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Synopsis

The profile of a delta formed by fine-grained mineral processing wastes, disposed of as aqueous slurries by subaerial deposition from a pipeline, has a significant bearing on the volume that is available for waste and water storage in a given containment structure. Earlier field data and laboratory experiments suggested that mine waste delta profiles could be predicted with good accuracy using data from small-scale laboratory deposition tests. The relationships between the profiles of full-size and laboratory-model deltas are analysed using the principles of kinematic similarity and a recent theory of delta formation based on engineering hydraulics. Measured profiles of full-size and model coal-mine tailings deltas are compared and the prediction of full-size profiles is discussed. It is shown that the data derived from laboratory-model deltas are insufficient to enable accurate prediction of full-size delta profiles. Initial slope data or other, equivalent data for the full-size delta are also required.

Fine-grained wastes from mineral processing plants are often disposed of as an aqueous slurry by pumping to a waste impoundment or open-pit for subaerial deposition. After discharge at the outlet point waste particles undergo hydraulic sorting according to their size and specific gravity and a delta with a sloping profile is formed. Reliable prediction of the delta profile is important in the design of tailings impoundments because it allows the designer to assess their storage capacity for both tailings and storm-water more accurately. The significance of the final profile becomes clear when it is realized that for a large impoundment of 300 ha, whose surface level may vary by tens of metres over the length of the impoundment, a depth of 1 m of tailings corresponds to a volume of 3 000 000 m^3.[1]

It has been demonstrated[2,3,4] that the profiles of a series of full-scale deltas of different lengths formed by the same tailings material can be represented by a single, dimensionless profile. Subsequent experiments[4] showed that this principle can be extended to short, laboratory-model deltas, suggesting that full-size tailings profiles could be predicted with good accuracy from small-scale laboratory deposition tests. More recent work by the present authors[5,6,7] has provided a theory of tailings delta formation based on engineering hydraulics,[7] which predicts the form of delta profiles. In the present contribution this theory and the principles of kinematic similarity and engineering hydraulics are used to clarify the relationships between full-size and model delta profiles. Profiles of laboratory-model deltas that were produced using coal tailings from Aberdare and Meandu collieries, southeastern Queensland, Australia, are compared with the corresponding full-size deltas. The results are consistent with the theoretical analyses and show that the data derived from model deltas are insufficient to enable the profiles of full-size deltas to be predicted accurately. Initial slope data or other, equivalent data for the full-size delta are also required.

Tailings delta profiles

Mine tailings are usually discharged on to tailings deltas from a cantilevered pipe outlet or outlets. The rim of the plunge pool that forms below the outlet constitutes the highest level on the delta, separating the plunge pool from the delta proper. In the following the term 'delta' is used to refer to the delta proper beyond the plunge pool. Most writers[1–4] refer to the delta as the 'beach'.

The recently proposed theoretical model[7] of delta formation assumes that the volumetric tailings discharge to the delta from the pipe outlet, the initial particle-size distribution and the initial gravimetric solids concentration, C_0, of the input tailings are constant. The model predicts dimensionless delta profiles that conform to

$$\frac{z}{z_0} = A\exp\left(-\omega\frac{x}{L}\right) - A\exp(-\omega) \qquad (1)$$

where x is longitudinal coordinate relative to the highest point on the delta, L is length of the delta, z is elevation of the delta bed relative to the level of the decant pond, $z_0 = z$ at $x = 0$ (Fig. 1), $A = (1 - \exp(-\omega))^{-1}$ and ω is a non-dimensional positive constant (Fig. 2) given by[7]

$$\omega = \ln\left(\frac{S_0}{S_L}\right) \qquad (2)$$

where S_0 and S_L are bed slopes at $x = 0$ and $x = L$, respectively.*

The equivalent dimensional profile equation is

$$y = y_0\exp(-\varepsilon x) \qquad (3)$$

where y is elevation of the bed relative to the (horizontal) asymptote to the delta profile, $y_0 = y$ at $x = 0$ (Fig. 1) and ε, a dimensional constant, is equal to ω/L.

Differentiating either equation 1 or equation 3 with respect to x leads to

$$S = S_0\exp(-\varepsilon x) = S_0\exp\left(-\omega\frac{x}{L}\right) \qquad (4)$$

where $S = -\partial z/\partial x$ (or $-\partial y/\partial x$) and $S_0 = y_0\varepsilon$.

Differentiating equation 1 with respect to x/L gives

$$S^* = S_0^*\exp\left(-\omega\frac{x}{L}\right) \qquad (5)$$

where the slope of the dimensionless profile (Fig. 2), S^*,

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*Symbols and their definitions are listed on pages A67–8.

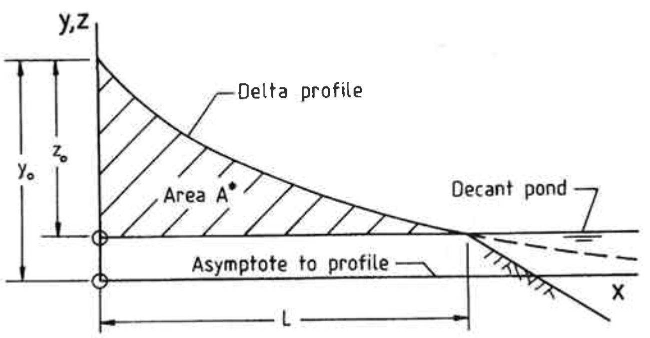

Fig. 1 Diagrammatic representation of tailings-delta profile

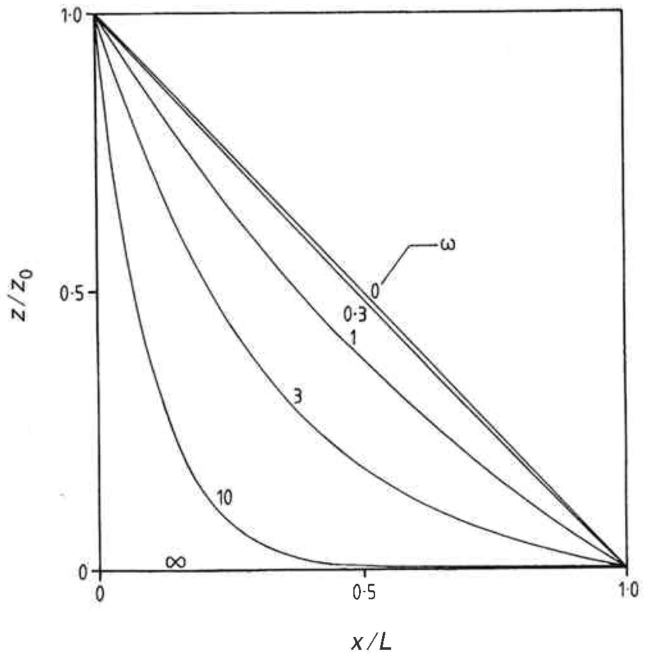

Fig. 2 Dimensionless delta profiles

equals $-\partial(z/z_0)/\partial(x/L)$ and S_0^* is given by

$$S_0^* = \omega A = \omega\left(1-\exp(-\omega)\right)^{-1} \tag{6}$$

The initial bed slope, S_0, is related to S_0^* by

$$S_0 = \frac{S_0^* z_0}{L} \tag{7}$$

Hence, although S_0^* is a function of ω only (equation 6), S_0 is not. Consequently, both ω and S_0 (or an equivalent parameter) are necessary to characterize the (dimensional) profile of any delta of given length L.

The recent theoretical model[7] of delta formation shows that tailings particles at any point on a delta are characterized by the dimensional particle-sorting parameter, G, given by

$$G = \left(G_s - 1\right)^{1+\frac{b}{3}} D^{1+b} \tag{8}$$

where G_s is specific gravity of the sediment, D is characteristic particle diameter and b is a dimensionless constant that is independent of L and characterizes sediment entrainment. Here, following earlier work,[2–6] D is taken as the median particle diameter.

The values of G at $x = 0$ and $x = L$ are denoted by G_0 and G_{min}, respectively. At a given mine both G_0 and G_{min} are determined by the mineral separation and refining processes and the hydraulic conditions in the plunge pool[7] and, hence, for a given delta are independent of L.

The parameters ω and S_0 are related to G by

$$\omega = \ln\left(\frac{G_0}{G_{\text{min}}}\right) \tag{9}$$

and

$$S_0 = c_1 G_0 \tag{10}$$

where c_1 is a dimensional constant that is independent of L.[7] Hence, both ω and S_0 are independent of L.

The evaluation of G_0, G_{min} or c_1 for full-size deltas involves lengthy laboratory procedures. It is impractical to evaluate these parameters for laboratory-model deltas owing to the difficulty of obtaining representative samples of the bed sediments of a size adequate for laboratory testing and the short duration and extremely shallow depth of flow. However, both ω and S_0 can be determined directly by fitting equation 1 to measured delta-profile data using least-squares (or similar) regression methods. Although L must be determined accurately, profile data are not required for the full length of the delta. This is advantageous on full-size deltas with extensive areas of soft tailings adjacent to the decant pond.

The empirical dimensionless profile equation given by Melent'ev and co-workers[8]

$$\frac{z}{z_0} = \left(1 - \frac{x}{L}\right)^n \tag{11}$$

where n is constant for given mine tailings at constant C_0, is comparable to equation 1 and has also been applied to mine tailings deltas.[1,2,4,5,9,10] Equations 1 and 11 both fit tailings delta profiles well.[5] However, unlike equation 1, equation 11 is not linked by theory to hydraulic sorting on the delta.[1,3,9,10] Also, both n and S_0 (or an equivalent parameter) are needed to characterize a dimensional delta profile based on equation 11, which therefore offers no significant advantages over equation 1.

Model tailings deltas

Neither the foregoing discussion nor the recently developed theory of delta formation[7] places any restriction on L. Both, therefore, apply equally to full-size and laboratory-model tailings deltas, which suggests that the theory can be applied without restriction to the prediction of delta profiles. This is supported in part by data from full-size and laboratory-model gold tailings deltas with a scale ratio for length, η_L (the ratio of the lengths of the longer and shorter deltas), of 83.3,[4] but few such data exist. The largest value of η_L from the available supporting field data is about 3.8.[2,3,4] Model deltas may be only about 2 m in length,[4,6] leading to η_L values in the range of 50 to 500 or more. Moreover, the extrapolation of laboratory profiles to large η_L values must also consider kinematic similarity.[11,12]

Kinematic similarity

For movable-bed physical models no single governing equation or set of equations can be found to determine the variation of alluvial bed resistance, suspended sediment load, bed load, channel width and so on. Governing parameters are therefore considered instead.[13]

Kinematic similarity applies between two hydraulic systems when both the flow boundaries and flow patterns are similar.[11,12] Flows on both full-size and laboratory-model deltas are essentially two-dimensional—that is, flow width/depth ≥ 10. The minimum set of parameters that influence the process of sediment transport in two-dimensional, free-surface flow comprises: the characteristic particle diameter, D; the gravimetric solids concentration, C; the density of the fluid, ρ; the density of the solids, ρ_s; the kinematic viscosity of the fluid, ν; the water depth, h, which equals the hydraulic radius in two-dimensional flow; the acceleration due to gravity, g; and the shear velocity at the bed.[12,14] Dimensional analysis yields the five dimensionless groups: D/h; C; ρ_s/ρ; θ, the bed shear stress due to bed roughness (Shields' parameter);[15] and D^*, the dimensionless particle size.[16] The groups θ and D^* are given by

$$\theta = \frac{h'S_f}{(G_s - 1)D} \tag{12}$$

and

$$D^* = D\left(\frac{(G_s - 1)g}{\nu^2}\right)^{\frac{1}{3}} \tag{13}$$

where h' is that part of the hydraulic radius associated with surface drag and S_f is friction slope.

The depth of flow, h, and h' are related by

$$h = h' + h'' \tag{14}$$

where h'' is that part of the hydraulic radius associated with form drag due to ripples or dunes on the bed.

Since flow on tailings deltas is quasi-steady and effectively uniform,[7] S_f equals the bed slope, S, and equation 12 becomes

$$\theta = \frac{h'S}{(G_s - 1)D} \tag{15}$$

Kinematic similarity is ensured if the scale ratios, η, for all five dimensionless groups equal unity.[14] In general, it is physically impossible for models to meet this requirement. Consequently, hydraulic modelling typically relies on scaling the dominant parameters only while ensuring that the effects of all other parameters are as small as possible.[11,12]

Laboratory-model deltas

It is extremely difficult to model the wide ranges of particle sizes and densities present in many tailings[1,7] and it is common practice to use the same tailings for both the laboratory-model and the full-size deltas.[4,6] In this case the η values for C, ρ_s/ρ and D^* all equal unity. However, the groups θ and D/h require further consideration.

Limited data[12,17] suggest that D/h has little effect for $D^* \leq 10$. Since $D^* \leq 10$ for most tailings, this suggests that the η value for D/h can be ignored. However, equation 14 shows that the mobile bed friction depends on h and, hence, D/h. Shields' parameter, θ, which is fundamental to sediment transport, cannot be ignored.[11-15] Equation 15 shows that for the η value for θ to equal unity when identical tailings are used for the model and prototype deltas, the η for the product $h'.S$ must equal unity. However, there is no means of ensuring this. It is therefore extremely unlikely that the mobile bed friction will be modelled adequately or that the laboratory-model and full-size deltas will be kinematically similar.

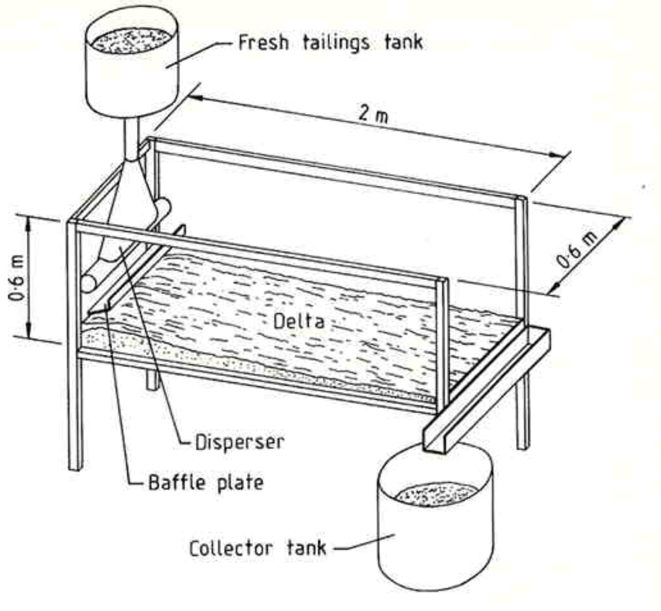

Fig. 3 Experimental arrangement for laboratory-model tailings delta

In recent model deltas tailings have been discharged either from a small-diameter pipe outfall[4] or through a disperser on to a baffle plate[6] (Fig. 3). It is unlikely that hydraulic similarity to full-size plunge pools is achieved by either arrangement. However, the ω values obtained from model and full-size deltas formed using the same tailings are almost identical within the limits of experimental error. This and equation 9 together imply that G_0 and G_{min} on the model and full-size deltas are identical and, hence, that the plunge pools are largely self-regulating. This hypothesis is consistent with limited laboratory-model data for plunge pools formed in bed sediments by water-only discharges.[18,19] Clearly, the hydraulics of plunge pools merits further study.

Model deltas formed in short flumes tend to fill the whole length of the flume, eliminating the decant pond that defines the downstream end of the delta and, hence, L (Fig. 1). Also, tailings are discharged directly to waste over a low weir (Fig. 3), forming a free overfall. Consequently, both the bed particle size and the bed slope at $x = L$ are greater than would be the case at the edge of a decant pond.[6,7] Since tailings deltas have essentially mild slopes, critical flow conditions occur slightly upstream of the overfall.[20] This constitutes a hydraulic control that is theoretically capable of affecting the flow over the whole delta, tending to reduce its concavity—and, hence, ω—and to increase the overall slope. The few available experimental data suggest that the effects of free overfalls on the curvature of model delta profiles are small. Nevertheless, it is clearly preferable to use flumes of length sufficient to allow a decant pond to form downstream of the delta.

Comparison of model and full-size delta profiles

Laboratory-model deltas for comparison with existing full-size deltas were formed using coal tailings from Aberdare and Meandu collieries. Typical particle-size distributions of these tailings are shown in Fig. 4. The tailings were discharged into one end of a Perspex flume and flowed to waste over a low weir at the other (shown with dimensions in Fig. 3). The model deltas were profiled at 100-mm centres on each of three lines at the quarter points of the flume width using a

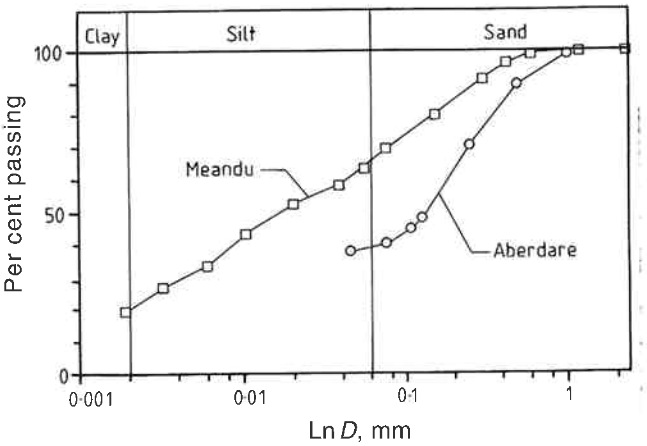

Fig. 4 Typical particle-size distribution curves for Aberdare and Meandu coal tailings

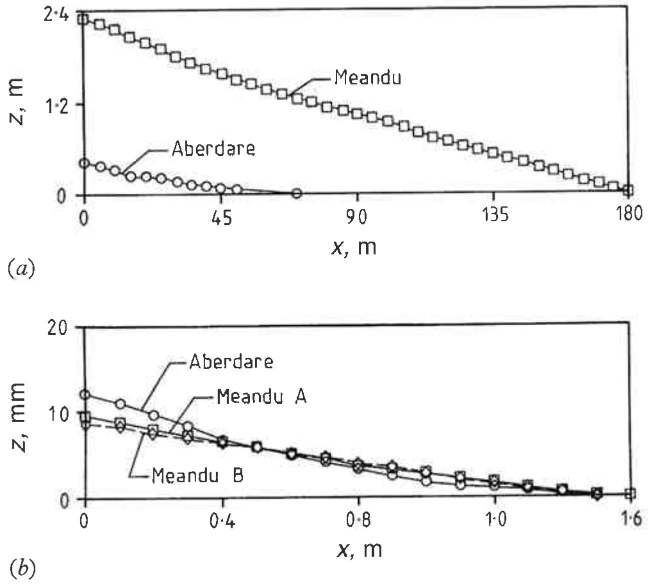

Fig. 5 Profiles of (*a*) full-size and (*b*) laboratory-model Aberdare and Meandu coal tailings deltas

simple vernier depth gauge capable of being read with a precision of 0.1 mm and an accuracy of about ±0.2 mm. The maximum deviations of the Aberdare and two Meandu model delta profiles from a straight slope were approximately 2.5 mm, 0.8 mm and 0.1 mm, respectively. Profiles of both the full-size and model deltas drawn with the vertical scale 25 times the horizontal scale are shown in Fig. 5. The initial slopes of the corresponding full-size and model deltas are directly comparable and clearly differ significantly.

The C_0 values and the profile parameters for the model and full-size deltas are presented in Table 1 (Aberdare) and Table 2 (Meandu). Data for the full-size deltas have been presented in an earlier contribution.[7] Equation 1 was fitted to the profile data for each delta by least-squares regression methods. (The methods used were more sophisticated than those originally used for the full-size deltas.[7] However, their profile parameters were changed only slightly.) The level of significance for all five deltas was less than 0.04%, indicating very strong correlations. Dimensionless profiles of the model and full-size deltas are shown in Fig. 6(*a*) (Aberdare) and Fig. 6(*b*) (Meandu). The model data constitute further strong support for the recent theoretical model.[7]

Table 1 Parameters characterizing full-size and laboratory-model Aberdare coal tailings deltas

	Full-size delta	**Model delta**
C_0	0.07–0.12	0.07
S_0	1.26×10^{-2}	1.74×10^{-2}
ε, m^{-1}	2.31×10^{-2}	1.124
R	−0.949	−0.991
L, m	70	1.5
η_L	—	46.7
ω	1.614	1.686

Table 2 Parameters characterizing full-size and laboratory-model Meandu coal tailings deltas

	Full-size delta	**Model 1**	**Model 2**
C_0	0.39	0.42	0.38
S_0	1.59×10^{-2}	8.18×10^{-3}	6.07×10^{-3}
ε, m^{-1}	2.84×10^{-3}	3.94×10^{-1}	6.12×10^{-2}
R	−0.999	−0.996	−0.995
L, m	180	1.6	1.5
η_L	—	112.5	120
ω	0.512	0.630	0.092

Only vestigial ripples were observed on the model deltas, whereas the bed forms present on the full-size deltas included ripples, dunes, plane beds and transitory antidunes.[6,7] This shows that the model θ were significantly smaller than the full-scale θ[11,12] and confirms that kinematic similarity was not achieved despite the moderate η_L values of the laboratory models.

The values of ω for the Aberdare deltas were almost identical. However, the ω values for the Meandu models differed significantly from that for the full-size delta (Table 2). This is partly attributable to the difficulty of measuring accurately the small absolute curvatures of the Meandu model profiles (Fig. 5). The absolute differences between the ω values for the Meandu full-size and model deltas were greater than that for the Aberdare deltas, suggesting that the repeatability of model delta profiles may be relatively poor and that the good agreement between the ω for the model and full-size Aberdare tailings deltas was somewhat fortuitous.

Since the purpose of predicting tailings delta profiles is to improve the estimate of the volume of tailings that can be stored in a given impoundment, the critical parameter in the present analysis is the area, A^*, under the profile shown in Fig. 1. This can be obtained by integrating equation 3. The elimination of ε and y_0 then gives

$$A^* = \frac{S_0 L^2}{\omega^2}\left(1-(1+\omega)\exp(-\omega)\right) \qquad (16)$$

The A^* values that were calculated for the Aberdare and Meandu deltas are presented in Table 3. The area A_1^* refers to the full-size delta, while A_2^* and A_3^* refer to the model deltas scaled up using the the values of S_0 derived from the model and the full-size deltas (Tables 1 and 2), respectively. The values of ω derived from the model deltas were used to calculate both A_2^* and A_3^*. (The means of the Meandu model ω and S_0 values were used for the calculations.) The tabulated errors are relative to A_1^* as the datum.

The errors in the predicted areas that are based solely on the model data (A_2^*) are unacceptably large. However, the errors in the areas calculated using the S_0 from the full-size

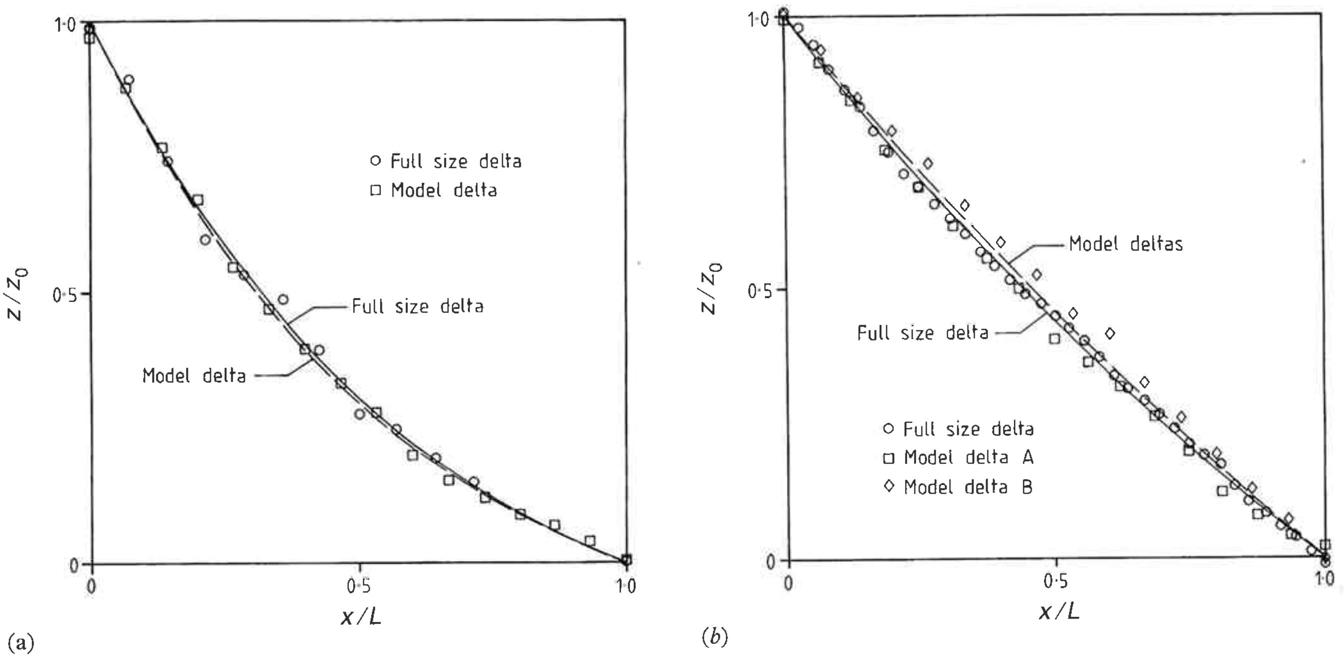

Fig. 6 Dimensionless profiles of full-size and laboratory-model coal tailings deltas: (*a*) Aberdare; (*b*) Meandu

Table 3 Comparison of areas under full-size and scaled-up laboratory-model delta profiles

Tailings	**Aberdare**	**Meandu**
Full-size deltas		
A_1^*, m^2	11.4	184.8
Scaled-up model deltas		
A_2^*, m^2	15.1	91.1
Error, %	+30.2	−50.7
A_3^*, m^2	10.9	203.6
Error, %	−4.0	+10.2

deltas (A_3^*) are quite reasonable, at about 10% or less. These results are consistent with the foregoing theoretical analysis.

Obviously, for actual profile predictions estimates of S_0 based on data from comparable, existing tailings impoundments must be used in place of the known values of S_0 for the full-size deltas that have been used in the present analysis. This is likely to increase significantly the errors in the estimated value of A^*. However, it is considered unlikely that these errors will be as large as those in estimates of A^* based on laboratory-model data alone. A theoretical basis for estimating S_0 is clearly desirable.

Conclusions

A theoretical analysis has shown that kinematic similarity of full-size and laboratory-model mine tailings deltas is unlikely to be achieved by current modelling practices. Consequently, the initial slope, S_0, of a full-size delta cannot be accurately predicted using only data from a laboratory-model delta. However, a recent theory of sorting on tailings deltas[7] suggests that the dimensionless parameter ω, which describes sorting on delta profiles, can be accurately estimated using data from model deltas, notwithstanding a lack of kinematic similarity. Further research into the hydraulics of the plunge pools that form at the upstream ends of deltas and into mobile bed friction on deltas with the aim of establishing a theoretical basis for estimating S_0 is clearly desirable.

A comparison of full-size and laboratory-model deltas formed from coal tailings from Aberdare and Meandu collieries, southeastern Queensland, Australia, has shown that the prediction of full-size tailings delta profiles solely on the basis of laboratory-model data is unacceptably inaccurate. Acceptable accuracy may be achieved by using an initial slope, S_0, derived from comparable full-size deltas, if available, and the ω value (which determines the concavity of the delta) derived from the model. These results are consistent with the theoretical analysis.

The comparison of the full-size and model deltas also showed that a free overfall at the downstream end of a model delta that is formed in a short flume may have only a small effect on the profile of the delta. However, the supporting data are few. A flume long enough to enable a decant pond to form at the downstream end of the model delta is preferable to a short flume.

The empirical equation for tailings delta profiles developed by Melent'ev and co-workers[8] is subject to the same considerations and constraints as the profile equation derived from the recently proposed theoretical model.[7] Consequently, its use offers few, if any, advantages.

Acknowledgement

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Symbols

A	$(1-\exp(-\omega))^{-1}$
A^*	Area under delta profile, m^2 (Fig. 1)
b	Dimensionless constant characterizing sediment entrainment

c_1	Constant relating S_0 and G_0, $\mathrm{mm}^{-(1+b)}$
C	Gravimetric solids concentration
D	Median particle diameter, mm
D^*	Dimensionless particle size
g	Gravitational acceleration, m s^{-2}
G	Particle-sorting parameter, $\mathrm{mm}^{(1+b)}$
G_s	Specific gravity of tailings
h	Depth of water and hydraulic radius for two-dimensional flow, m
h'	Component of hydraulic radius associated with surface drag, m
h''	Component of hydraulic radius associated with form drag, m
L	Overall length of delta profile, m
n	Constant defining profile
R	Linear correlation coefficient
S	Bed slope
S_f	Friction slope
S^*	Slope of dimensionless delta profile
x	Distance down profile measured from its highest point, m
y	Height above asymptote to delta profile of sediment deposited on bed, m
z	Height above level of decant pond of sediment deposited on bed, m

Greek

ε	Constant defining slope for particular delta, m^{-1}
η	Scale ratio
θ	Dimensionless bed shear stress due to bed roughness
ν	Kinematic viscosity of water, $\mathrm{mm}^2\ \mathrm{s}^{-1}$
ρ	Density of water, kg m^{-3}
ρ_s	Density of solids, kg m^{-3}
ω	Dimensionless positive constant defining profile for particular delta; given by εL

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