The flow of slurry from a breached tailings dam

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SYNOPSIS

The mechanism of the flow of tailings slurry is examined, and a mathematical model is derived to describe the flow. Predictions based on the model are then compared with the flow that actually occurred near the shaft at Bafokeng after the No. 1 tailings dam had failed. The predictions are found to be of acceptable accuracy.

SAMEVATTING

Die meganisme van die vloei van uitskotflodder word ondersoek en daar word 'n wiskundige model afgelei om die vloei te beskryf. Voorspellings op grond van die model word dan vergelyk met die vloei wat werklik naby die skag by Bafokeng voorgekom het nadat die uitskotdam No. 1 gebreek het. Daar is gevind dat die akkuraatheid van die voorspellings aanvaarbaar is.

Introduction

On the morning of 11th November, 1974, the south-western wall of the No. 1 tailings dam at Bafokeng failed, with disastrous results[1-3]. Before the failure, the dam (900m by 900m in plan and 20m high) contained about $13\times10^6 m^3$ of tailings. About $3\times10^6 m^3$ of liquified tailings slurry flowed through the breach in the wall, engulfed a vertical shaft of the mine, and flowed on down the valley of the Kwa-Leragane River.

The slurry demolished or damaged many of the surface structures at the shaft, and carried away with it vehicles and items of equipment waiting to be taken underground. A large quantity of slurry flowed down the shaft, trapping some workers underground and tearing loose certain of the shaft equipment. Twelve died in the disaster.

At a distance of 4 km from the breach in the dam, the flood of slurry had spread to a width of 0,8 km and was 10 m deep. The flood continued down the Kwa-Leragane River into the Elands River, and an estimated $2\times10^6 m^3$ of tailings eventually flowed into the Vaalkop Dam, 45 km downstream of Bafokeng.

It should not be assumed, on the basis of the happenings at Bafokeng, that every failure of a tailings dam will result in a flow slide. In fact, a flow slide such as that which occurred at Bafokeng probably represents the exception rather than the rule. In most cases, the material of which the failed wall of a tailings dam consists will assume a flatter slope and come to rest without travelling very far from the site of the failure. Fig. 1 illustrates an example of such a slumping failure. It also appears that the mobility of tailings may be very dependent on the condition of the ground surface over which the material is flowing. If the ground surface is already covered by a sheet of flowing stormwater, the viscosity of the tailings at the interface between the tailings and the ground surface will be much reduced, and this will facilitate the flow of the material. This is probably why the tailings from Bafokeng, lubricated by water in the river channel, flowed so far down the Kwa-Leragane–Elands river valleys. The flow slide at Aberfan[4] appears to have been another such occurrence in which the base of the flowing mass was lubricated by an extraneous source of water. Slides such as this are not readily susceptible to analysis.

Properties of Tailings

The particle-size distribution of tailings taken from the pool of the Bafokeng No. 1 tailings dam is shown in Fig. 2 (curve A): 87 per cent of the material lies within the silt particle-size range, while 1 per cent consists of fine sand and 18 per cent of clay-size particles. This is the material that flowed out of the breached dam. The material deposited around the walls of the dam is considerably coarser (curve B).

Fig. 3 shows the relationship between the viscosity of a slurry of Bafokeng fine tailings (curve A in Fig. 1) and the water content. The viscosity is dependent both on the water content and the rate of shear strain $d\gamma/dt$. At water contents above 30 per cent, the viscosity is particularly dependent on the rate of shear strain. (The measurements shown in Fig 3 were made by use of a variable-speed co-axial cyclinder viscometer.)

Fig 4 shows the relationship between consolidation stress and water content in the fine tailings. Reference to this diagram shows that the water contents corresponding to the range of measurable viscosities represent very low consolidation stresses. No direct information is available on the depth of tailings that flowed out of the dam. However, the area of the flow scar was about 290 000 m^2 and, hence, based on the estimated volume of material involved in the flow ($3\times10^6 m^3$), the average depth *in situ* must have been about 10 m. Based on an average saturated density of 18 kN/m^3, the effective stress at a depth of 10 m (if the tailings were consolidated normally) would have been 80 kPa. This would have corresponded to a water content of about 32 per cent and a viscosity of between 2 Pa.s and 6 Pa.s (depending on the rate of shear). The effect of shear rate of γ/dt on the measured viscosity at a water content of 32 per cent is shown in the inset on Fig. 4.

A viscosity of 6 Pa.s therefore seems to be about the upper limit to the viscosity of the slurry that took part in the flow failure.

Flow of Slurry from Breached Dam

The problem is to make a mathematical model of the

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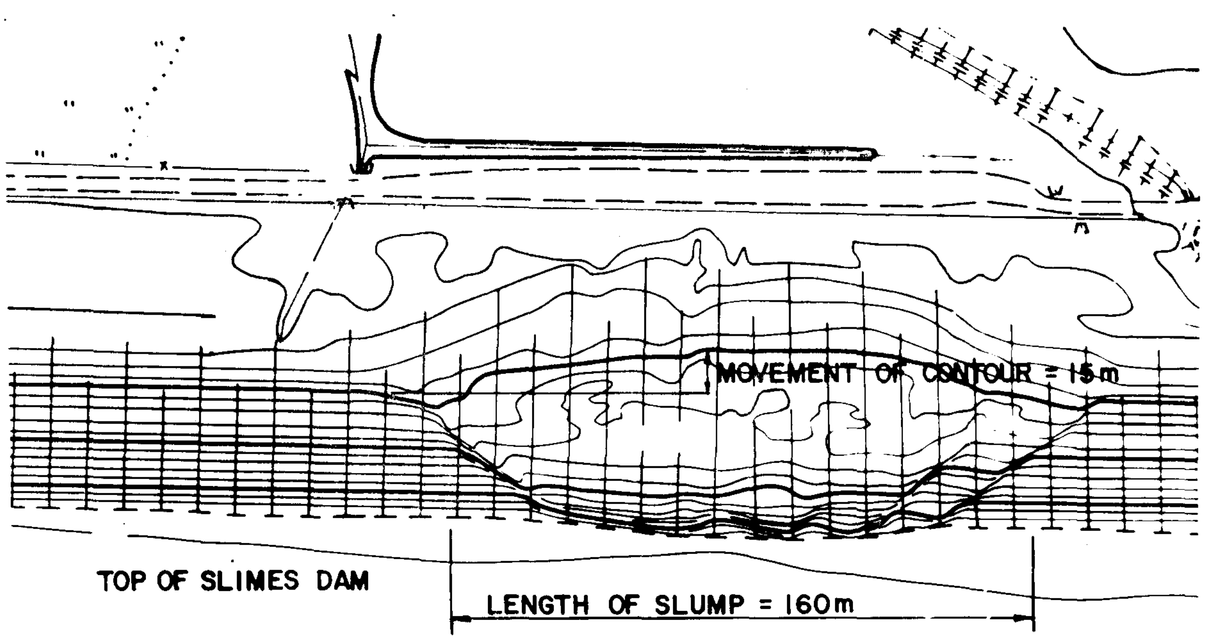


Fig. 1—Failure of a slimes dam similar to that at Bafokeng, illustrating the slump mode of failure (scale 1 : 2500)

flow of a slurry from a breached dam after the slurry has passed through the breach, taking the following factors into consideration.

(i) The pool area of the breached dam will act as a reservoir for the escaping slurry, and, at points reasonably adjacent to the breach, the flow of slurry will, for a limited time, assume the characteristics of a steady flow, i.e. the volume of slurry passing any two points will be the same over a short interval of time. This condition will be described algebraically by a continuity equation.

(ii) The slurry will usually spread after escaping from the breach, the degree to which it spreads depending on the topography, which will direct and channel the flow, and on the shape of the surface of the flowing slurry.

(iii) As the flow proceeds from the dam, it will be retarded by friction or viscous shear at the interface between the slurry and the ground surface, and will be retarded or accelerated by the slope of the ground, depending on whether it is uphill or downhill in the direction of flow. This condition will be described by an equation of motion.

(iv) Initial conditions of flow through the breach have to be assumed, as does the width of flow at various distances downstream of the breach. At the breach itself, the width of the breach, the depth of flow, and the flow velocity, all have to be reasonably assumed.

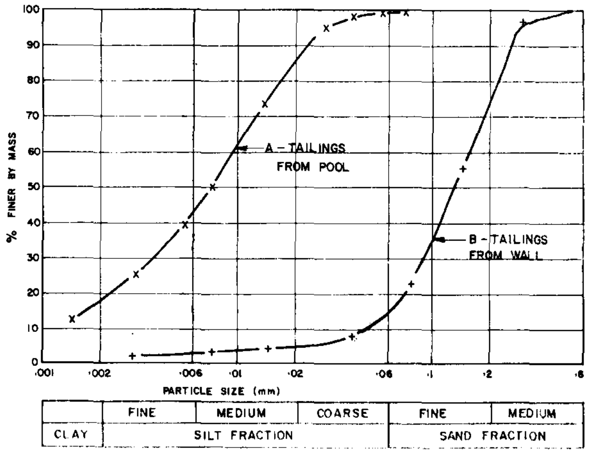


Fig. 2—Particle-size distribution of tailings from the pool of the Bafokeng tailings dam

Analysis

The dimensions and symbols used are shown in Fig. 5. The equation of motion is derived by consideration of the equilibrium of the element between sections 0 and 1 in Fig. 5 as follows.

Downstream forces on element – upstream forces on element = (mass of element) × acceleration:

$$\gamma A_0 z_0 + W\frac{\Delta h}{\Delta x} - \frac{\tau(Y_0+Y_1)}{2}\Delta x - \gamma A_1 z_1$$
$$= \frac{\gamma}{g}\ \frac{(A_0+A.)}{2}\ \Delta x.\ a.$$

Since $W = \gamma\dfrac{(A_0+A_1)}{2}\ \Delta x$,

$$\gamma A_0 z_0 + \gamma(A_0+A_1)\ \Delta h - \tau(Y_0+Y_1)\ \Delta x - \gamma A_1 z_1$$
$$= \frac{\gamma a}{g}\ \frac{(A_0+A_1)}{2}\ \Delta x, \quad \dots\dots\dots \quad (1)$$

where $\Delta h = z_1 - z_0$

For continuity of flow between sections 0 and 1, (2)

$$v_0 A_0 = v_1 A_1. \quad \dots\dots\dots$$

Also,

$$v = v_0 + a\,\Delta t$$
$$\simeq v_0 + \frac{2a\,\Delta x}{v_0+v_1}.$$

Hence,

$$v_1^2 = v_0^2 + 2a\,\Delta x \quad \dots\dots\dots \quad (3)$$

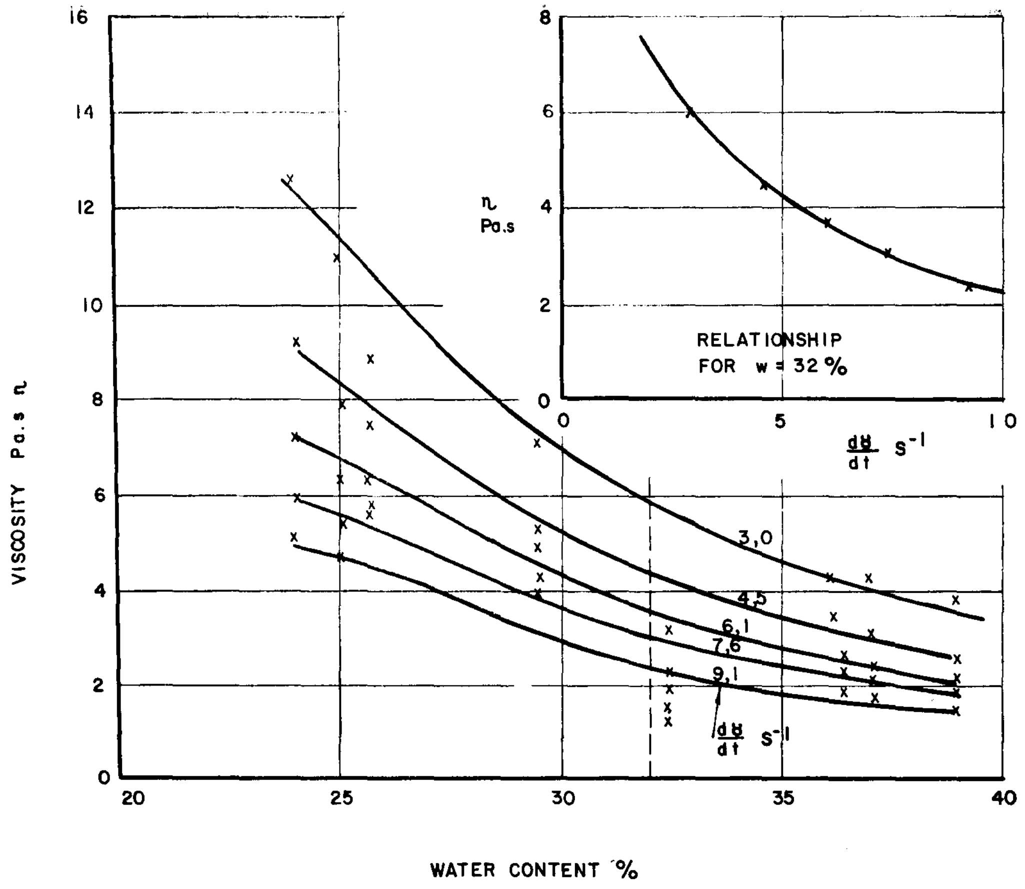


Fig. 3—Relationship between viscosity, water content, and rate of shear for Bafokeng mines

The shape of the slurry surface is assumed to be parabolic according to the expression

$$z = Dy^2+Ey+F \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; (4)$$

Computer Solution of Equations

Equations (1), (2), (3), and (4) are solved iteratively as follows:

(i) Estimate the velocity, v_1.
(ii) Calculate the acceleration, a, from (3).
(iii) Calculate the cross-sectional area, A_1, from (2).
(iv) In a separate iterative loop, find that value of F in (4) which gives a cross-sectional area within 1 per cent of the A_1 calculated in (iii).
(v) Find the extent of the flow in the y-direction (i.e. the intersection of the slurry and ground surfaces), and hence calculate y_1.
(vi) Calculate the centre of pressure of the downstream cross-section.
(vii) Evaluate the left- and right-hand sides of (1), and calculate the resulting force imbalance.
(viii) Use this imbalance to obtain an improved estimate of v_1.
(ix) If the imbalance is still too great, go to (i).

As the solution to (i) is not always unique, it is necessary to specify an initial estimate of the velocity, v_1, interactively for the computer at each step. The solution then obtained can be accepted or rejected at the user's discretion. It is also necessary to specify the D and E values in (4) at each step so that the flow is forced to follow the natural terrain and is allowed to spread out as the velocity decreases. Negative velocities or unreasonably large velocities are automatically rejected by the program, but sometimes the iterative scheme above finds a local rather than a global minimum in the force imbalance. However, these local minima are easily identified and rejected. It should also be mentioned that the very low curvature of the slurry surface (D in (4)) necessitated the use of double-precision arithmetic in steps (iv) and (v).

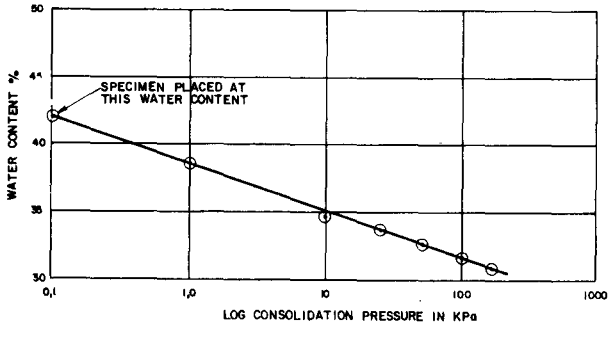


Fig. 4—Consolidation curve for slurry

Initial Values for the Analysis

In the estimation of initial flow conditions following a

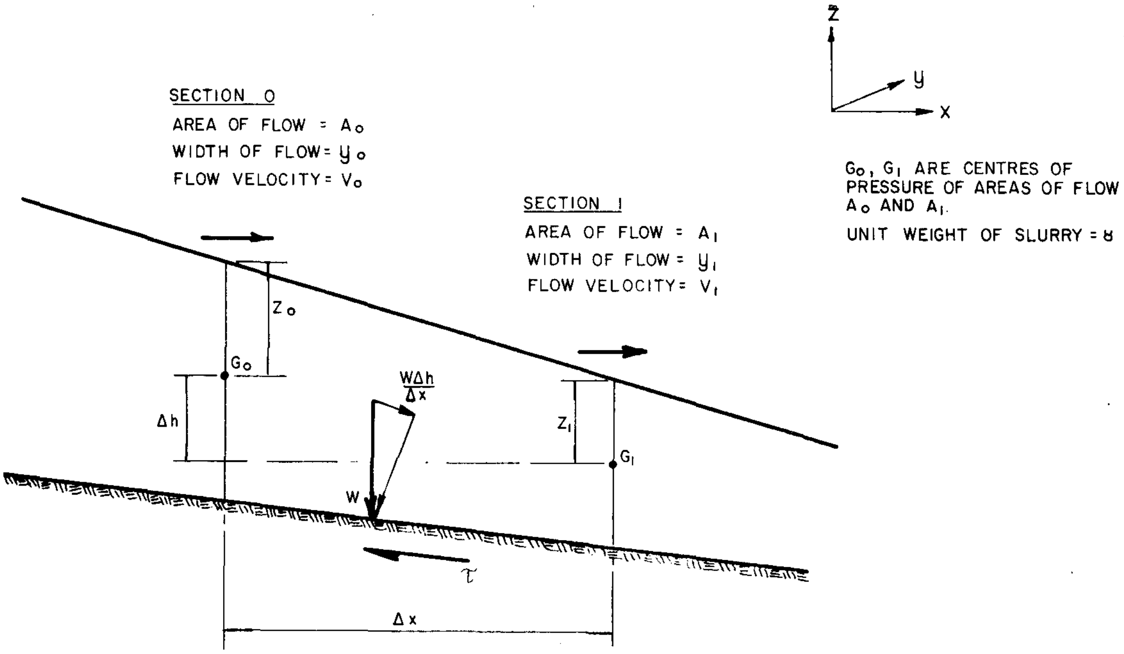
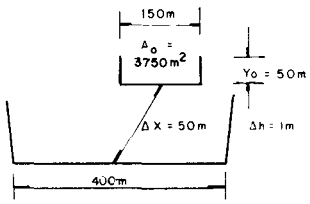


Fig. 5—Free body diagram of the flow of slurry at steady state

CURVE No	Ve (m/s)	D eq. 4	V_1 (m/s)	a (m/s²)	τ (kPa)	AREA A (m²)	MAX. DEPTH OF FLOW (m)
1	7,75	-2×10^{-5}	22,31	4,3758	2,5	1302,78	3,522
2	7,75	-2×10^{-4}	22,22	4,3383	2,5	1307,73	5,771
3	7,75	-2×10^{-6}	22,314	4,3784	2,5	1302,46	3,282
4	7,75	-2×10^{-5}	8,284	0,0857	25,0	3508,10	9,028
5	7,75	-2×10^{-5}	25,474	5,83	0,25	1140,85	3,118
6	30,0	-2×10^{-5}	35,894	3,8836	0,25	3134,25	8,094
7	14,9	-2×10^{-5}	26,634	4,8838	0,25	2096,38	5,505
8	2,0	-2×10^{-5}	0,966	-0,0307	0,25	7767,52	19,639



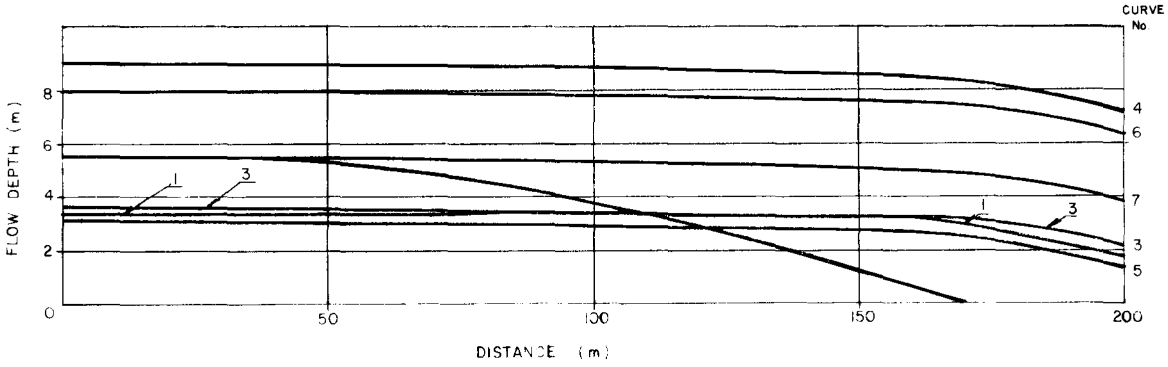


Fig. 6—Effect of the assumptions on the depth and velocity of flow

breach, the hydraulic dam-break problem or surge-wave problem (Dressler[5], Streeter[6], Henderson[7]) was examined. According to these analyses, the theoretical flow velocity at the break is given by

$$v = \tfrac{2}{3}\sqrt{gz}, \quad \ldots \quad (5)$$

where z is the depth of liquid retained by the dam.

Another approximation of the initial velocity is the discharge velocity over a low weir with a depth of flow equal to half the dam height, i.e.

$$v_0 = \tfrac{1}{2}\sqrt{gz}. \quad \ldots \quad (6)$$

The initial depth of flow in the dam-break problem is given as

$$z_1 = \tfrac{4}{9}\,z. \quad \ldots \quad (7)$$

Dressler[4] found that, for rough channels, a better approximation of the initial height is

$$z_1 = 0{,}5\,z. \quad \ldots \quad (8)$$

Also of importance is the relative magnitude of the shear, or viscous drag force, between the slurry and ground interface. As seen earlier (Fig. 4), this force results from the viscosity of the flowing slurry and depends on the water content of the slurry and the shear strain rate to which the slurry is subjected.

The magnitude of the shear stress, τ, is given by

$$\tau = \eta\frac{d\gamma}{\mathrm{dt}}, \quad \ldots \quad (9)$$

and $d\gamma/\mathrm{dt}$ is approximated by

$$\frac{d\gamma}{\mathrm{dt}} = 2v/z, \quad \ldots \quad (10)$$

where z = total flow depth
v = average velocity over the section under consideration.

In order to determine the sensitivity of the calculations to variations in the initial assumptions, a series of analyses was performed in which the initial velocity, the shear stress, and the value of D in equation (4) were varied. The following were the other values assumed for these calculations:

Initial area of breach, $A_0 = 3750\text{m}^2$ (total height of 50m (y_0 in Fig. 1) and width of 150m)
Density of slurry, $\gamma = 1800$ kg/m^3
Length of step, $\triangle x = 50$m
Drop in height, $\triangle h = 1$m.

The width of the second section was taken as 400m with vertical sides.

The values assumed for the parameters and the results obtained are shown in Fig. 6. The following conclusions can be drawn from these results.

(i) The magnitude of D does not influence the values of v_1 and acceleration a, but does considerably influence the maximum flow depth (curves 1, 2, and 3). Because the slurry surface is expected to be rather flat at large distances from the breach, a value of $D = -2\times10^{-5}$ was adopted.

(ii) The magnitude of τ has only a minor influence on v_1, acceleration a, and the maximum flow depth (see curves 1, 4, and 5). The magnitude of the term $[\tau(y_0+y_1)\triangle x]/2$ is generally much smaller than the remaining terms in equation (1). Some idea of the value of τ in the Bafokeng failure can be gained by the application of equations (9) and (10): for example, for an average velocity of 10m/s and a flow depth of 1m,

$$\frac{d\gamma}{\mathrm{dt}} = 20\ \mathrm{s}^{-1},$$

which is beyond the range of the measurements shown in Fig. 4. However, it will be seen that η will be less than 2 Pa.s and τ will therefore be less than 40 Pa.

(iii) The magnitude of the initial velocity, v_0, influences the results markedly (see curves 5, 6, and 7). The value of V_0 of 7,75 m/s is half of the value obtained from equation (6), while V_0 of 14,9 m/s was obtained from equation (5). The values of V_0 of 30,0 m/s and 2 m/s were assumed to be the maximum and minimum values possible.

Intuitively, it was felt that the value predicted by equation (6) was probably reasonable, and this choice was used as a starting value for further calculations.

Analysis of 1974 Slurry Flow

A back analysis of the 1974 failure at Bafokeng was important as a means of calibrating the analysis. Unfortunately, the available written and photographic evidence tends to concentrate on the mode of failure of the dam, rather than on the effects of the ensuing flow of slurry. However, the following relevant information could be abstracted from the records of the court enquiry.

Velocity of the Flow

(*a*) Approximately $3\times10^6\text{m}^3$ of tailings escaped from the dam in 40 to 60 minutes.

If the area of the flow through the breach measured 100m wide by 10m deep (see (iii) below), the average escape velocity would have been about 10m/s.

(*b*) The cladding of the winder house was seriously damaged to a height of about 5m, but the structure of the building remained intact. A 5m depth of stagnant slurry adjacent to an obstruction such as the winder house would correspond to an unobstructed flow velocity of about 10m/s.

(*c*) The flow was sufficiently strong to erode away part of an earth base for a concrete water reservoir 300 m from the breach, but not strong enough to damage the reservoir.

(*d*) The flow was not strong enough to seriously injure persons caught in it by eddies, turbulence, and undercurrents (as would be expected in turbulent flow). More damage appeared to be caused by the slime saturating clothes and entering orifices such as eyes, mouths, and noses. Experience of falling during waterskiing indicates that the velocity was probably less than 40 km/h or 11m/s.

From the above evidence it seems reasonable to assume that velocities close to the breach were of the order of 10 m/s (36 km/h).

Depth of the Flow

(*a*) The initial wave of slurry was sufficient to just flow over a concrete apron next to the shaft, which was 150m away from the breach. The

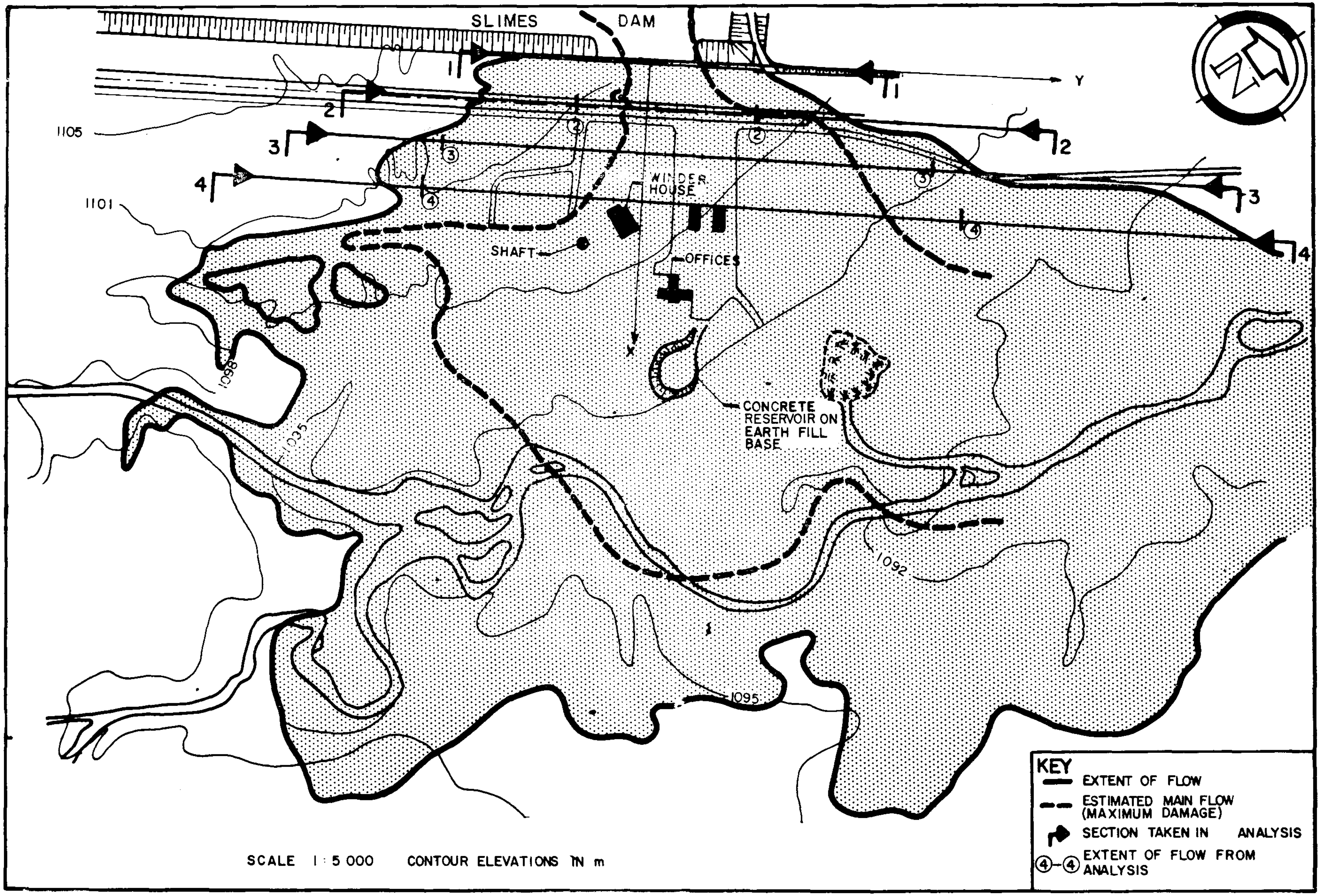


Fig. 7—Failure of Bafokeng slimes dam

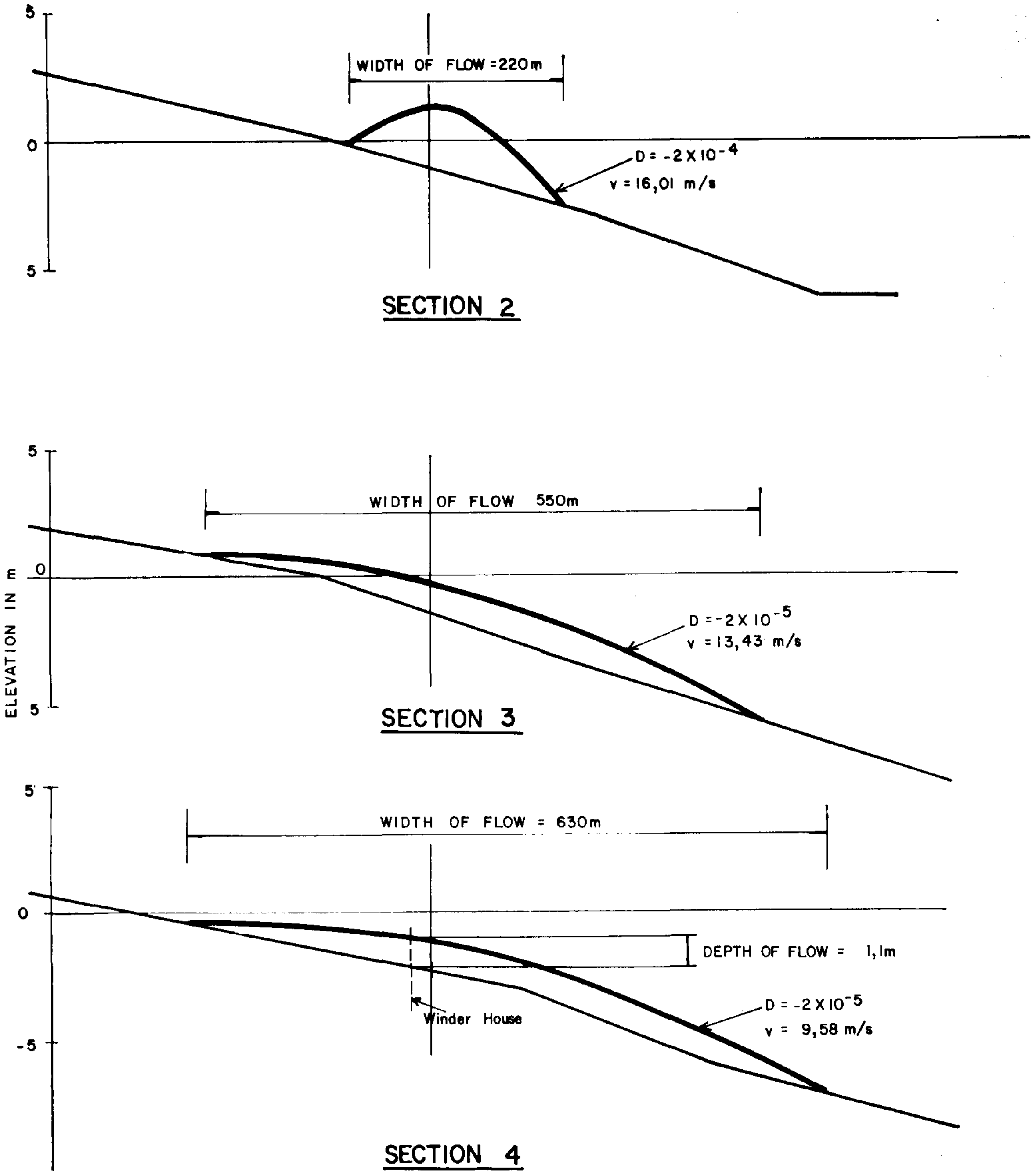


Fig. 8—The flow profiles and parameter values assumed

depth of flow at that point was approximately 1m.

(*b*) The flow was not deep enough to submerge motor cars parked directly in line with the breach. (As the main wall broke, one person attempted to drive his car through the slurry to get it to high ground.)

(*c*) Persons washed away in the slurry were attempting to reach the water reservoir, which remained above the flow.

(*d*) The depth of the flow at the water reservoir 300m away was estimated to have been less than 1m.

(*e*) The unobstructed flow in the vicinity of the winder house was approximately 1,5m deep.

These observations indicate that the steady depth of flow in the area studied was only about 1 to 1,5m. (Obstructions in the flow path, such as the winder house, would have increased this height locally.)

Width of the Breach

(*a*) According to eyewitness accounts, the initial breach was approximately 5m deep and between 10 and 20m wide.

(*b*) The final breach of the 20m high wall was about 110m wide at the bottom.

Survey of the Area

Results of a survey of the area after the failure are shown in Fig. 7. The outlines of the flow, as interpreted from air photographs, are also shown. It is clear that the flow did not proceed perpendicular to the breach but followed natural drainage channels.

The flow at the winder house was analysed by the consideration of four sections at 50m intervals as shown in Fig. 7. The flow profiles, parameter values assumed, and results obtained are shown in Fig. 8.

From the calculations for section 4 it can be seen that the predicted depth of flow at the winder house is about 1,1m while the velocity is 9,58 m/s. These values compare well with the information summarized above.

Discussion and Conclusions

The analysis proposed above for the flow of a slurry appears to provide a realistic model of the process in that it predicts realistic depths of flow. The analysis was developed to enable the safety of surface installations in the vicinity of tailings dams to be examined. For this purpose, the static or stagnant depth of the slurry adjacent to an obstruction is required. The static depth is obtained by the addition of the velocity head to the dynamic flow depth:

$$z\ (\text{static}) = z\ (\text{dynamic}) + v^2/2g \quad (11)$$

In the case considered, $v^2/2g$ has a value of about 5m, which, when added to the dynamic flow depth, compares favourably with the observed height to which the cladding of the winder house was damaged.

It is by no means easy to apply the analysis to a particular case since starting values have to be assumed for many of the variables involved. In particular, the following must be assumed largely on the basis of engineering judgement:

(i) the position of a potential breach,
(ii) the width and depth of the breach,
(iii) the height of the dam at the time of failure, and
(iv) the course taken by the escaping slurry.

Notwithstanding these uncertainties, it is considered that the analysis provides a useful addition to the tool kit of the tailings-disposal engineer.

It would be useful for the engineer to be able to analyse and predict the flow of the slurry once it entered the Kwa-Leragane River. However, at that stage the slurry became diluted to an unknown extent by the water in the river. Hence, although the same principles would apply, the continuity equation would be complicated by the unknown increase in the volume of flow.

Acknowledgement

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Professor G. S. Marwaha

Professor Gurbachan Singh Marwaha, FIME, FIMM, FIE (India), Director of the Indian School of Mines, has been designated President-Elect of the Association of Indian Universities. The membership of this Association consists of Vice-Chancellors and Directors of the 128 universities and university-level institutes in India. He is the first mining engineer, indeed the first from the whole field of mineral sciences and technology, to be so honoured in India, and one of very few mining engineers anywhere to achieve such a distinction.

Earlier in the year, he was elected President of the Mining, Geological and Metallurgical Institute, India, which is a constituent member of the Commonwealth Mining and Metallurgical Congress.

Professor Marwaha has been associated with the Institution of Mining Engineers since 1945, and since 1967 he has served as Co-opted Member for India on its Council. In 1973 he became the first recipient of the IME Overseas Award. A Member (later Fellow) of the Institution of Mining and Metallurgy since 1959, he has represented India and Pakistan on its Council since 1968.