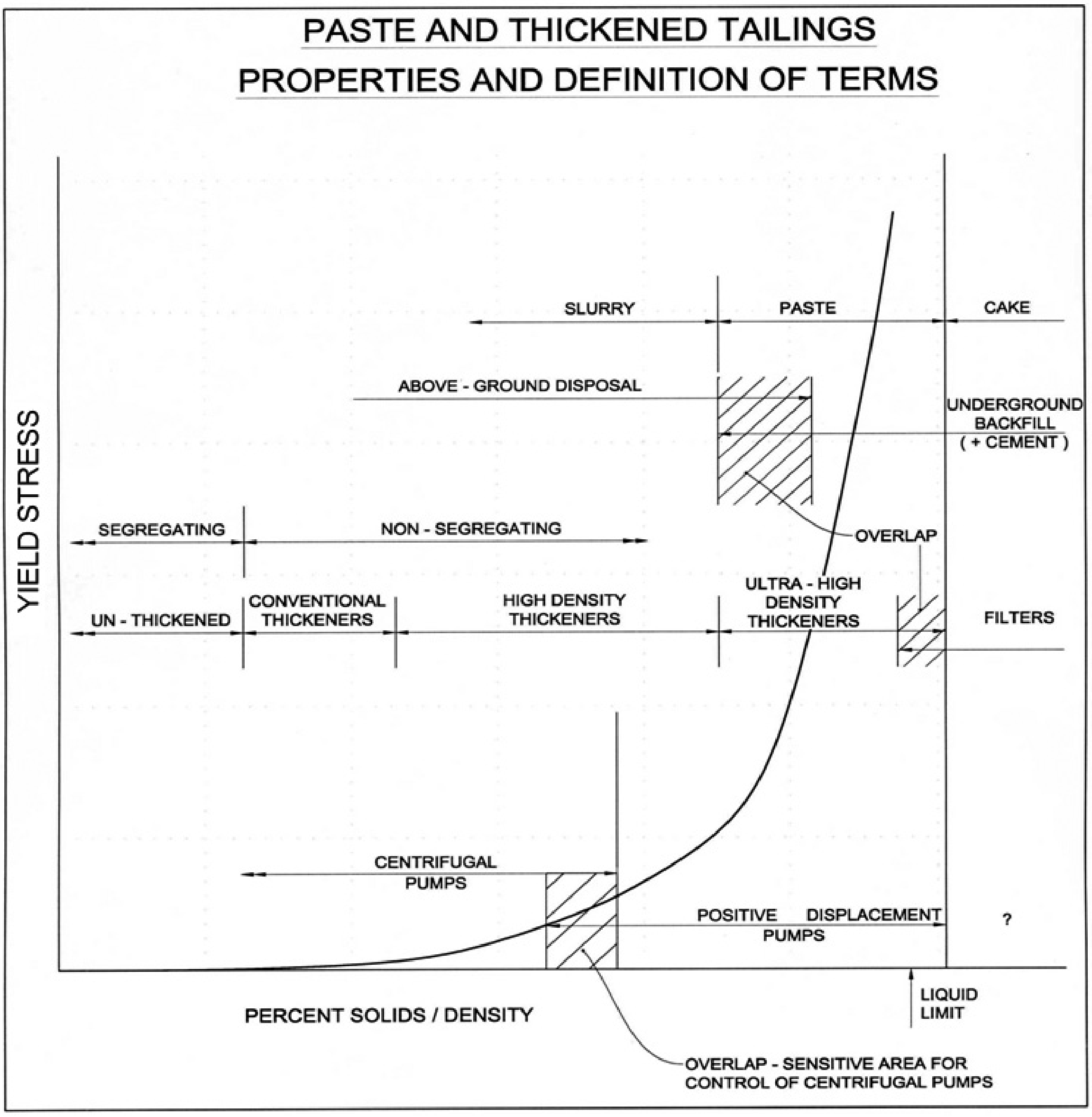

Figure 2 The continuum of tailings slurry properties across the range of solids concentrations (Jewell and Fourie, 2006)

The horizontal axis is tailings slurry density (percent solids) and the vertical axis is a measure of strength, probably most appropriately yield strength but it could be plastic viscosity, slump, or some other strength based parameter. Practitioners of many disciplines, from geomechanics to rheologists to pump and pipeline engineers, will seek to impose their own thresholds and ranges, as shown. Particular thresholds, for example the segregation/non-segregation threshold with respect to the degree of thickening, will vary from slurry to slurry. But underlying this is the fact that the plot is a continuous curve and not a series of hard-edged steps.

4 Catalogue of paste and thickened tailings schemes

The table on the following pages (Table 1) represents a catalogue of thickened and paste tailings disposal schemes that the authors have compiled, mostly from published data, including papers and case studies presented at paste and thickened tailings seminars. The list covers full scale schemes only, and is limited to surface disposal including in-pit disposal. Underground backfill schemes are not included. It is not imagined that the list is complete and the authors would welcome hearing of additional examples that readers may be able to supply.

Comments on the list as presented are as follows:

- Schemes are located in eight countries but 19 of the 32 schemes, i.e. 60%, are in Australia.
- The growth in the number of thickened tailings and paste surface disposal schemes with time is plotted on Figure 3.
- The distribution of schemes according to thickener type is shown in Table 2.
- Of the eight paste schemes, the bauxite stack at Vaudreuil in Canada dates from 1987, all of the remainder are from 2002 onwards.
- The range of mineral types is broad, as shown in Table 3.
- The distribution of the stack types is as shown in Table 4.

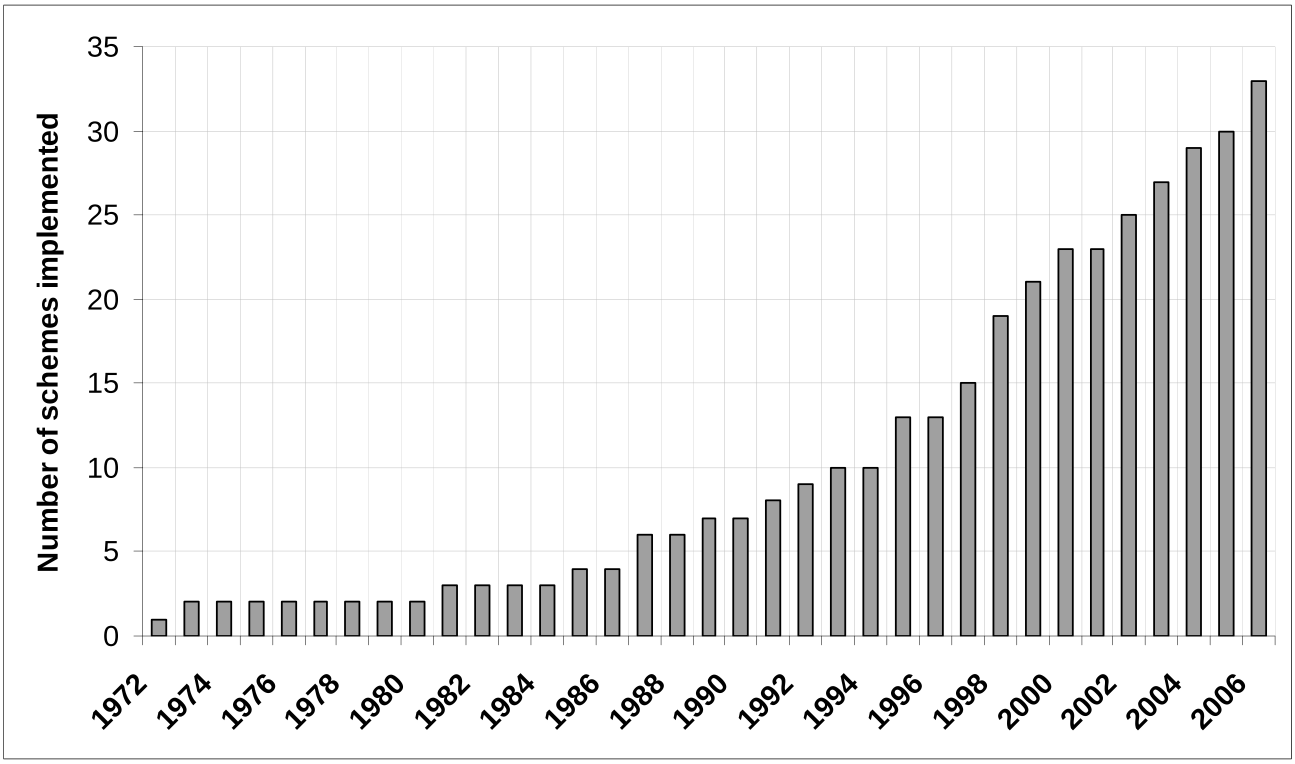

Figure 3 Number of surface disposal schemes with time

Table 1 Listing of thickened and paste tailings schemes implemented world-wide

Mine site	Location	Ore type	Start year	Status	Typical rate Mtpa	Thickener details				Floc. rate g/t	Tailings slurry properties		Disposal scheme	Beach slope achieved		Reference
						Type	No.	Dia. m	Unit load $t/m^2.hr$		SG	Conc. % w/w		Max %	Range or typical %	
Surface disposal:																
Kidd Creek	Ontario, Canada	Copper/zinc	1973	Active	2.92	HC	1	35	0.37	20 to 25		63	CTD	2.5	1.5	Lord, 2003
Elura	NSW, Australia	Zinc	1981	Active	1.0							60	CTD Segmented	1.7		Williams & Seddon, 1999
Argyle	WA, Australia	Diamond	1985	Deactivated	3.3-6.5							72(??)	CTD Segmented	10 target		McMahon et al, 1996
Peak[1]	NSW, Australia	Gold	1992	Active	0.4	HR	1	8	0.97	10 to 15		55-62	CTD	2.5 +	1.5-2.0	Williams & Seddon, 1999; ATC Internal
Union Reefs	NT, Australia	Gold	1995	Closed 2001	2.0-3.0	HR	1					<55	DVD	0.9		Williams & Seddon, 2003
McArthur River	NT, Australia	Lead	1995	Active	2.4							60	CTD	1.0		Williams & Seddon, 1999
Cluff Lake	Saskatchewan, Canada	Uranium	1995	Closed 2002	0.32	HD	1	26	0.02		2.7	52	DVD	3.0		Lord, 2003
Ernest Henry	Qld, Australia	Copper	1997	Active	7.0	HC	1	70	0.22		3.3	75	CTD	1.1		Williams & Seddon, 1999
Mount Keith	WA, Australia	Nickel	1997	Active	10.5							44	CTD Multiple	2.0		Williams & Seddon, 1999
	WA, Australia	Nickel	1997	Active	10.5							44	CTD Multiple	1.0		Bentel, Discussion Paste 2007
Blendevale (Pillara)	WA, Australia	Lead	1998	Closed	1.5							65	CTD	1.5		Williams & Seddon, 1999
Warkworth #2_ Redbank	NSW, Australia	Ash	1998	Active	0.1							70	Side hill	5.0		ATC Internal
Ekati	Canada	Diamond	1998	Active	1.6	HR DC	2	12	0.86		2.7	40	Surface	1.0	1	Lord, 2003
Strathcona	Canada	Nickel	1998	Active	0.5	HR DC	1	10	0.23	20	2.9	45		1.5	1.25 - 1.5	Paste, 2006
Century	Qld, Australia	Zinc	1999	Active	4.3	HR	1	45	0.33	32 to 38	2.8	52-58	DVD	1.0	0.6-1.0	Murphy, 2006
Sunrise Dam	WA, Australia	Gold	2000	Active	3.6	HR	1	24	0.97	19		64	CTD	2.0	1.0-2.0	Williams & Seddon, 2004
Bulyanhulu	Tanzania	Gold	2000	Active	0.7	O								10 max		Landriault, 2000
Myra Falls	Canada	Copper/zinc	2003	Active		P	1	25				65-68		3.0		Lord, 2003
Kimberley CTP[2]	S.Africa	Diamond	2003	Active	8.6	P	5	15	0.36	<50		44-57	CTD	1.5	1	Houman & Johnson, 2003
Osborne	Qld, Australia	Copper / gold	2004	Active	1.34	HR	1	9	0.77		3.6	72-76	CTD	4.0	3	McPhail et al 2004, Brent and Dobb, 2006

Thickeners	
HR	High Rate
HR DC	High Rate Deep Cone
HD	High Density
HC	High Compression
P	Paste
O	Other, refer notes

Disposal Schemes	
CTD	Central Thickened Discharge
DVD	Down Valley Discharge

Notes:	
1	Max slope increased to 5% after switch to multi-spigot discharge
2	This is now planned to be a continuing surface disposal facility

Table 1 (cont.) Listing of thickened and paste tailings schemes implemented world-wide

Mine site	Location	Ore type	Start year	Status	Typical rate	Thickener details				Floc. rate	Tailings slurry properties		Disposal scheme	Beach slope achieved		Reference
					Mtpa	Type	No.	Dia. m	Unit load t/m^2.hr	g/t	SG	Conc. % w/w		Max %	Range or typical %	
Surface disposal (continued):																
Cobriza	Peru	Copper	2004	Active	1.8	P	1	14	0.43	35	3.73	77	DVD / side hill			V.Gonzales (D.O.E) Paste 2005, p261+
Miduk	Iran	Copper	2005	Active	4.8	P	4	16	0.73	25 to 30		63	DVD	2.5		ATC Internal
Ellendale E4 (TSF 2A)	WA, Australia	Diamond	2006	Active	3.7	HR	1	34	0.50	80	2.8	47-49	DVD			ATC Internal
Douglas	Vic, Australia	Mineral sands	2006	Active	2.0	HR	1				2.7		CTD			ATC Internal
Lone Mountain	USA (East)	Coal	1997	Closed 2007	0.8	Belt Press[3]	4	na	na	55	1.9	55	Trucked, side hill	2.0	1	Gupta & Johnson, Paste 2007
	USA (East)	Coal	2007		0.8	P[4]	1	15	0.55	55	1.9	55	DVD	2.0	1	Gupta & Johnson, Paste 2007
In-dump disposal schemes:																
La Quinua[5]	Peru	Gold	2008	Active ?	5.0	HR	1	32	0.76	11	2.8	69	DVD			Kerr et al., Paste 2007
In-pit disposal schemes:																
EKAPA	S.Africa	Diamond	2002	Active	0.8	P	1	15	0.17	80-100	2.65	53-57	In pit			Hohne et al, 2004
Pajingo	Australia	Gold	2002	Active	0.73	P	1	14	0.17			59-61	In pit			Gregory, 2003
Hazelwood	Australia	Lignite Ash	2006	Active	0.2	HR	1	22	0.02	80-100	3.0	40-45	In pit	low	<1%	New, Kearn & Sweeney, Paste 2007
Granites	Australia	Gold	1999	Closed[6]	0.2	HR	1				2.75	55-60	In pit	2.0	n/a	ATC Internal
Red mud:																
Gove	NT, Australia	Bauxite	1972	Active									CTD			No details published
Vaudreuil (Jonquiere)	Canada	Bauxite	1987	Active	0.45	P	1	12	0.49		~3.0	45		4.0	3.0-4.0	Lord,2003
Alcoa Kwinana	WA, Australia	Bauxite	1989	Active	1.9	HC	1	50	0.12	60	~3.1	50	Dry stacking	1.2	1.0 - 1.2	Cooling, 2000
Alcoa Pinjarra	WA, Australia	Bauxite	1987	Active	3.3	HC	1	90	0.06	50-80	~3.1	50	Dry stacking	1.2	1.0 - 1.2	Cooling, 2000
Alcoa Wagerup	WA, Australia	Bauxite	1991	Active	2.2	HC	1	70	0.07	60	~3.1	50	Dry stacking	1.2	1.0 - 1.2	Cooling, 2000
Aughinish	Ireland	Bauxite	1993	Active	1.7	O						63	CTD	2.7	1.5 - 2.7	Phil Newman, Paste 2006

Thickeners	
HR	High Rate
HR DC	High Rate Deep Cone
HC	High Compression
P	Paste
O	Other, refer notes

Disposal Schemes	
CTD	Central Thickened Discharge
DVD	Down Valley Discharge

Notes:	
3	Belt pressed to be decomissioned following commisioning of paste thickener
4	Westech Deep Bed paste thickener at TSF site
5	Knight Piésold / Paterson and Cooke
6	Thickened tailings used to cap in-pit deposit

Table 2 Distribution of schemes according to thickener type

Thickener Type	Qty
High rate	9
High compression/high density, including Ecat	7
Paste	8
Other and belt press	3

Table 3 Range of mineral types

Mineral Type	Qty
Base metals – copper, zinc, lead and nickel	13
Gold	6
Uranium	1
Mineral sands	1
Diamonds	5
Coal	4
Bauxite	6

Table 4 Distribution of the stack types

Stack Type	Qty
CTD	14
DVD, including side-hill	9
In-pit	4
“Dry-stack” (red mud)	3

5 Issues that confront us

5.1 Prediction of beach slope

The beach slope is undoubtedly the most important parameter needed for the design of a surface disposal stack, both CTD and DVD. Williams (2001) presented a review of the state-of-the-art for slope forecasting and suggested a research approach. This has now been followed up by two PhD studies, one by Behnam Pirouz from Iran, and the second by Tim Fitton at RMIT University in Melbourne, Australia.

Fundamental to the research approach is acceptance of the geomorphological model for beach build-up that states that tailings flows across the beach, not in uniform ever-expanding sheets, but in self-formed channels. At the distal end of the channel, flow fans out in localised sheets and slides to a halt. Deposition only occurs in the terminal fans. No deposition occurs in the channels. The channels are simply the tailing’s means of conveying themselves to the deposition area. The channels randomly re-direct themselves, through the full 360° range in the case of a CTD stack, to achieve an even build-up of tailings over the whole cone (see Figures 4 and 5).

Figure 4 **Myra Falls, Canada (tailings.info web page)**

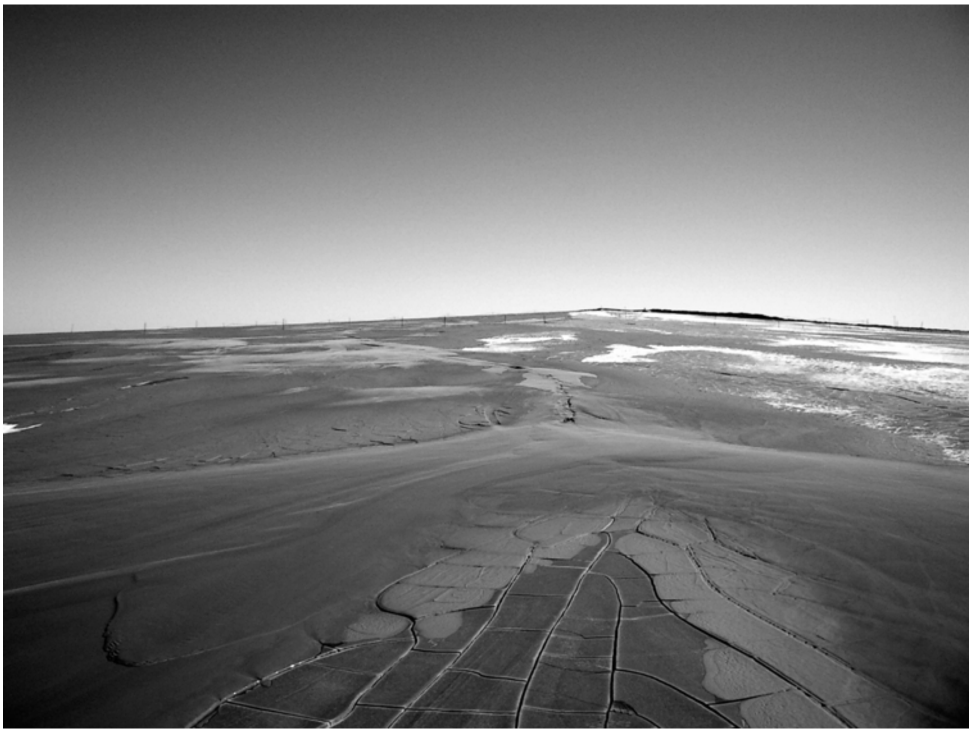

Figure 5 **Peak Gold mine, New South Wales**

By observation, the slopes of the deposition fans are steeper than the channels. But the fans are localised features. The channel slope will ultimately dictate the overall stack slope. The key to the development of predictive models has been the detailed observation and measurement of channel flow in a large flow-through flume (see Figures 6, 7 and 8).

Figure 6 Large scale flume used during the Peak and Sunrise Dam experimental work

Good agreement was obtained between predictive models and flume measurements made by both researchers, at the two mines that hosted the field work, Peak Gold mine at Cobar in New South Wales (Pirouz and Williams, 2007, Fitton et al., 2007) and Sunrise Dam Gold mine in Western Australia (Fitton et al., 2007).

An important corollary to the geomorphological model is that small-scale stack tests or flume deposition tests are not valid as slope prediction tools. The determination of the laminar/turbulent transition in self-formed channels is necessary. This is usually expressed in terms of Reynolds number, Re. Reynolds number cannot be scaled. Given this constraint, it is a requirement for any predictive method that it must be able to proceed on the basis of laboratory data such as particle size distribution, rheology, specific gravity of solids, mineralogy, etc. since the opportunity to carry out full scale tests rarely exists.

Figure 7 A self-formed channel in a bed of freshly deposited tailings

Figure 8 Velocity and density probes being immersed into the tailings channel in the flume

5.2 Pipeline transport

The task for pipeline design for tailings slurries is quite simply to determine the friction head loss. It is, needless to say, desirable to keep this to a minimum but, with the slurry being a suspension of solids in water, it is also necessary that the solids do not settle out and form a stationary bed in the pipeline ultimately risking pipeline blockage. The critical velocity needed to create enough turbulence to avoid this can be determined using well-published methods such as the one presented in the Warman's Slurry Pumping Handbook (2000). Given a velocity and hence pipe diameter, a friction factor can be estimated and then used in a head loss equation of the Darcy-Weisbach type.

However, such methods assume a Newtonian fluid and a settling slurry. At higher densities represented by the top end of thickened tailings and by paste these assumptions become increasingly less valid. The slurries exhibit non-Newtonian behaviour in rheology tests and will not segregate or settle to any significant extent, or at all, when left to stand under static conditions. The option exists to design the pipeline for laminar rather than turbulent flow, indeed for very high density slurries it may be impractical to achieve turbulent conditions.

Given the tendency for ever more effective thickener technology to become available, the transport of such slurries is certainly an issue that confronts us.

Somewhat counter-intuitively, the laminar flow condition for such high-density slurries does not necessarily mean that a stationary or slow-moving bed in the bottom of the pipe is avoided. Under shearing conditions, the shear strength that is sufficient to prevent particles from settling out under static conditions is no longer effective. This has been well demonstrated by the work undertaken by Pullum (2007) involving observation of flow through an optical window in the pipeline as well as by magnetic resonance imaging (MRI) and electrical resistance tomography (ERT) techniques. Pullum suggests that there should be a distinction between very fine suspensions where the inter-particle forces will dominate, and coarser slimes. He proposes a threshold of 20 microns. For the latter, the "coarse" particles are those whose behaviour is dominated by inertial and body forces. Examples of very fine suspensions would be red mud or the clay slimes from mineral sand mining or from diamond mining. These materials can be expected to act as true homogeneous slurries under laminar flow.

Notwithstanding, the challenge is still to determine the minimum practical head loss regime. For laminar flow:

$$\frac{\Delta p}{L} = \frac{4\tau_w}{D} \tag{1}$$

where $\frac{\Delta p}{L}$ = pressure gradient,

τ_w = wall shear stress, Pa

D = pipe diameter, m

The wall shear stress can be calculated using the following equation:

$$\tau_w = \mu \frac{8V}{D} \tag{2}$$

where μ = dynamic viscosity, Pa.s

V = velocity, m/s

Combining Equations (1) and (2) yields:

$$\frac{\Delta p}{L} = \frac{32\mu V}{D^2} \tag{3}$$

For “coarse” non-Newtonian, high density slurries, in order to avoid the settled bed problem and to achieve pseudo-homogeneous conditions, it will be necessary to find the transition between laminar and turbulent flow and aim to be just into the turbulent regime. This also happens to be the most efficient point for minimising power consumption. The determination of Reynolds number, and the transition value for Reynolds number, becomes the key focus for pipeline design purposes.

Most highly thickened slurries will exhibit a yield-pseudoplastic rheogram, see Figure 9. This is best represented by the Herschel-Bulkley power law equation, equation (4).

$$\tau = \tau_y + K\dot{\gamma}^n \tag{4}$$

where τ = shear stress, Pa

τ_y = yield stress, Pa

K = the Herschel-Bulkley factor

$\dot{\gamma}$ = shear rate, s^{-1}

n = flow behaviour index.

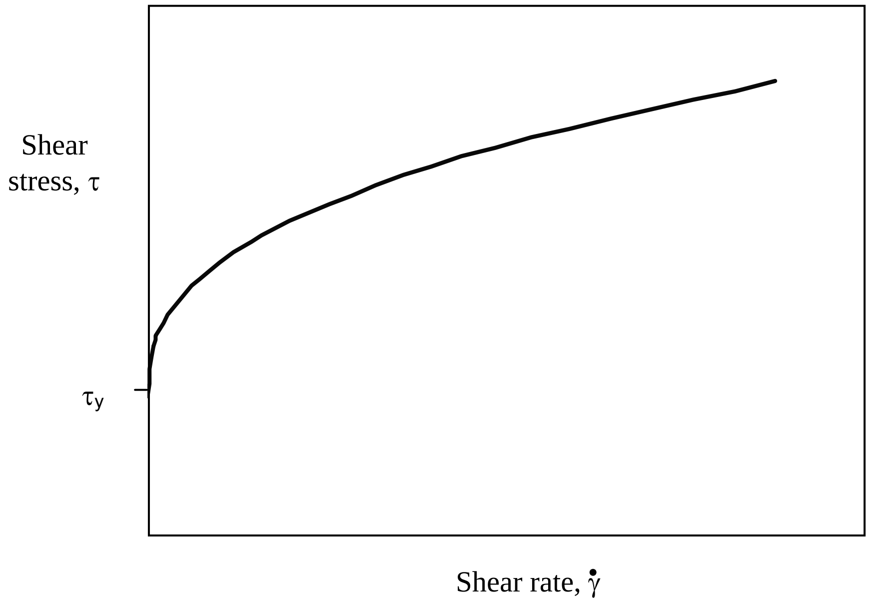

Figure 9 Yield-pseudoplastic rheogram

Slatter (1999) has developed a modified Reynolds number equation to suit yield-pseudoplastic fluids that includes yield stress, τ_y, as well as a viscosity term in the denominator:

$$\mathrm{Re}_3 = \frac{8\rho V^2}{\tau_y + K\left(\frac{8V}{D}\right)^n} \tag{5}$$

where Re_3 = modified Herschel-Bulkley Reynolds number

ρ = fluid density, kg/m^3

V = velocity, m/s

D = internal pipe diameter, m

Slatter (1995, 1999) also examines the nature of the transition from laminar to turbulent flow for yield-pseudoplastic fluids. Modified Reynolds number transitional values in the range 1740 to 7577 are proposed based on pipe loop experimental testing.

For flow of truly homogeneous yield-pseudoplastic slurries, the existence of a yield strength at zero shear rate will result in an un-sheared plug of slurry moving in the centre of the pipe surrounded by an annular shearing zone (Pullum, 2007). This requires further adjustment of the Re_3 Reynolds number such that V_{ann} and D_{shear} are used and apply only to the sheared portion of the flow.

For "coarse" slurries, even though they are non-segregating under static conditions, Pullum's testing, as stated above, has shown that a slow-moving bed of the coarse particles forms. He concludes that stratified flow analysis is necessary in order to properly model this behaviour but that above the bed, that part of the slurry that is non-segregating under shearing (he suggests the <20 micron fraction) forms a velocity profile of the truly homogeneous yield-pseudoplastic type, i.e. an unsheared plug surrounded by a shearing annulus.

The reader will now appreciate that the calculation of head loss under these quite complex conditions has moved a long way from the traditional methods to be found in the Warman's Slurry Pumping Handbook (2000). It is not within the scope of this paper to present solutions to these problems, merely to identify them as issues that confront us. The pipeline transport of very thick slurries certainly comes into this category.

Experts in the field need to be consulted and large diameter, slurry-specific pipe loop testing will probably be required.

It is also important that pipeline design be checked for “turn down” conditions, i.e. reduced tonnage and/or reduced slurry percent solids. If critical velocities are not maintained, sedimentation and pipe blockage can result.

5.3 Seepage to groundwater

There is no argument as to the importance of contaminated seepage from a regulatory and environmental standpoint. An objective for the design of a surface disposal stack of thickened or paste tailings will be to avoid the ponding of water on the tailings. The topography of the site sometimes frustrates this. If ponding is unavoidable, for an off-tailings pond the seepage issue must be addressed. If the beneficial uses of the groundwater will be adversely affected, this will require control measures such as a clay lining, grouting, or the use of membranes or geosynthetics. But if the avoidance of a pond is achievable, the question that confronts us is the scope for seepage from the stack itself. There is a perception that groundwater contamination and tailings disposal are synonymous, but this need not be so. Figures 10 and 11 show the results of auger hole drilling and sampling through the CTD stacks at Elura and Peak mines at Cobar in New South Wales.

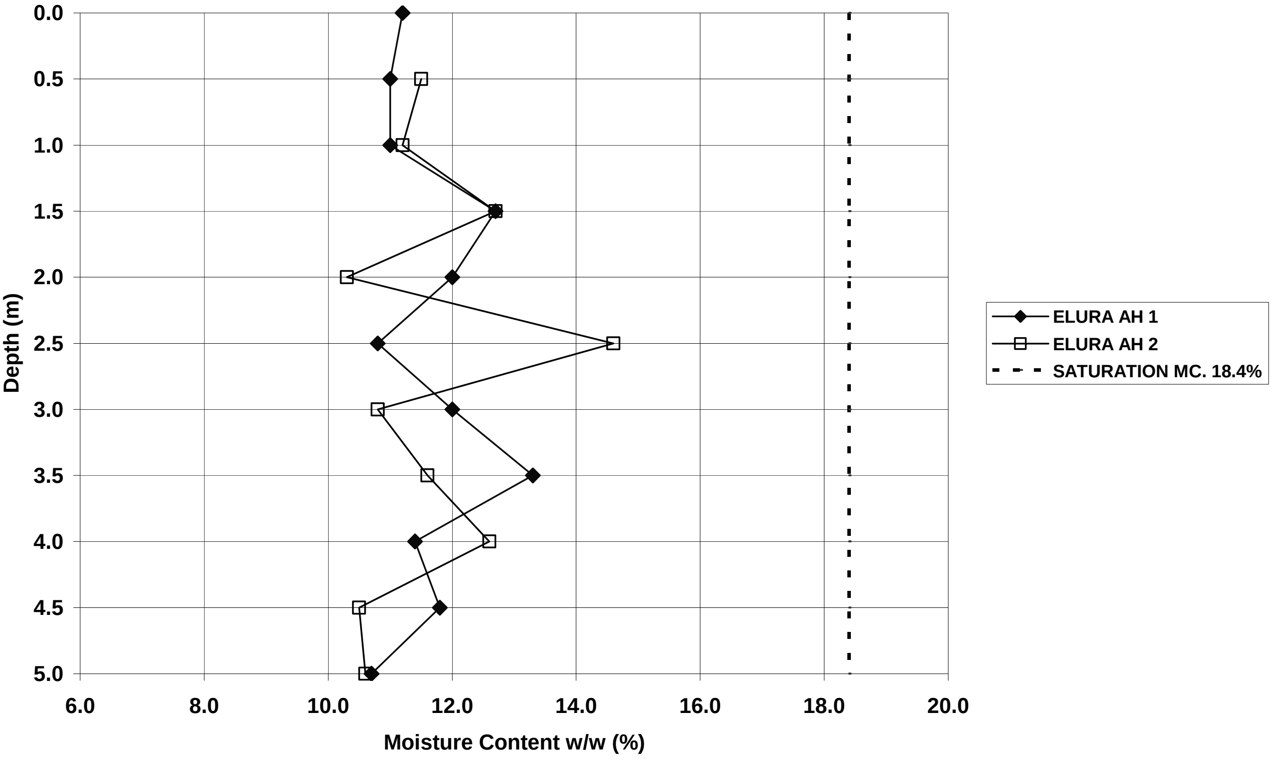

Figure 10 Moisture content versus depth, Elura (Williams, 2000)

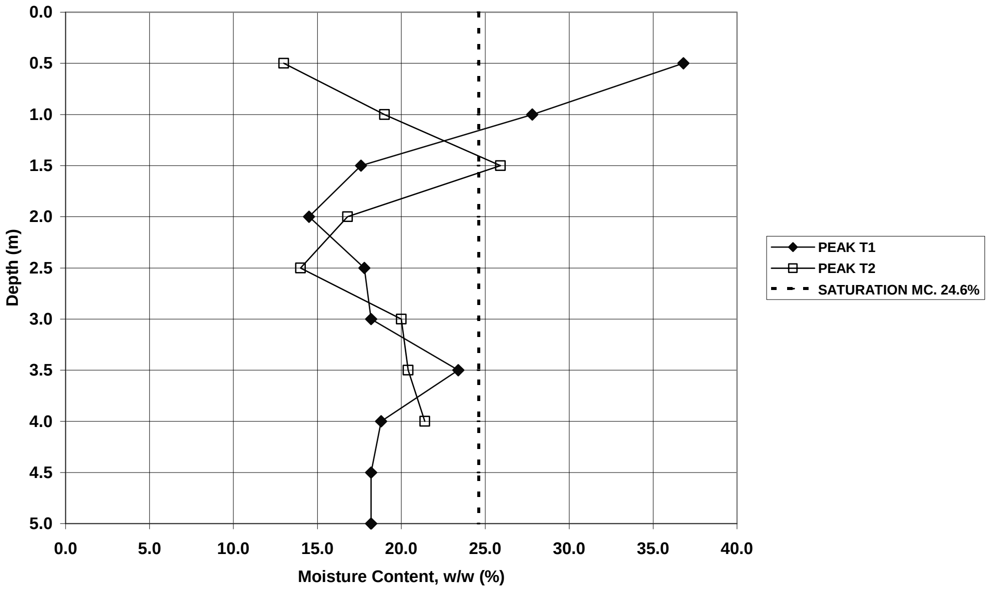

Figure 11 Moisture content versus depth, Peak (Williams, 2000)

Both sites show unsaturated tailings over the full depth sampled, at some locations extending into the underlying natural ground. Clearly there is no seepage to groundwater occurring from the stack at these two sites.

The sequence of events is that saturated tailings are deposited on the beach. Excess bleed water runs off. Thereafter, the water content of the tailings is reduced by evaporation. Rainfall will run off whilst the tailings remain saturated. Evaporation will continue after rainfall ceases. Evaporation will cause shrinkage of the tailings until the shrinkage limit density is reached. Further evaporation will result in the tailings becoming unsaturated. Periodically, a fresh layer of wet tailings will be deposited over the top of the drying bed.

In order to evaluate whether seepage will or will not occur under these circumstances, it is necessary to study the saturation state of the tailings. This can be studied simplistically by comparing the evaporation rate with the water loading rate (WLR) of a stack:

$$WLR = \frac{1000R(w_{isd} - w_{sld})}{A} \tag{6}$$

Where WLR = Water loading rate, mm/day.

w_{isd} = The moisture content at the initial settled density, w/w.

w_{sld} = The moisture content at the shrinkage limit density, w/w.

R = Tailings production rate, t/day.

A = Stack area, m^2.

If the daily evaporation rate exceeds the WLR then the deposit will be unsaturated.

The behaviour in reality is more complex than this. It can be modelled using unsaturated one-dimensional flow models such as SOILCOVER or VADOSE/W. As an example for this paper, VADOSE/W was used for a hypothetical site in the Northern Territory of Australia where the rainfall is relatively high, in this instance 1262 mm for the selected year. It is, however, seasonal so that the opportunity exists to study the response under sustained dry weather as well as some quite heavy rainfall events. The annual evaporation for the selected year was 2789 mm. The unsaturated parameters of the tailings were obtained from the Australian Tailings Consultants database of tailings samples. The daily data are plotted in Figure 12a and 12b.

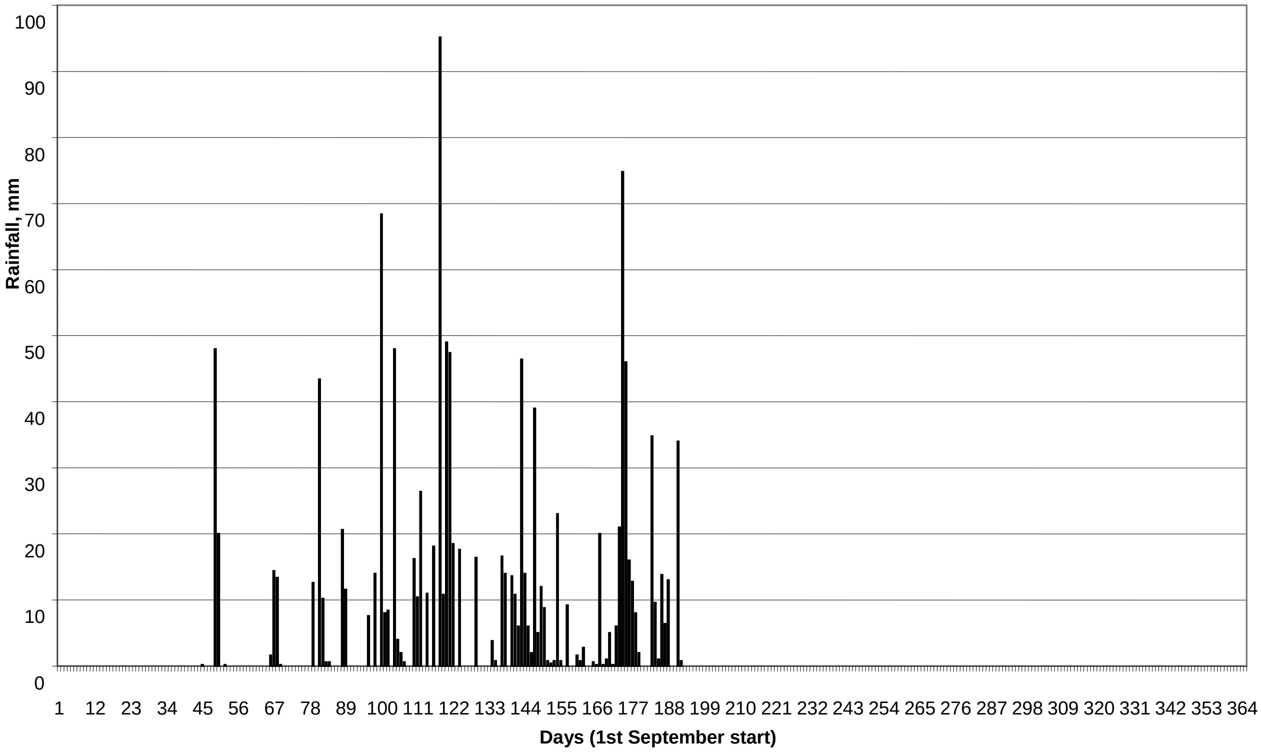

Figure 12(a) **Douglas River rainfall, September 1996 – August 1997**

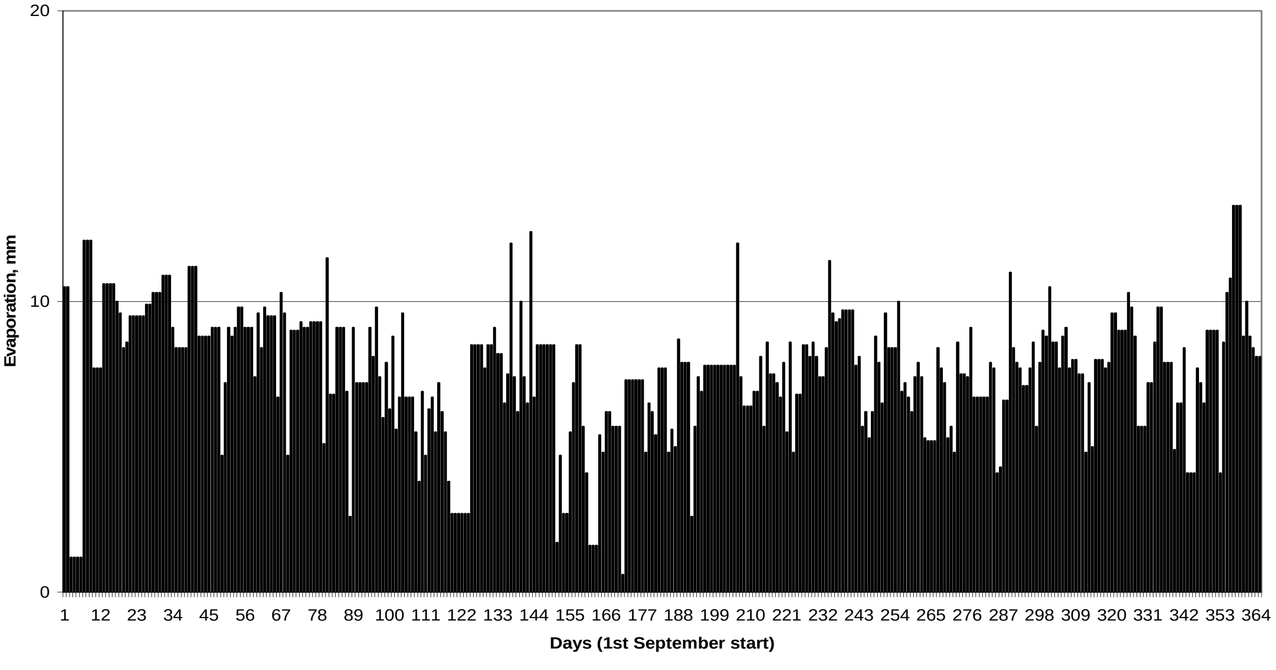

Figure 12(b) **Douglas River evaporation, September 1996 – August 1997**

The tailings used in the model had a P_{80} of 100 microns and a P_{20} of 10 microns. The saturated permeability was 7.3 x 10^{-8}m/s at 1.39t/m^3 dry density. The modelled profile was 5 m deep with a starting condition of 100% saturation at the impervious boundary at the base and 50 kPa suction (90% saturation) at the surface. The year commenced on 1st September. Three cases were run involving the addition of 100, 200 and 300 mm of fresh tailings at the start of each month. VADOSE/W is a seepage modelling programme that does not model consolidation, so its use thereby assumes that the tailings volume does not change. It is acknowledged that this is not strictly accurate, but in the context of predicting the degree of saturation of the tailings over a 12 months period as it is subjected to climatic effects and newly-arriving layers of fresh tailings slurry it is considered that this approach will be a reasonable approximation to the real situation. VADOSE/W is a two dimensional seepage modelling program that applies the Penman-Wilson evaporation model (Wilson (1990) modified the Penman (1948) method) within its own finite element analysis method. Evaporation and rainfall data must be put in by the user. Precipitation is handled within the VADOSE/W two dimensional finite element analysis method, based on the assumption that rainfall is absorbed into the tailings surface based on a suction/permeability curve that is put in by the user.

The results are shown on Figures 13 to 18 as the suction and saturation profiles versus time for each of the cases. Looking at Figures 13 and 14 for the 100 mm case, the profile can be seen to be drying out, notwithstanding the addition of wet tailings, as the dry season continues through October. Wet weather occurs in December, January and February wetting up the profile, particularly near the surface, until the dry season returns in May through to the end of August. Virtually constant 23% saturation exists throughout the profile by the end of the twelve month period. Cracking is not modelled in VADOSE/W. This programme simply assumes that the tailings surface remains closed. This assumption is conservative, since it is understood that cracking promotes and accelerates the drying process.

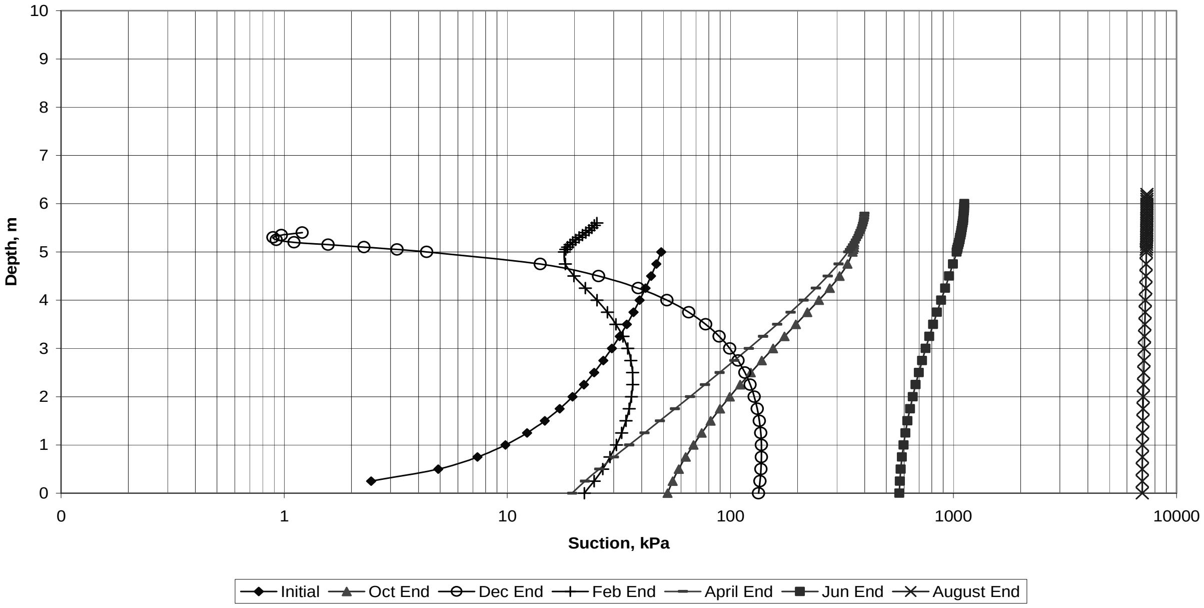

Figure 13 **Suction plot (100 mm layer tailings added per month)**

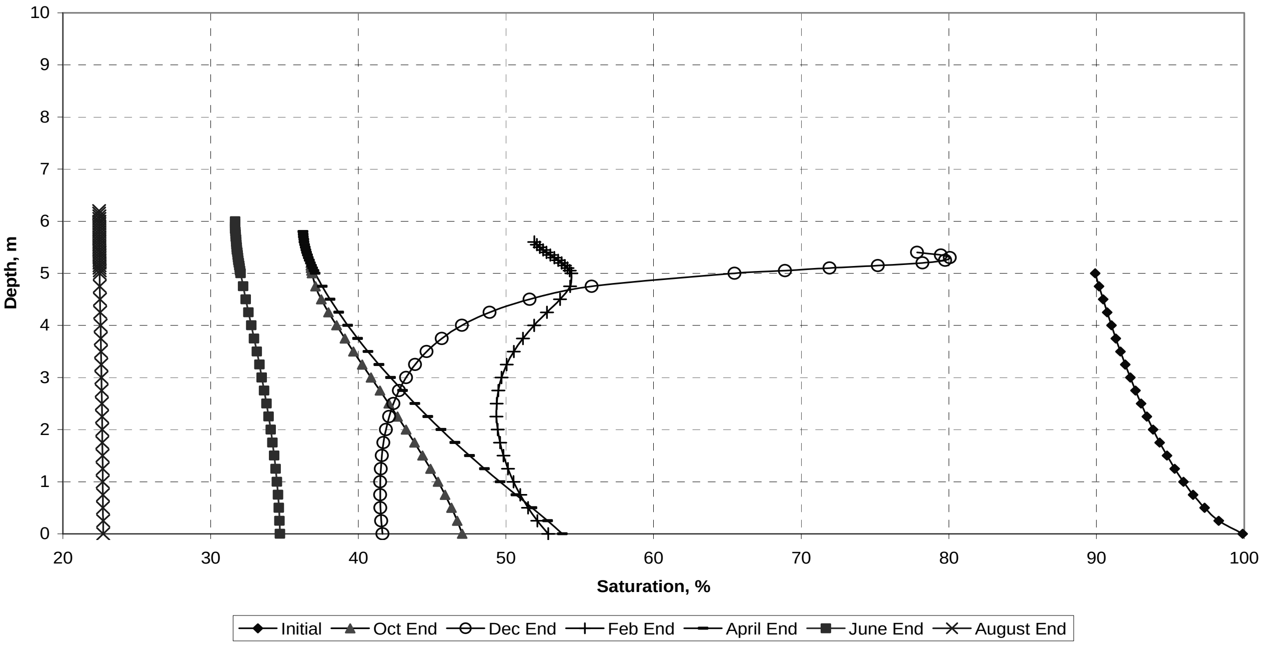

Figure 14 Saturation plot (100 m layer tailings added per month)

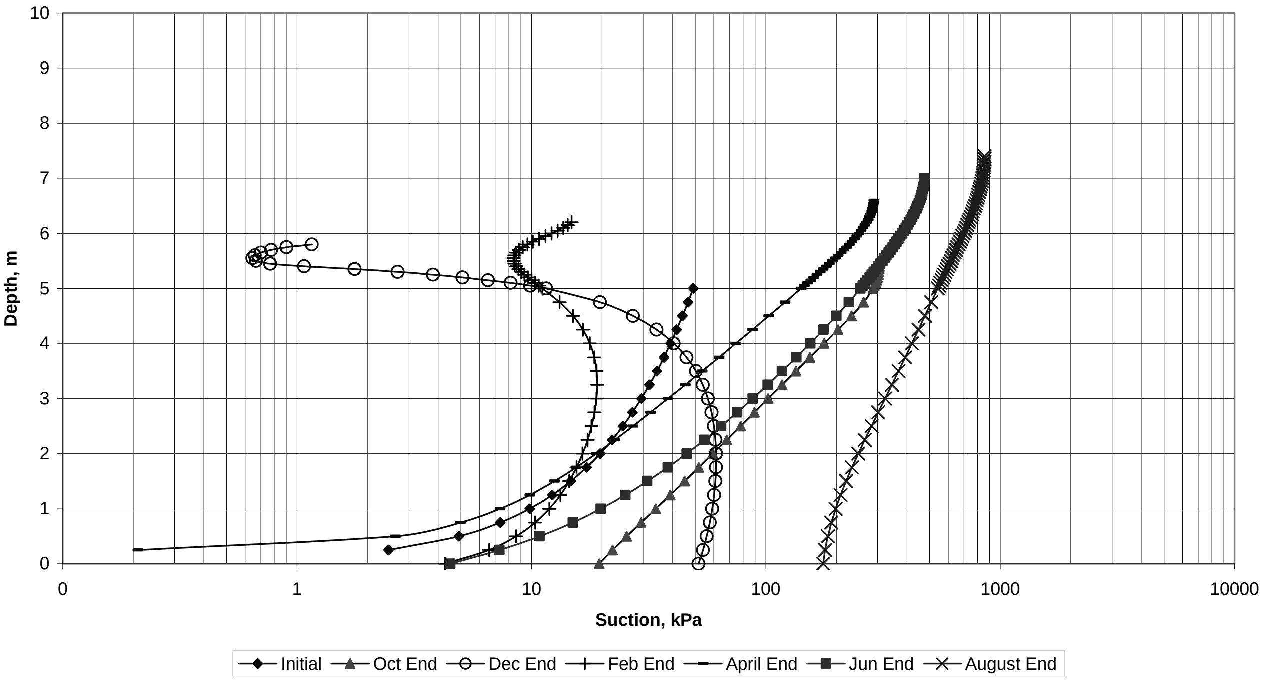

Figure 15 Suction plot (200 mm layer tailings added per month)

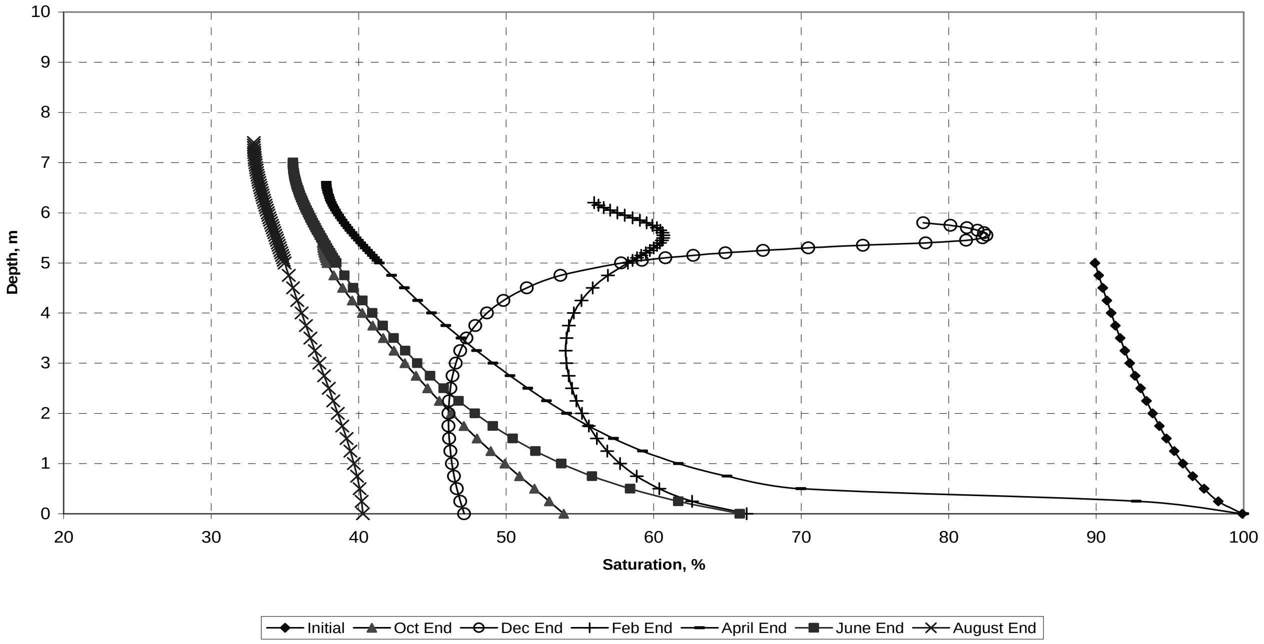

Figure 16 Saturation plot (200 mm layer tailings added per month)

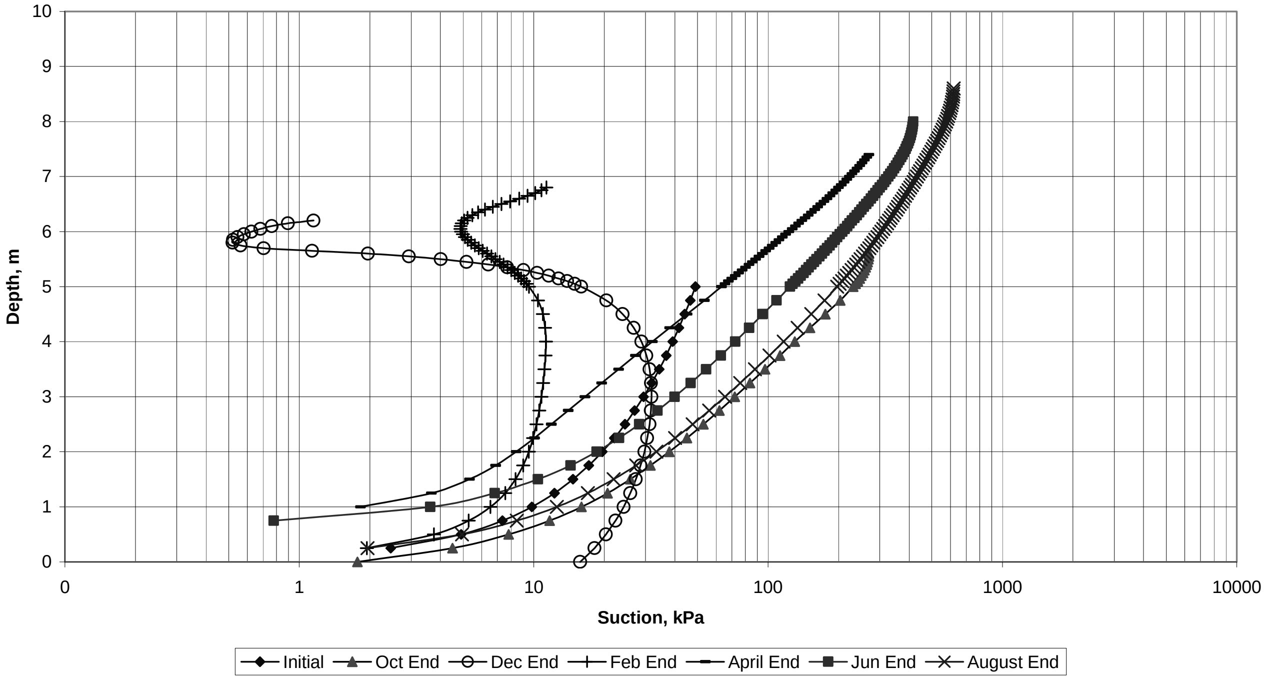

Figure 17 Suction plot (300 mm layer per month)

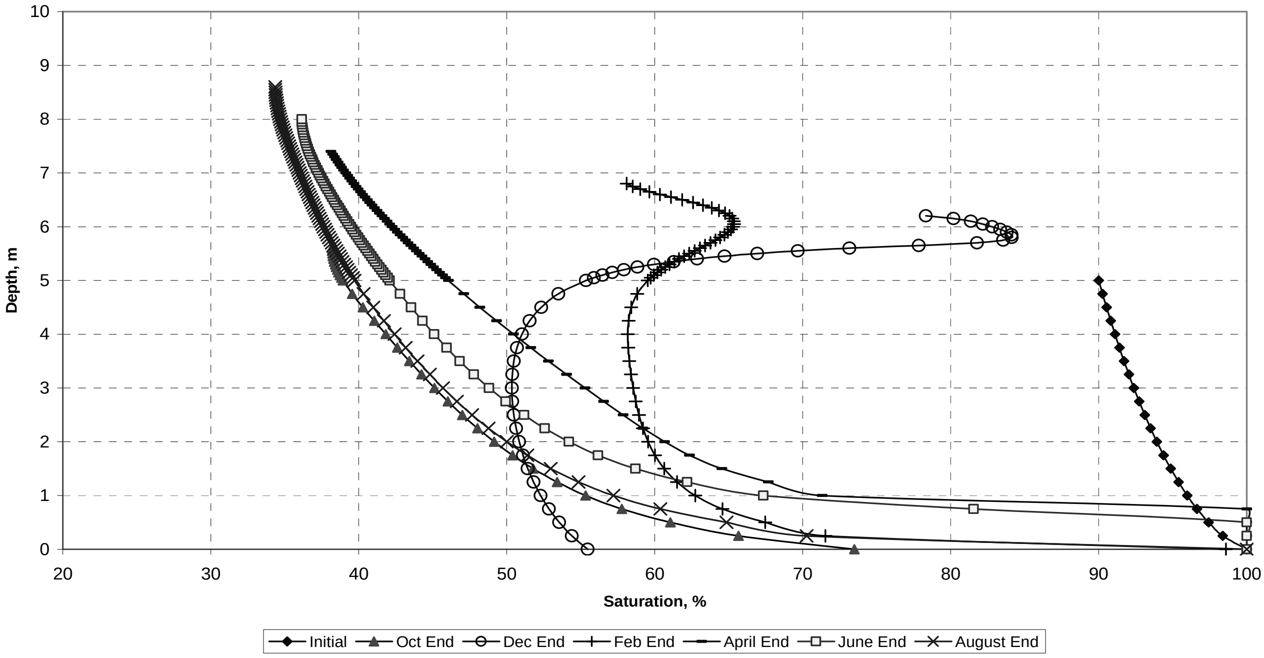

Figure 18 Saturation plot (300 mm layer tailings added per month)

For 200 mm layers of wet tailings per month, Figures 15 and 16, there is sufficient flux of infiltration during the wet season to actually saturate the tailings at the base of the profile at the end of April. Drying then resumes. The final end-of-year figures are 37% saturation at the surface and 40% at the base.

For the 300 mm per month addition, Figures 17 and 18, the flux is much greater, continuing through to the end of May. The final saturation profile is 34% at the surface but still 100% at the base.

Since the model was only 1-D, it must necessarily be an approximation and in this instance it is influenced by the adoption of an impervious base. Three-D modelling would be more accurate but would be much more complicated. The aspect ratio (height to diameter) of a tailings stack is typically very low, however, so that the results are still very useful.

The conclusion from the modelling is that, with the severity of the Northern Territory wet season rainfall, whilst the tailings will be unsaturated throughout the whole profile for virtually the whole year, somewhere around 1.5–2.0 m annual rate of rise of the tailings is the limit if seasonal flux of infiltration through the tailings is to be avoided. The modelling supports the field measurements at Elura and Peak where the climate is much drier and the rate of rise was only 0.5–1.0 m/yr.

5.4 Beach stability under earthquake loading

This issue for stacked tailings deposits, CTD or DVD, was reviewed in some detail by Seddon (2007). It is undoubtedly a confronting issue, particularly in countries with a level of seismic risk. In Chile, for example, where a number of serious tailings dam failures involving liquefaction have occurred, there is legislation that disallows tailings to be stored above the elevation of a retaining embankment.

A number of conditions must exist before large scale flow-slide failure of a tailings stack will occur during or immediately following an earthquake:

(i) The tailings must be saturated. Without full saturation, or very close to it, shaking will not generate the necessary excess pore pressures needed to create the liquefied condition.

(ii) A sufficiently large earthquake must occur, i.e. large accelerations for an appreciable number of shaking cycles, to generate the strains necessary to induce liquefaction. A summary of an accepted method of calculating the factor of safety against liquefaction (FS_2) as a function of magnitude and intensity of a seismic west is given in Seddon (2007). An approximate guide for typical (saturated) tailings, would be that liquefaction could be expected if an earthquake of Magnitude 6 - 6.5 is close enough to cause peak acceleration in the range 0.1-0.15 g.

(iii) The large strains from (ii) will leave the tailings in their so-called steady-state condition. The reduced shear strength in this condition may be less than the pre-earthquake strength. If the post-liquefaction shear strength is too low, a slope failure will occur.

Point (iii) is important. Liquefaction in this context is an unfortunate choice of word. It implies that tailings will behave like water and will therefore flow like water. This is not the case. Tailings will still possess a positive, although low, shear strength, both during and after the earthquake. Whether or not a flow failure will occur will depend on the slope of the beach. Seddon (2007) showed that surficial sliding was unlikely to occur at slopes flatter than 5% and that deep-seated failures would require much steeper slope angles than 5%.

Point (i) is also significant in the context of the saturation modelling and field measurements discussed in Section 5.3. It is possible for a well designed stack to be unsaturated in which case the liquefaction issue does not arise. The Elura and Peak stacks, for example, are never going to liquefy no matter how hard they are shaken.

5.5 Closure strategies and long-term behaviour

The ultimate objective for long-term closure of a tailings storage facility (TSF) is that the tailings should stay where they have been put. They shouldn’t blow away, be washed away, or release contained contaminants at damaging concentrations into the surface or groundwater environment. In the short-term, so far as the commercial operations of a mining company are concerned, it is desirable if the completion of the closure strategy can be implemented as soon as possible after the mine ceases to operate.

With respect to the first criterion, CTD schemes do particularly well. Conventional above-ground tailings TSFs rely on embankments for containment. It is not easy to be convinced of the ultra long-term (geological time) integrity of an earth/rockfill embankment. The face slopes are often much steeper than the natural slopes of the surrounding terrain and this does not augur well. The flat slopes of a CTD stack are likely to be much more in keeping with the surrounding terrain.

DVD schemes are more problematic. They are more likely to be in steeper, hilly, even mountainous, terrain and to have a retaining embankment at the toe. Flattening the downstream face of the embankment, rock armouring, and careful attention to run-off management will probably be required.

With respect to the second requirement, the high strengths associated with densification due to evaporative drying, leading, as we have seen, to an unsaturated condition can permit the very early access of even quite heavy earthmoving equipment onto the tailings surface. Rehabilitation of the Union Reefs tailings dam in the Northern Territory of Australia (Williams et al., 2003) is a good example. Union Reefs was a DVD scheme. The cover layer of 1–2 m of waste rock was hauled and placed directly onto the tailings surface using 90 t mine trucks immediately following cessation of operations. Mine operators and regulators have an understandable preference for progressive closure rather than leaving it all to the end of mine life. This is possible with multi-cell conventional disposal, but multiple CTD stacks would be very inefficient and costly. Radial bunding, as in pie slices, could be feasible.

6 Conclusion

A search of published data reveals 32 central thickened discharge (CTD) and down valley discharge (DVD) schemes that have or are being operated around the world – there may be more. The first application of the technique was by Robinsky in the mid 1970s at Kidd Creek at Timmins in Ontario, Canada. Implementation of the idea was initially slow but the catalogue shows new thickened tailings surface disposal schemes appearing at the rate of two per year since 1995.

With respect to the major issues that confront the technique:

- Recent research has made advances in the understanding of beaching and the prediction of beach slopes. Thereafter, careful attention by operators and management is necessary to ensure optimum and consistent thickener performance.
- Improved thickener technology presents the challenge of pipeline design for non-Newtonian fluids. In this department too, research is keeping pace. Design of pumping and pipeline design is particularly challenging when the slurry density range for thickener operation could lead to settling and pipe blockages under laminar flow and may require worst case design in turbulent flow, with associated cost and energy implications.
- It is frequently assumed that tailings disposal and seepage to groundwater go hand in hand. Field measurements at two CTD stacks show the tailings to be unsaturated so that this assumption is not valid in these two cases. Some illustrative 1-D computer modelling shows how this outcome is not unexpected and suggests an approach for the design of stacks in this regard.
- The assumption of liquefaction following earthquake shaking, in turn leading to disastrous flow-slides, is not an automatic consequence for paste and thickened tailings stacks. Geotechnical engineering is well advanced in this area. Mining companies, regulators, and other practitioners working in this field need to allow this expertise to be applied before jumping to conclusions.
- The flat slopes of CTD stacks create a terrain more in keeping with the natural terrain and offer better scope for very long-term stability.
- The high density, and hence high strengths, that are associated with evaporative drying of tailings stacks permits early access for earthmoving equipment for the placement of cover materials for closure.

Acknowledgements

The dissemination and debate of the ideas, issues, and solutions to the problems that the “stacking” of paste and thickened tailings generates owes much to these annual international seminars. A wide range of engineering disciplines and practitioners in the field are brought together on these occasions and this is of considerable value. The authors would like to thank the Australian Centre for Geomechanics for organising the series, and the organising committees in each country each year for their hard work.

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