The behaviour of mine tailings during hydraulic deposition


SYNOPSIS
The environmentally acceptable disposal of fine-particled mining and industrial wastes by the formation of hydraulic-fill tailings dams is becoming an increasingly important aspect of the total mining endeavour. Relatively little is known of the behaviour of waste slurries during deposition. This paper describes and analyses the following aspects of slurry behaviour:

- the relationship between viscosity, shear strength, and water content,
- the slope assumed by a thickened slurry,
- particle-size sorting on a hydraulic-fill beach,
- gradients of hydraulic-fill beaches, and
- internal erosion during the deposition of slurry.

Introduction
The disposal of fine-grained mining and industrial wastes by the formation of hydraulic-fill tailings dams is becoming a design and construction activity of ever-increasing scale and importance to the mining industry. Technical knowledge of waste problems is sparse, and the disposal of mine waste has been identified as a high-priority area for geotechnical research.

Hydraulic filling is used world-wide because

- wastes such as mine tailings, phosphogypsum, pulverized fuel ash, and coal-washery sludges are usually produced by wet processes or are removed from the plant by sluicing, and
- hydraulic transportation by pipeline to the disposal site is currently the cheapest form of solids transportation.

The quantities of waste transported and disposed of on surface by hydraulic means are enormous, and are growing at a greater rate than the demand for, and production rate of, the products from which they derive. This is because of the trend towards increasingly large-scale exploitation of low-grade orebodies, high-ash coals, etc. Some idea of the enormity of today’s waste-disposal problems is given by Table I. Further information on production for a more extensive range of wastes has been given by Blight.

Environmental pressures, decreasing availability of land, and increasing costs have encouraged a trend towards fewer but larger waste deposits. In the U.S.A., several tailings dams of up to 180 m have either been planned or are under construction, and will contain 500 Mt of waste or more. In South Africa, seven gold-tailings dams currently under construction are planned to contain between 50 and 150 Mt and to be up to 80 m in height. In addition to the surface disposal of mining wastes, interest is increasing in the disposal of waste underground, where it can provide both structural support and access in the mining of orebodies of large vertical extent. The practice of underground filling may entail the pumping of tailings slurries over relatively large distances both vertically and horizontally. In one case, tailings-cement slurry was pumped a distance of 2 km vertically and 3.5 km horizontally before being deposited as a stope filling.

This paper considers the following aspects of the transportation and deposition of waste slurry:

- relationships between viscosity, shear strength, and water content for slurries,
- the slope assumed by thickened slurries on deposition,
- the gradation of particle sizes that results from
the deposition of slurries on hydraulic-fill beaches, (iv) profiles of hydraulic-fill beaches and cyclone underflow cones, and (v) internal erosion resulting from the flow of slurries through drying cracks in previously deposited tailings.

Relationships between Viscosity, Shear Strength, and Water Content

A knowledge of the relationship between the viscosity or shear strength and the water content of tailings slurries is important in the assessment of

1. head losses in slurry pumping lines;
2. the slope assumed by thickened slurries when deposited by the thickened-discharge method;
3. the flow pattern of a slurry after it has escaped through a breach in the outer wall of a tailings dam.

A wide range of water contents is of interest. For deposition on a conventional tailings dam, the water content of the tailings during transportation from the mill to the dam is typically in the range 150 to 100 per cent by mass of dry solids (a relative density for the slurry of 1.3 to 1.5). For deposition by the thickened-discharge method, the water content is typically about 50 per cent (relative density 1.7 to 1.8). For the slurry filling of underground mining excavations, the water content ranges from 50 to 30 per cent (relative density 1.7 to 1.9). Actual water contents depend very much on the particle-size distribution of the slurry and on any clay minerals present. The relative densities are, of course, influenced by that of the particles.

A number of methods are in common use for the measurement of viscosity, which can be measured in absolute or relative terms. The variable-speed coaxial-cylinder type of viscometer has been found to be suitable for the measurement of the absolute viscosity of tailings slurries, and all the measurements reported here were made with an instrument of this type (the Ferranti portable viscometer, model VL). It was found necessary for the range of cylinders supplied with the standard instrument to be extended by means of a number of specially made cylinders. The instrument was calibrated in absolute terms by the application of torque through a system of weights, strings, and pulleys pivoted on ball races.

The viscosity of Newtonian fluids is defined by the relationship

\[ \tau = \eta \frac{d\gamma}{dt} \]  

in which \( \tau \) is the shear strength of the fluid, \( \eta \) is its viscosity, and \( \frac{d\gamma}{dt} \) is the rate of shear strain.

However, tailings slurries are non-Newtonian and behave more as Bingham plastics, for which viscosity is related to shear strength by

\[ \eta = \eta_a + \frac{\tau_0}{d\gamma/dt} \]  

\[ \tau = \tau_0 + \frac{d\gamma}{dt} \eta_a \]  

In (2), \( \tau_0 \) is a yield shear strength that applies when \( d\gamma/dt = 0 \).

The coaxial-cylinder viscometer relies on the torque generated at a given rate of rotation to indicate shear strength and viscosity. If the conventional interpretation of the viscometer readings is followed, what is actually measured is an apparent viscosity:

\[ \eta_a = \eta + \frac{\tau_0}{d\gamma/dt} \]  

If the true viscosity is required, the value of \( \tau_0 \) has first to be established from the relationship between \( \tau \) and \( d\gamma/dt \). The true viscosity can then be determined from

\[ \eta = \frac{\tau - \tau_0}{d\gamma/dt} \]  

As most flow relationships have been derived for viscous fluids and not Bingham plastics, the apparent viscosity, \( \eta_a \), is in fact a useful engineering property for approximating the behaviour of a slurry to that of a Newtonian fluid.

Fig. 1, which shows the properties of a tailings slurry from a diamond (kimberlite) operation at a water content of 125 per cent, illustrates the relationship between shear strength and rate of shear strain, and indicates a yield shear strength, \( \tau_0 \), of 0.35 Pa. The fact that the shear strength does not increase linearly with the rate of shear strain shows that, although the behaviour of the slurry approximates that of a Bingham plastic, it is actually more complex than equation (2) would indicate.

Fig. 2 shows relationships between apparent viscosity, \( \eta_a \), and rate of shear strain (calculated from equation (1)) and between ‘true’ viscosity, \( \eta \), and rate of shear strain (from equation (2)). It is again clear that equation (2) is only an approximation to the real behaviour of the slurry.

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* All water contents are given on the basis of dry mass.
Flow of Slurry in Pipelines

Head losses in the flow of both Newtonian and non-Newtonian fluids through pipes can be estimated by the application of the D'Arcy–Weisbach equation:

\[ \frac{1}{V^2} i = 6h/L = \frac{1}{2} \rho \frac{v^2}{d} \]

where \( i = \Delta h/L \) is the hydraulic gradient along the pipe, \( h \) is the head loss, \( L \) is the length, \( d \) is the diameter of the pipe, \( v \) is the flow velocity, \( \rho \) is the density of the fluid, and \( f \) is a dimensionless friction factor.

For laminar flow of Newtonian fluids, equation (6) is identical to the Hagen–Poiseuille equation:

\[ f = \frac{32}{\rho \pi d^4} \]  

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This equation can be applied to mine tailings slurries if the apparent viscosity, \( \eta_a \), at the appropriate water content and rate of shear strain is used to approximate the flow behaviour of the slurry to that of a Newtonian fluid. Alternatively, a more rigorous expression such as that for a Bingham plastic can be applied. It appears that the transition from laminar to turbulent flow can be expected at Reynolds numbers exceeding about 2000. For turbulent flow, it has also been suggested that flow behaviour can be approximated by use of the apparent viscosity, \( \eta_a \). Fig. 6 is the familiar Moody diagram relating the friction factor to the Reynolds number for both viscous and turbulent flow with the apparent viscosity replacing the true viscosity.

The limited data available to the authors on the pumping of slurries are illustrated in Fig. 6. The data all relate to slurries of high viscosity (in the range 0.3 to 1 Pa s) and lie in the laminar-flow region. The results show that, in this region of the Moody diagram, friction factors can be predicted reasonably accurately from measured slurry densities and viscosities. This region of flow applies particularly to the transport of thickened slurries such as those used for underground filling and for the thickened-discharge method of tailings disposal. It is recommended that equation (7) be used for the preliminary design of pipelines for the transportation of thickened slurries.

**Slope of a Thickened Slurry Surface**

In the thickened-discharge method of tailings disposal, a thickened slurry is deposited from a point upstream of the outer retaining wall (Fig. 7) and is allowed to flow towards the wall. Because of the reduced water content of the thickened slurry, little or no supernatant or bleeding water arises during deposition. The material comes to rest at a flat slope to form a roughly conical surface having a small slope away from the point of deposition. The system has the advantage of considerably increasing the storage capacity of a given disposal area. To illustrate this statement, Fig. 7 shows a section through a small tailings impoundment that is to be constructed by the thickened-discharge method. The difference in stored volume between a conventional system in which material is beached upstream from the impounding wall and the thickened discharge method is immediately obvious. The method has the disadvantage that storm-water run-off and any supernatant water collects immediately adjacent to the impounding wall, which must be designed either to retain or to pass this water.

Fig. 8 shows the relationship between the storage volume and the elevation of the tailings surface corresponding to Fig. 7. When the elevation of the tailings at the dam is 65 m, this particular impoundment can hold 67 per cent more tailings when operated by the thickened-discharge method than by conventional filling. In the design of such a system, the relationship between the water content of the tailings and the slope assumed by the deposited material has to be predicted. Robinsky has presented empirical curves relating the slope of the slurry surface to the water content of the tailings slurry, but there is a need for a more rational method of predicting the slope. If the relationship between shear strength and water content is known, the slope can be predicted rationally on the basis of the theory of infinite slope stability. The slurry is assumed to behave as a purely cohesive \((\phi = 0)\) material for which \( c = c_t \), the yield shear strength contained by equations (2) and (5a). If the depth of deposition of each slurry layer is \( s \), then the consideration of the sliding equilibrium of an infinite slope of slurry results in the conclusion that it will come to rest in limiting equilibrium at an angle of inclination, \( i \), given by

\[
i = \sin^{-1} \left( \frac{c_t}{\gamma h} \right).
\]

Fig. 9 shows a comparison between slope angles predicted from equation (9) and angles measured in laboratory tests. The material was a froth-flotation discard from a process for the upgrading of calcium carbonate. The slurry was spread to a thickness of 5 mm on a horizontal sheet of plate glass, and the sheet was tilted slowly until the slurry started to slide. The tilt was then slightly decreased and, if the slurry retained this slope, the angle was noted as a point in Fig. 9. Because the slurry was sliding on a glass surface rather than on a surface of slurry, the experimentally observed values of \( i \) probably represent a lower limit to the inclinations corresponding to equation (9). The agreement between the predictions of equation (9) and the observed angles is nevertheless considered sufficiently satisfactory for practical design purposes. The thickened-discharge method of deposition has much to commend it, especially now that a rational method of design has been demonstrated.

**Flow of Slurry after Breaching of a Dam**

Failure of the outside wall of a hydraulic-fill tailings impoundment may cause the contents of the impoundment to liquefy and flow out through the breach. Blight et al. and Jeyapalan have shown that the progress of
Fig. 6—Moody diagram showing some experimental results for the pumping of thick slurries

the slurry after it has left the breach can be predicted rationally. Both these papers consider the situation in which the escaping slurry has a high water content and a very low shear strength, as was the case, for example, in the Buffalo Creek failure described by Wahler et al.\textsuperscript{19}.

Slurries having much higher shear strengths are not as mobile as those at Buffalo Creek or Bafokeng\textsuperscript{12}, but they ooze and spread from a breach to take up an equilibrium surface slope in much the same way as the thickened-tailings slurries dealt with earlier. The distance to which such a slurry will spread can be calculated by considerations of force equilibrium as demonstrated by Lucia et al.\textsuperscript{15}.

The basis of such an analysis is shown in Fig. 10. It is assumed that the slurry will flow and its surface slope will flatten until an equilibrium is established between the fluid pressure exerted by the slurry retained in the breach (of depth \(H\)) and the shear strength along the base of the wedge of slurry. At that stage, movement will cease. The height of the ‘tongue’ of the slide will be the
height to which an unsupported bank of slurry will stand unsupported. The relationship between the length of flow ($L$) and the depth of slurry at the breach ($H$) for given values of shear strength ($\tau$), density ($\rho g$), and topographical gradient ($i$) can be written

$$\frac{L}{H} = \frac{1}{\tau / \rho g H (1 - 2 \sin i) - \sin i}.$$  \hspace{1cm} (10)

This relationship can be shown graphically by plotting of the dimensionless ratios $L/H$ and $\tau / \rho g H$ for various values of $i$ as shown in Fig. 10.

For the thickened-tailings slurry referred to in Fig. 9, with $i = 0$ and $\rho g = 13$ kN m$^{-3}$, the height of the tongue of the slide would be only 1.5 mm and, for $H = 5$ m,

$$\frac{\tau}{\rho g H} = 3 \times 10^{-4}.$$  

In this case $L/H$ is very large, and the slurry would flow for a great distance (1700 m). For a value of $L/H = 12$,

a strength of 2.6 kPa is required, in which case the tongue of the slide would be 0.8 m high and the slurry would travel for 60 m. Equation (10) can be used in the estimation of the consequences of a dam failure, especially where escaping slurry may damage or inundate surface installations.

**Particle-size Gradation on Hydraulic-fill Beaches**

Although tailings slurries may be transported as reasonably homogeneous materials, this state ceases to exist once the slurry has been deposited in the tailings impoundment.

In conventional hydraulic-fill construction, tailings slurry is deposited along the length of the impounding wall and runs down the beach to the pool from which the plant return water is decanted.

The tailings slurry is usually deposited at a number of separate points, and the flow spreads after deposition, resulting in some decrease of velocity as the slurry moves down the beach. Fig. 11, for example, shows a plan and surface contours of a typical multi-delivery point ring-dyke dam used for the disposal of gold tailings (9 deposition points are shown).
Because the coarser particles contained by the slurry settle more rapidly than the finer particles, a gradation of particle size down the beach results, with coarser material adjacent to the points of deposition and progressively finer material being deposited with increasing distance from these points. Fig. 12 illustrates the particle-size sorting that has taken place on a 280 m long beach of diamond tailings. Particle-size sorting also occurs vertically within each layer of deposition. Vertical sorting and the anisotropy that results from it has been examined by Blight and Steffen.

The inset in Fig. 12 shows the results of a separate set of measurements taken on the same beach some 12 months later. The distance down the beach, \( H \), has been normalized by dividing by the distance from the point of deposition to the edge of the pool, \( x \). For the construction of both diagrams, samples were taken that penetrated three layers of deposition.

The particle-size gradation on a beach can have a significant effect on the stability of the tailings dam. If the walls and outer zone of the beaches consist of coarser, more pervious material, the phreatic surface will be lower and the dam more stable. Advantage can be taken of the particle-size gradation that results from hydraulic filling only if it can be predicted at the design stage from an analysis of the total tailings product, or if a similar dam constructed of a similar product is available to sample. In what follows, an attempt is made to derive a method of predicting the predominant particle size, and hence indirectly the permeability, at any point along a hydraulic beach. If this can be done, the position of the phreatic surface can be predicted, and hence the shear strength of the wall can be established.

Consider a particle of diameter \( D \) moving down a beach of gradient \( i \) at a horizontal velocity \( V_h \) while it simultaneously settles at velocity \( V_v \). Following Graf and ignoring the interference of adjacent particles in the slurry, the settling velocity will be given by

\[
V_v = \frac{4(\rho_s - \rho_w)gD}{\rho_w 3C} = KD \text{ (say)},
\]

in which \( \rho_s \) is the density of the particle, \( \rho_w \) is the density of the slurrying liquid, and \( C \) is a coefficient.

If the depth of the sheet of flowing slurry is \( \delta \), the maximum time taken for a particle of diameter \( D \) to settle onto the surface of the beach will be

\[
t_s = \frac{\delta}{V_v}.
\]

In this time, the particle will have travelled down the beach a maximum horizontal distance of

\[
H = \frac{\delta}{V_v},
\]

and \( V_v \) will be governed by an equation similar to that of open-channel flow of the form

\[
v = C(\delta^3/2).
\]

Hence,

\[
D = \frac{C \delta^3/2}{KH}.
\]

In other words, the predominant particle size to be found at a distance \( H \) from the point of deposition will be roughly inversely proportional to \( H \). This is the form of relationship shown in Fig. 12. Alternatively, if the settling velocity is governed by Stokes' law,

\[
v = \frac{(\rho_s - \rho_w)gD^2}{18 \eta} = K^2D^2 \text{ (say)},
\]

and

\[
D = \frac{C \delta^3/2}{KH},
\]

i.e. the predominant particle size to be found at distance \( H \) from the point of deposition will be inversely proportional to the square root of \( H \).

The above analysis is necessarily approximate because of the idealizations on which it is based. Apart from the particle interference that must occur, the gradient, \( i \), of the beach surface varies with \( H \), and, as the flow spreads from the deposition point, \( \delta \) decreases. It is also probable that some transport of the material down the beach occurs after it has settled out of the slurry. This may result in further particle sorting if there is any rolling motion of settled particles along the beach surface. It is also possible that material deposited during one deposition cycle could be eroded, picked up, and re-deposited during a subsequent deposition cycle.

Then there is the question of the beach gradient, \( i \), which both equations (14) and (14a) contain. It is probable that \( i \) and \( D \) are variables that are interlinked in some complex way. The question of beach gradient will be investigated later, but for the time being the variability of the beach gradient will be ignored.
Fig. 11—Plan of a typical ring-dyke tailings dam (reproduced by kind permission of Messrs Steffen, Robertson and Kirsten Inc.)
is a photograph showing rill flow occurring down a beach of platinum tailings. The unstable nature of the flow is evident from the hydraulic jump in the photograph. This instability is probably responsible for much of the scatter evident in Fig. 12. The overflowing of rills and the resultant deposition of fine material high up the beach can result in a layered fill in which the vertical permeability is considerably less than the horizontal permeability. This, in turn, can lead to a raised phreatic surface with its attendant slope-stability problems. A ratio of horizontal to vertical permeability of 4000 has been measured on a beach of diamond tailings. In that dam a conventional phreatic surface was not present at all, but was replaced by a series of horizontal perched water tables.

It is important to note that, because of the presence of process chemicals in the water, many tailings slurries are strongly flocculated. A particle-size analysis carried out by hydrometer in the conventional way using distilled water and deflocculants will therefore not be representative of the effective particle-size distribution on a hydraulic beach. For this reason, all the particle-size analyses used in this section were conducted on plant-return water, and no attempt was made to deflocculate the slurries.

If equation (14) is valid, the product, $D_H$, should be constant at all points along a beach for which $H$ exceeds zero, while, if equation (14a) is valid, the product, $D^2 H$, should be constant. The two possibilities are explored in Figs. 14 and 15. In these figures, the ratio $H/X$ is the ratio of the distance $H$ from the point of deposition to the length $X$ of the beach, measured to the edge of the pool.

Fig. 12—The particle-size sorting that occurs on a hydraulic beach

Because the particles are effectively settling through a viscous slurry and not through water, $v_v$ in the above analysis is very small. For example, if we consider a 20 mm thick sheet of slurry flowing down a 280 m beach at 1 m/s, the settling velocity of particles precipitating out at the end of the beach will be a maximum of only $70 \times 10^{-4}$ m/s.

The idealized laminar-sheet flow assumed for the analysis does not always occur. Instead, an unstable, meandering, and turbulent rill flow is often observed. When such a rill or channel overflows, the settling regime is upset and fine material is deposited higher up the beach than equation (14) or (14a) would predict. Fig. 13

Fig. 13—Unstable rill flow occurring on a hydraulic beach, showing a hydraulic jump in the centre of the photograph
Fig. 14—Particle-size distribution along a beach of diamond tailings 280 m long

\[ A = \frac{D_{50}}{D_{50}} \text{ (at } H \text{ down the beach)} \]  \( \ldots \) \( \ldots \) \( (15) \)

\( D_{50} \) is the particle size at which 50 per cent by mass of the solids at any point is finer than \( D_{50} \). \( D_{50} \) was chosen arbitrarily as a representative particle size at any distance \( H \) down the beach.

Fig. 14 represents the results of particle-size determinations on specimens taken along the same 280 m long beach of diamond tailings referred to in Fig. 12. Fig. 15 presents similar data for four beaches of platinum tailings that vary in length from 40 to 90 m. Whether equation (14) or (14a) is followed, there is a lot of scatter about the mean value of either \( AH/X \) or \( A^2H/X \). Not surprisingly, the mean values for these ratios vary with the material under consideration. In the case of the platinum tailings, the mean value of \( AH/X \) for the 90 m beach is fairly close to that for all four beaches. The data appear to fit better than in the case of \( A^2H/X \). Similar results to those shown in Figs. 14 and 15 have been obtained for gold tailings.

Based on the available data, the following tentative conclusions have been drawn.

(i) The particle size at a given distance along a hydraulic beach from the point of discharge can be roughly predicted from the relationship \( AH/X = M \) (for \( H \) greater than zero), \( \ldots \) \( (16) \)

(ii) \( M \) is approximately constant for all tailings of a given type and for all lengths of beaches greater than 40 m, but has to be established for each type of tailings.

It is known that, if a beach is too short, a relationship such as (16) does not hold. Sampling of a beach of diamond tailings 9 m long, for example, showed that virtually no particle separation was occurring over that distance. One possible reason for the lack of rapid separation is the high viscosity of the clay 'floc' in suspension that constitute much of a diamond-tailings slurry.

So far, the investigation of particle-size distribution has stopped at the edge of the pool, i.e. only deposition in air has been investigated. It is known that an abrupt change in the depositional regime occurs as soon as the tailings slurry reaches and runs into water. Limited measurements have shown that \( A \) (equation (15)) decreases suddenly beyond the edge of the pool (i.e. for \( X > L \)), and the beach gradient steepens suddenly beyond the water's edge. The under-water regime usually applies only at a considerable distance from the outer perimeter of a tailings dam, and for this reason is less important in considerations of the stability of tailings dams.

Gradients of Hydraulic-fill Beaches

As mentioned earlier, the gradient of a hydraulic-fill beach varies along its length and is probably related to the particle-size separation that occurs on the beach. The coarser material, which settles out first, drains rapid-
ly and develops shear strength faster than the finer material, which settles out further down the beach and drains more slowly. Hence, equation (9) would predict a progressive flattening of the beach gradient. Fig. 16 illustrates typical variations in surface shear strength along the beaches of an operational platinum-tailings dam. Strengths were not measured during deposition, but a few hours afterwards, when sufficient capillary strength had developed to make the area accessible. The actual decline in surface strength from $H/X = 0$ to $H/X = 1$ during deposition is almost certainly larger than that shown in Fig. 16.

**Fig. 16—Variation of shear strength along three hydraulic beaches**

The application of equation (9) to the data of Fig. 16 predicts that the slope angle of the beach at the pool would be 30 to 50 per cent of the slope at the point of deposition. Measurement indicates that the slope decreases from 4.7° to 0.8°, a reduction to 17 per cent of the initial value. This appears to support the view that the strength of the settled slurry is an important factor in determining beach gradients. However, as the flow spreads, delta-like, from the point of deposition and in so doing decreases in velocity (Fig. 11), the requirements of continuity and conservation of energy probably also have an influence on the gradients that develop.

Figure 17 illustrates beach profiles measured on six platinum-tailings dams. If the profiles are plotted on a dimensionless basis as in Fig. 18, they reduce to a single ‘master’ profile that can be approximated by an expression of the form

$$h/Y = Y/X \left(1 - H/X\right)^n.$$  \hspace{1cm} (17)

The variables $h$, $H$, $X$, and $Y$ are defined in Fig. 17, and $n$ is an exponent that is characteristic of the tailings material. It should be noted that $Y/X$ represents the ‘average’ gradient along the beach.

Fig. 19 compares dimensionless beach profiles for four different types of tailings. The profiles for platinum, diamond, and gold tailings were measured on hydraulic-fill beaches, but that for copper tailings represents the average profile of a series of cyclone underflow cones. It is interesting to see that such repeatable results with very little scatter can be obtained for beach and cyclone-cone profiles, whereas particle-size profiles, which are of more direct use to the designer, cannot be predicted nearly so certainly.

As shown earlier when the flow of thickened slurries was considered, a small change in the angle of a beach, and particularly of a cyclone underflow cone, can mean an important variation in the volume of stored tailings. It is therefore useful to have an expression such as equation (17) when tailings-disposal systems are being planned. This is of particular importance when the design of a tailings dam depends on the deposition of a given...
proportion of the total tailings to form an embankment of a predetermined profile.

| Internal Erosion during the Deposition of Slurry |

The deposition of tailings slurry on a dam is an intermittent process. Material deposited on one section of a dam is usually left to drain and dry out for a few days before the next layer is deposited. For example, the deposition cycle on the dam shown in Fig. 11 would be either 9 or 4½ days. The drying process has the beneficial effect of considerably reducing the void ratio of the tailings, but also results in the formation of a network of shrinkage cracks in the surface of the layer of dried slurry. When the next layer of slurry is deposited, these drying cracks are filled with slurry. During subsequent drying cycles, the slurry in the shrinkage cracks also shrinks, with the result that a network of open sub-surface cracks may form in the tailings deposit. Fig. 20 is a sketch of a system of open shrinkage cracks that were observed in the side of a test pit in the surface of an operational tailings dam. The system of open cracks was observed to extend to a depth of 500 mm below the surface. As overburden builds up, the cracks appear to close but remain as incipient surfaces of weakness.

The photograph in Fig. 21 shows the surface of a fresh vertical cut in an abandoned tailings dam. The network of old shrinkage cracks is shown up by the oxidation of pyrite that has occurred preferentially along these surfaces. The height of the cut is more than 2 m.

The network of sub-surface open cracks formed by drying shrinkage constitutes potential channels for piping erosion either when slurry is deposited on the dam or when, in exceptionally wet weather, water accumulates on the surface of the dam. This internal erosion often results in troublesome maintenance work when slurry erodes a pipe back to the outer slope of the dam and issues from the slope at a distance of 1 to 3 m below the crest. In isolated instances, piping along shrinkage cracks is suspected of being responsible for large-scale failures. The failure at Bafokeng, for instance, in which several lives were lost and extensive damage was done to property, appears to have been initiated by piping erosion. Fig. 22 shows sketches of two erosion pipes found below the surface of a dam, while Fig. 23 shows the mouth of an erosion pipe near the crest of a small dam. In this case, the exit of the pipe was 5 m below the crest.
Summary

In the course of describing the behaviour of mine tailings during hydraulic deposition, this paper dealt with the following:

1. A method of establishing relationships between water content, viscosity, and shear strength was given, and the application of these relationships to the following aspects of tailings disposal was described:

(a) the design of pipelines for the transportation of thickened slurries;
(b) the design of surface slopes for the disposal of tailings by the thickened-discharge method;
(c) the investigation of the distance travelled by a slurry after escaping from a breach in a dam wall.

2. Methods of predicting both the particle-size gradation along a hydraulic-fill beach and the profile assumed by the beach were developed. Particle-size gradation can be used in the prediction of the position of the phreatic surface, and hence can help in the analysis of the stability of a proposed dam. A knowledge of the beach profile assists in an analysis of the volume-height-area relationships for dams.

3. A troublesome phenomenon, that of internal erosion during the deposition of slurry, was described, and preventive measures were tentatively suggested.

List of Symbols in Order of Appearance

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<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Explanation</th>
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<tr>
<td>( \tau )</td>
<td>kilopascal (kPa)</td>
<td>shear strength</td>
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<td>( \eta )</td>
<td>Pascal second (Pas)</td>
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<td>( \gamma )</td>
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<td>( w )</td>
<td>dimensionless</td>
<td>water content</td>
</tr>
<tr>
<td>( K )</td>
<td>empirical constant</td>
<td>empirical exponent</td>
</tr>
<tr>
<td>( n )</td>
<td>metre/metre (m/m)</td>
<td>flow gradient, slope of surface</td>
</tr>
</tbody>
</table>
Fig. 23—Mouth of erosion pipe initiated by flow along shrinkage cracks in hydraulically placed tailings

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
<th>Description</th>
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<tbody>
<tr>
<td>Δh</td>
<td>metre (m)</td>
<td>change of head</td>
</tr>
<tr>
<td>L</td>
<td>metre (m)</td>
<td>flow distance</td>
</tr>
<tr>
<td>f</td>
<td>dimensionless</td>
<td>friction factor</td>
</tr>
<tr>
<td>d</td>
<td>metre (m)</td>
<td>pipe diameter</td>
</tr>
<tr>
<td>v</td>
<td>metre/second (m/s)</td>
<td>flow velocity</td>
</tr>
<tr>
<td>g</td>
<td>metre/(second)² (m/s²)</td>
<td>gravitational acceleration</td>
</tr>
<tr>
<td>N</td>
<td>dimensionless</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>ρ</td>
<td>kilogram/(metre)³</td>
<td>mass per unit volume</td>
</tr>
<tr>
<td>δ</td>
<td>metre (m)</td>
<td>depth of deposition</td>
</tr>
<tr>
<td>h</td>
<td>metre (m)</td>
<td>depth or height</td>
</tr>
<tr>
<td>C</td>
<td>empirical constant</td>
<td>particle size</td>
</tr>
<tr>
<td>D</td>
<td>metre (m)</td>
<td>distance</td>
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<tr>
<td>H</td>
<td>metre (m)</td>
<td>ratio of particle sizes</td>
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<tr>
<td>A</td>
<td>dimensionless</td>
<td>size of particle</td>
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<td>X</td>
<td>metre (m)</td>
<td>distance</td>
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<tr>
<td>M</td>
<td>metre (m)</td>
<td>depth or height</td>
</tr>
</tbody>
</table>

Acknowledgements

The work on beach profiles and some of the the work on particle-size sorting on beaches was conducted while G. M. Bentel was sponsored by the South African Council for Scientific and Industrial Research, the University of the Witwatersrand, Messrs Steffen, Robertson & Kirsten, Inc., and Fraser F. Alexander & Co. (Pty) Ltd. Thanks are due to these bodies for their generous support.

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