Failure of a Mine Waste Dump in Zimbabwe: Causes and Consequences

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ABSTRACT / A combination of factors are considered important in causing the failure and subsequent development of a flowslide of a gold mine waste dump (or tailings dam) at Arcturus, near Harare, Zimbabwe. These factors comprise poor basal drainage, steep perimeter walls, saturation of the walls and basal sediments through continued spigoting of slurry during a period of heavy rainfall, and the effect of this saturation on the tailings. Properties of the tailings, eyewitness accounts, documentary evidence, and site characteristics are discussed. The failure and subsequent development of a fatal 300-m flowslide are reconstructed in a five-phase developmental model. The general applicability of the results is discussed.

Introduction

For economic reasons, mine waste is disposed of in the form of dumps, tailings dams, or spoil heaps. Slurry and tailings in settling ponds are, like much mining waste, in a state of loose packing so that not only can slip take place, but there is also the possibility that flowslides might occur. Such mass movements of material can cause damage to property and, in some cases, serious loss of life, as demonstrated in the tragic incident at Aberfan in South Wales in 1966. This article examines a more localized, but nevertheless spectacular incident of failure of a tailings dam at Arcturus Gold Mine some 30 km east of Harare, Zimbabwe (Fig. 1).

At about 1930 h on 31 January 1978, a breach approximately 55 m wide suddenly developed in the west wall of a large waste dump at Arcturus mine. An estimated 30,000 tons of debris was evacuated from this breach, forming a flowslide about 300 m in length (Fig. 2); This demolished two pole-and-mud huts, killing one child and injuring another. The official inquiry (Ministry of Mines unpublished data) on the failure of the waste dump focused primarily on the issue of the heavy rainfall preceding the collapse and the ability of the penstocks (vertical drains) to cope with the abnormal accumulation of water on top of the dump. The inquiry instigated by the then Rhodesia Department of Mines concluded that provided the penstocks had remained intact, they could have siphoned off the excess water from both the slurry and the rainfall, thus ruling out the development of a large pond on the surface of the dump. Failure was blamed on the steep perimeter walls of the dump and, as a result, it was recommended that future waste dumps should have much lower-angled slopes.

The mine was visited by the authors in May 1987 to review the causes and geomorphological consequences of the collapse. Although the lower part of the flowslide had been leveled by bulldozers, the upper flowslide and the dump itself had altered little since the immediate aftermath of the collapse after the excess water within and on the surface of the dump had drained away. This lack of change in the morphology of the dump since 1978 was verified by comparison of oblique and vertical aerial photographs taken shortly after the failure with those taken several years later. This article presents the results of an investigation of the site characteristics, surface morphology, and engineering properties of the dump material. The study demonstrates that, in addition to oversteep perimeter walls, there were several other factors in the site and construction of the dump that led ultimately to its failure and to the destructive flowslide.

Waste Dump Construction

The Arcturus dump was constructed using the upstream method, commonly used on slimes dams throughout Zimbabwe (MacKechnie 1975). This involves spigoting of run-of-the-mill tailings (crushed rock) as a slurry on to a dump surface from a number of pipes laid around a perimeter wall. The perimeter wall is normally constructed of coarser tailings excavated from the margins of the dump. The aim of spigoting is to discharge a uniform sheet of slurry towards the center of a dump. Since the coarser tailings settle

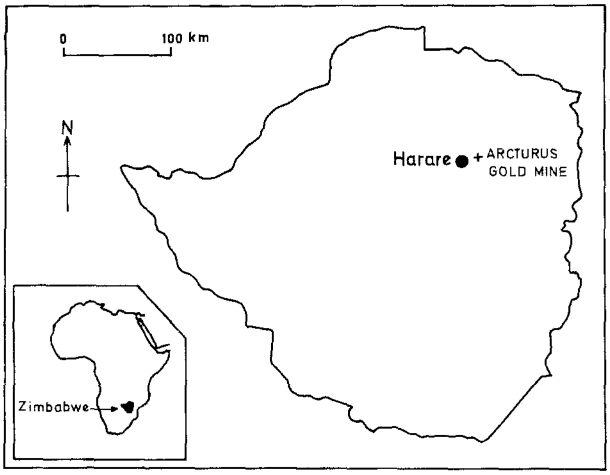

Figure 1. Location of Arcturus Gold Mine, Zimbabwe.

out near the edges of the dump and the finer material is carried in suspension into a central pond, this procedure results in a particle size gradient from the margins to the middle of a dump (Fig. 3). Following sedimentation of the fine tailings in the central pond, the clear water is decanted via penstocks and may be recycled in the extractive processing. As the dump surface builds up, the perimeter dykes are raised and additional pipe segments are added to the penstock drains (Fig. 3).

Setting and Morphology of Arcturus Dump

The dump is located on a low saddle-shaped ridge between two small hills (Fig. 4); this ground slopes eastward and westward of the long axis of the dump at angles of 5–6°. The basal drainage beneath the dump as well as the internal seepage, however, are predominantly towards the central part of the western perimeter wall that eventually collapsed (Fig. 4, inset).

The base of the dump measures 310 × 150 m, narrowing to 275 × 112 m on the upper surface. A detailed history of the dump construction was not available to the authors, but pertinent details could be derived from aerial photographs. The 1965 aerial photographs indicated that the dump, at that stage, had been in operation for several years. Between 1965 and 1978 the average rate of build-up is estimated at 1 m/yr, well within the recommended maximum rate of 6 m/yr for such dumps (Blight 1969). The perimeter walls varied in inclination from 38° to 42°, with basal sections approaching 45°. The height of the outer walls varies from 25 m in the west to under 10 m in the southeast. A low-angled pediment slope fringes the western and eastern margins of the dump and is produced by surficial erosion of the perimeter walls and limited basal seepage.

Figure 5A shows how the microtopography of the dump surface might have appeared prior to failure. Its elongated, shallow, dishlike form, with a maximum relief of just over 1.5 m, would have facilitated free drainage of slurry from the perimeter walls towards the central pond. This idealized surface was reconstructed from measurements of the postfailure surface of the dump (Fig. 5B) by replacing the western half with a mirror-image of the eastern half, which was virtually unaffected by the dump collapse. Clearly, during and following failure, there was considerable deformation of the western half of the dump as shown by the configuration of the contours in Figure 5B, indicating tilting of the surface towards the breached wall. Tension cracks curve along concentric arcs that pass around and through the collapsed area of the dump.

The earliest signs of instability of the dump and weakness in the western wall were reported in 1972, with the development of a large cavity similar to that present in the east wall today (Fig. 6). The remedial measures taken to fill this cavity and stabilize the perimeter wall are summarized in Table 1, along with subsequent events leading up to and just after the failure of the dump. The arcuate scar in the central western wall (Fig. 7) was clearly indicative of a major instability problem, as demonstrated by the largely unsuccessful efforts to plug the cavity in the days prior to collapse.

Engineering Properties of Tailings

A summary of selected engineering properties of 10 samples from different sites on the surface and within the waste dump is given in Table 2. The sediments were so fine that efforts to carry out triaxial shear tests on reconstructed tailings cores proved unsuccessful. Sample 1 contains the coarsest sediment of the materials analyzed, with 50 percent by weight of sand. This reflects its origins from near the west perimeter wall where the coarsest tailings would have been deposited during operation of the mine dump. The 7 percent clay content of this sample may have resulted from surface washing of fines during collapse since, in comparison, other surface samples have a lower clay content. The highest dry density and lowest void ratio of all ten samples were recorded for sample 1.

The most readily apparent variation in the tailings with depth is the change in color from light and dark brown layers to alternating brown and grey layers (sample 6 at 9 m depth) to mainly greenish grey layers in the lower part of the dump. Samples 6–10, which were taken from the lower 9–23 m of the dump from exposures in one of the main gullies, generally have lower percentages of sand and slightly higher percentages of

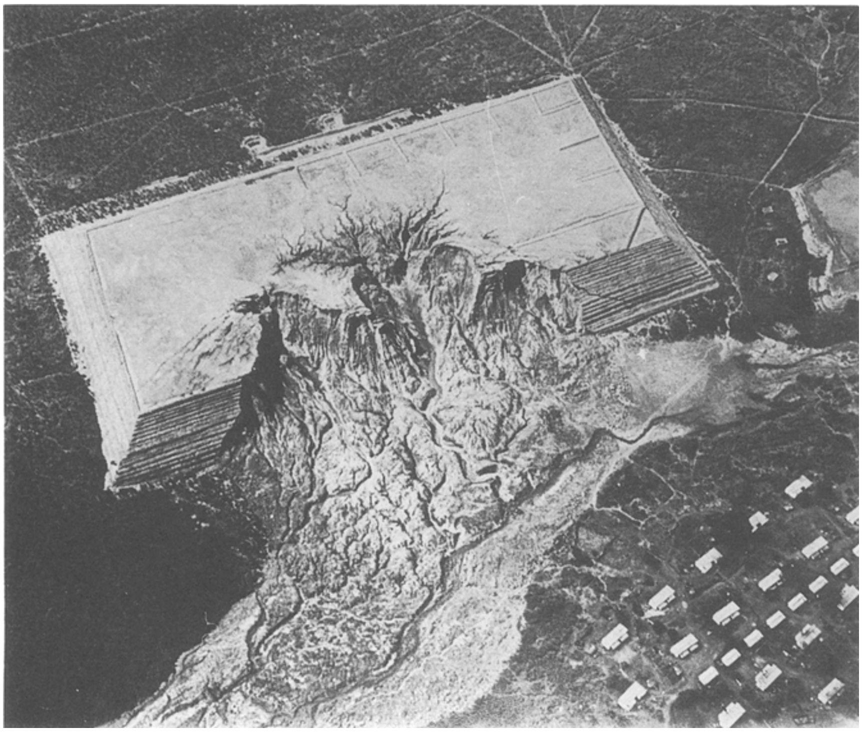

Figure 2. Oblique air photograph taken in 1978 shortly after collapse of the waste dump. The main complex and wash apron of the flowslide are clearly shown. Small paddocks to direct slurry towards the central pond can be seen together with a short retaining wall across the southwestern corner (right-hand side) of the dump and remnants of the retaining wall built parallel to the west wall a few days prior to failure (see Table 1 and Fig. 8). Mine workers' dwellings in the lower right of the photograph indicate scale.

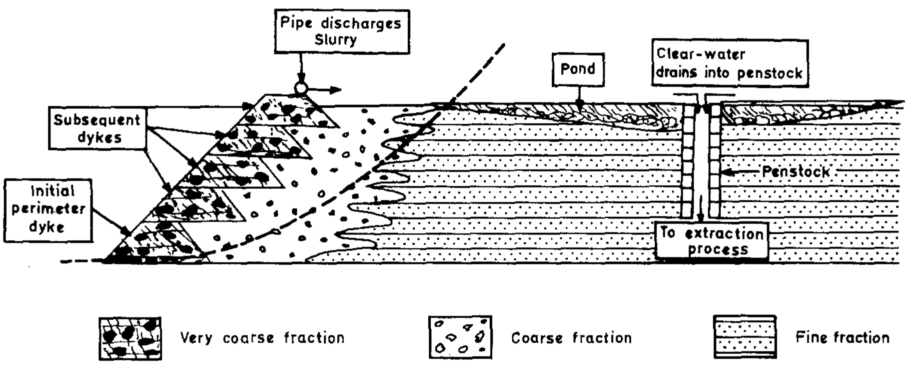

Figure 3. Method of waste dump (tailings dam) construction (modified after MacKechnie 1975). Note position of hypothetical failure arc passing through fine fraction.

clay and silt than samples from the upper part of the dump. Most notably, in these lower layers, samples 8 and 9 have very low dry density values of 1340 and 1380 kg/m^3 and high void ratios of between 0.96 and 1.05. The void ratios exceed the critical void ratio for similar fine tailings elsewhere in Zimbabwe (MacKechnie 1975).

The basal fine sediments do not resemble the fines near the central pond area on the dump surface in terms of color, texture, or engineering properties. Since samples 8 and 9 came from positions approximately midway between the penstocks and the west perimeter wall, they should have been coarser rather than finer than those samples. It can only be concluded that the basal tailings supplied to the dump during the 1960s differed in nature from those supplied later, although why this change occurred was not documented. At the time of field observations, the greenish grey basal sediments had moisture contents in the range 25–31 percent, appreciably higher than that of the coarser surface sediments (under 15 percent).

Causes of Dump Failure

Five main factors combined to bring about failure of the waste dump. These factors were (not necessarily in order of significance) heavy rainfall, drainage, steepness of perimeter walls, local topography, and the properties of the tailings.

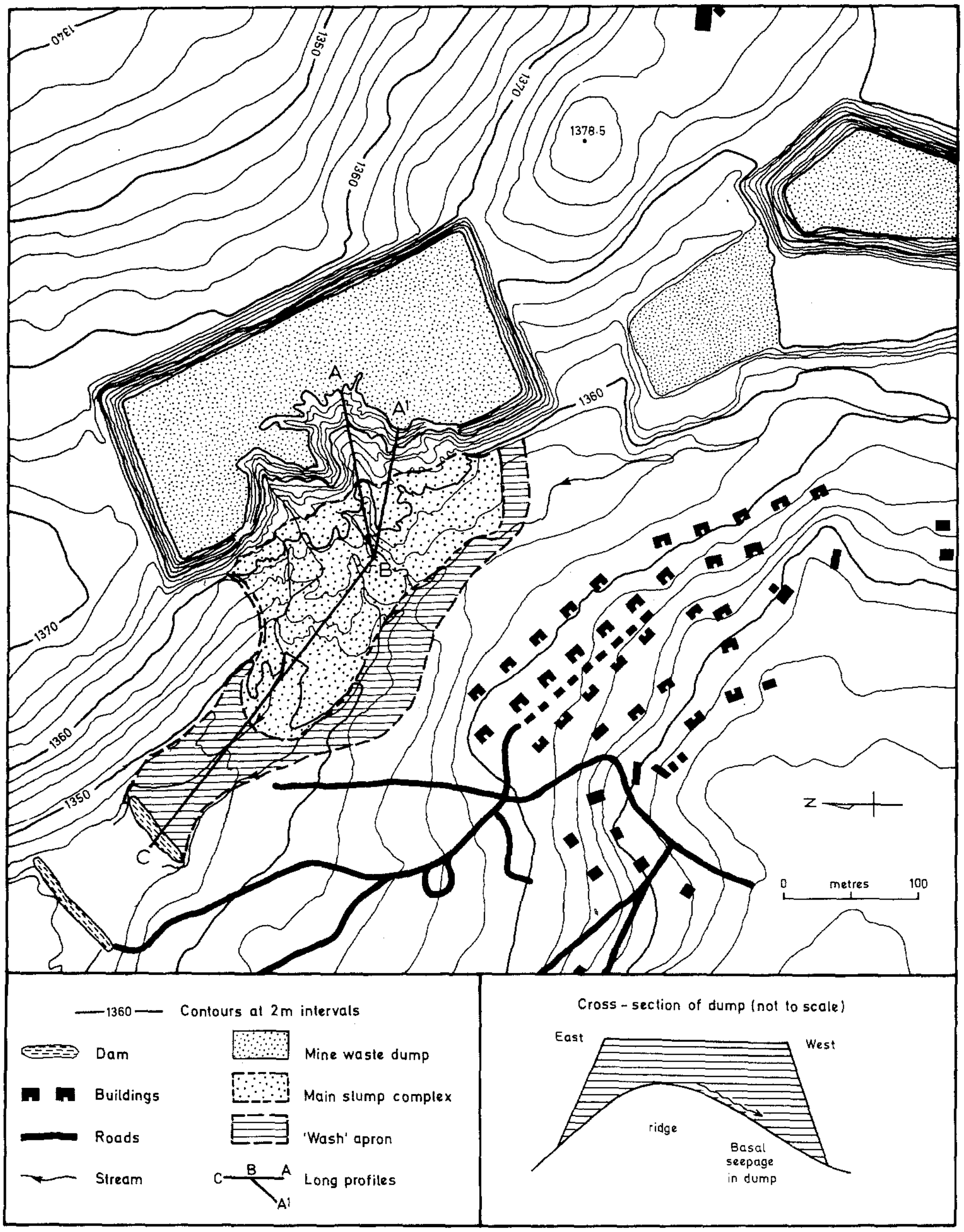

Figure 4. Waste dump, flowslide, and surroundings, Arcturus Mine. Inset shows likely basal seepage routes in the dump.

Heavy Rainfall

Nearly 1800 mm of rainfall was recorded in the 1977–1978 wet season (October to April). This was nearly double that of the mean annual rainfall for Arcturus based on over 50 years of records prior to this very wet season (Department of Meteorological Services, 1977). Over one third of this rainfall occurred during the four weeks prior to the failure, particularly in the last four days of January when 183 mm of rain was recorded at the mine. The most important effects of the heavy rainfall would have been to wet the dam walls, reducing their strength (see below) and to exacerbate the problem of saturation of the internal tailings already subject to continued spigoting of slurry. It seems doubtful that the heavy rainfall exceeded the capacity of the penstocks (capable of evacuating some 3 million l/h) unless they had become damaged.

Drainage

It seems that no special attention was paid to basal

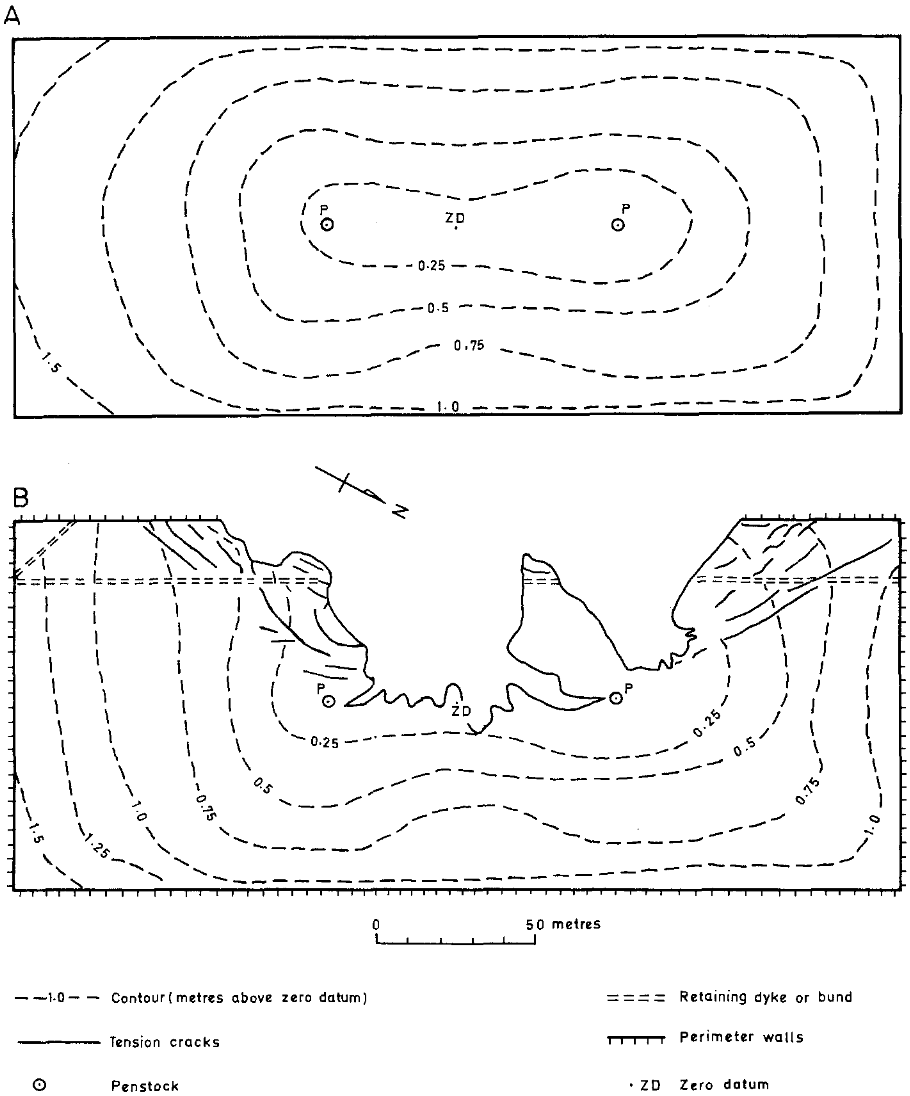

Figure 5. (A) Idealized reconstruction of the prefailure waste dump surface. (B) Postfailure form of waste dump surface.

drainage during the initial stages of construction of the dump. Basal seepage would have been concentrated towards the central parts of the two longer sides of the dump, particularly the west wall (Fig. 4, inset). The inadequacy of basal drainage is indicated by the reported common practice of periodically easing internal drainage by driving steel pipes into the dump walls, especially in the two to three years prior to failure.

Surface drainage and the ability of the penstocks to cope with continued slurry inputs and heavy rainfall were primary concerns in the official inquiry referred to earlier (Table 1). It was concluded that the calculated maximum rate of flow down the two 448-mm-diameter penstocks could have coped easily with the excessively heavy rains, particularly in view of the reduced area of the dump once the new retaining bund (low wall of tailings) had been built parallel to the west wall a few days prior to the collapse. In fact, calculations were based on the incorrect assumption that this bund was 30 m and not the measured 17 m from the west wall. Moreover, there was no way of draining water between this bund and the perimeter wall so ponding undoubtedly occurred in this area, a point noted in the official inquiry.

The ability of the penstocks to cope with abnormal amounts of surface water depended, however, upon the vertical drains remaining intact. In view of the continued development of cavities during the week prior to failure, it seems a distinct possibility that the penstocks underwent some damage, thus reducing their efficiency. Equally, and probably more, importantly, these cavities would have provided direct drainage routes to the internal parts of the dump. Evidence given in the official inquiry shows that cavities did develop between

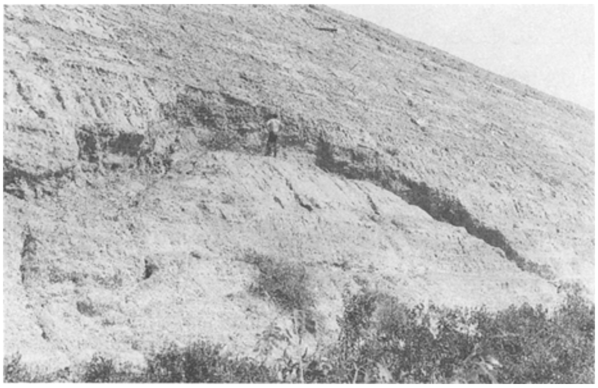

Figure 6. Arcuate scar developed in east wall of waste dump.

the new retaining bund and the west perimeter wall in the period prior to collapse. Consequently, water ponded up in this section could have drained readily into the dump, increasing the likelihood of saturation of the basal sediments.

Furthermore, development of large cavities in the days leading up to failure could have led to sagging of the dump surface near the west wall. In this event, the surface pond would have extended somewhat farther towards this wall. The bund constructed to retain the water in the central part of the dump was in fact made of very wet material (Fig. 8), which collapsed easily, forming a barrier barely 10–15 cm in height. With prolonged heavy rains, it is a strong possibility that the bund was overtopped as the surface water level rose and the pond shifted towards the west wall. An additional problem arising from poor drainage might have been the rise of the phreatic line within the dump towards the surface of the outer wall.

Steepness of Perimeter Walls

Excessively steep slopes (>38°) were regarded as the main cause of failure. This is certainly confirmed by reference to Figure 9, which gives the maximum safe slope angle for the Arcturus dump of 35° based on typical engineering properties of such tailings, the height of the dump, and assuming an impervious base and a start date of deposition of 1960, which yields an annual rate of deposition about 1.6 m/yr. In fact, the official inquiry determined that subsequent tailings dams at Arcturus should not have walls steeper than 30°, and recent regulations state that angles ideally should not exceed 26° (R. Svotwa personal communication). There can be little doubt that the steepness of the perimeter walls did play an important role in the disaster, but to attach blame almost exclusively to this factor is considered by the authors to be an oversimplification. If perimeter wall steepness had been the overriding factor, then the nearby, now-abandoned dump with equally steep and high walls (Fig. 4) could be expected at least to show signs of collapse, yet this is not the case.

Table 1. Signs of dump instability and actions taken

Date	Event	Remedial action
Early 1972	An arcuate scar 60 m wide, 1.5 m across and ca. 10 m deep develops in the west wall.	Scar is filled with 1040 tons of dry rock waste over four days; a buttress wall is built at the base of the scar (Fig. 7).
Week prior to failure	Cavities reappear in west wall and also more localized cavities appear in east wall.	Cavities in west wall are filled with rock waste.
Four days prior to failure	Continued redevelopment of cavities within west wall.	Slurry, discharge pipes are moved "approximately 30 m away"[a] from the west wall and a new retaining bund is built just west of the pipes (Fig. 8).
1930 h on 31 January 1978	Collapse of central part of west wall with a "loud bang" according to mine residents; resulting flowslide engulfs two huts killing one child and injuring another.	Emergency operations to rescue children; construction of series of bunds on intact dump surface to reduce further runoff draining into breached wall and the extension of a surface gully system (Fig. 2).
Postfailure	Official Ministry of Mines inquiry instigated on 1 February and completed by 7 March.	Recommendation that retaining walls on future waste dumps should not exceed angles of 30°.

[a]Field observations in May 1987 showed that this retaining bund was, in fact, only 17 m from the west wall.

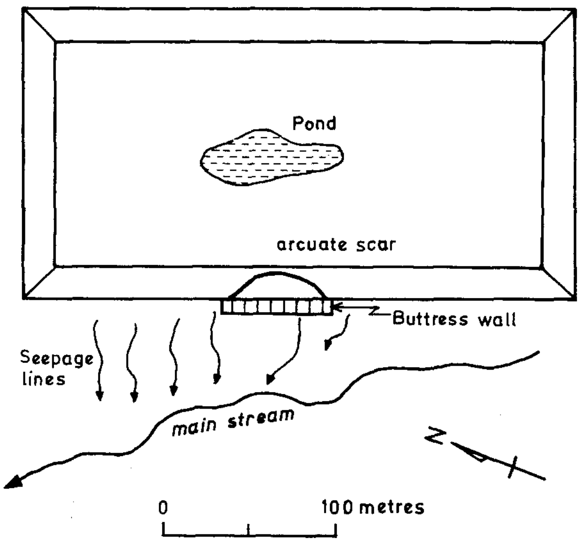

Figure 7. Location of buttress wall and arcuate scar in west wall, based on 1972 air photography.

Local Topography

The siting of the dump on a col with basal drainage directed towards the two longer sides exacerbated problems of poor drainage near the failure site. Thick salt encrustations along the bases of the perimeter walls indicated that there had been prolonged slow seepage in the past, as one would expect. However, the form of the underlying natural slope served to concentrate water in the central parts of the western wall. The gradual build-up of water could have gone unnoticed until the cavities in this wall started opening up. Consequently, poor siting of the dump and poor drainage provision are regarded as important factors contributing to the eventual failure of the dump.

Engineering Properties of Tailings

The method of building tailings dams like that at Arcturus leads to the tailings undergoing wetting and drying cycles, during which the pore water pressure fluctuates between positive and low negative and high negative values, causing in turn fluctuations in intergranular pressure and hence also fluctuations in shear strength. Desiccation leads to overconsolidation of the tailings through capillary forces, which increases the intergranular pressure (Donaldson 1960). Thus the stability of the perimeter wall depends heavily on it being well dried out. However, the strength of the wall material would have been much reduced in the period leading up to failure due to the heavy rainfall and continued spigoting of tailings onto the dump, which had already begun to sag on its western margin, leading to an exacerbation of the wetting problem at the west wall because of leakage from the pond and disruption of internal drainage as sagging took place. Two other aspects of the tailings are important in explaining the shear failure of the wall and liquefaction of the tailings that gave rise to the flowslide. First, from the very manner of failure, it is clear that the failure arc (Bishop 1973) was entirely within the tailings and did not extend into the underlying more-resistant foundation soil. Extreme narrowness of the wall will cause this failure surface to pass through the weaker material laid under water on the floor of the dump as shown in Figure 3, rather than be contained within the coarser and, therefore, stronger material in the wall. However, in the case of the Arcturus dump, particle size analysis shows that there is little difference between the coarseness of wall and inner tailings (cf. samples 1, 2, and 3, Table 2). Second, the high void ratios of the basal tailings (samples 8 and 9, Table 2), through which the failure scars

Table 2. Engineering properties of waste dump sediments

Sample no.	Site	Munsell color	Sand (%)	Silt (%)	Clay (%)	Dry density (kg/m^3)[a]	Void ratio[b]
1	West wall margin	Yellowish brown	50	43	7	1660	0.63–0.66
2	Surface, near west wall	Yellowish brown	38	60	2	1520	0.78–0.81
3	Surface near penstock	Yellowish brown	30	68	2	1640	0.65–0.68
4	3 m depth	Brown	33	65	2	1650	0.64–0.67
5	6 m depth	Brown	37	61	2	1550	0.74–0.77
6	9 m depth	Brown and grey layers	23	68	9	1570	0.72–0.75
7	12 m depth	Light grey	23	73	4	1510	0.79–0.82
8	16 m depth	Greenish grey	17	76	7	1340	1.01–1.05
9	19–20 m depth	Greenish grey	23	68	9	1380	0.96–0.99
10	22–23 m depth	Greenish grey	30	66	4	1570	0.72–0.75

[a]Tests carried out on intact lumps of sediment.

[b]Range for specific gravity values of 2.70 and 2.75 g/cm^3

Figure 8. Retaining bund (foreground) built 17 m away from the west wall four days prior to failure in an attempt to reduce the degree of saturation of the area subject to tension crack formation near the west wall (see Table 1).

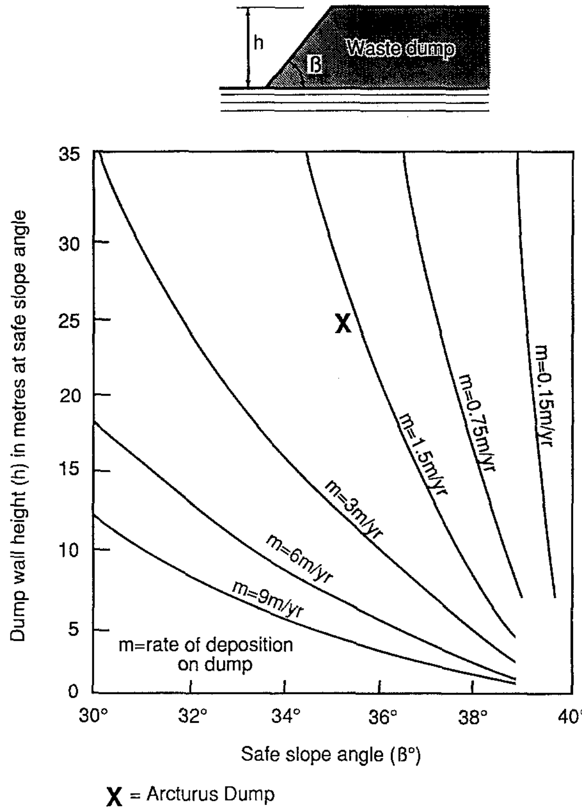

Figure 9. Design graph for tailings dam with impervious bases (after Blight 1969). The safe slope angle for the Arcturus dump is indicated.

passed, are similar to or exceed the critical void ratios calculated for comparable fine tailings (0.96–1.01) by MacKechnie (1975).

With void ratios exceeding the critical value, a dangerous situation develops. On disturbance, the void ratio tends to be reduced, and if the water content in the basal tailings is more than sufficient to saturate the tailings at the critical void ratio, the full reduction in volume is not possible and there is a sharp rise in the pore pressure, a fall in the effective stress, and hence a temporary reduction in shear strength (Scott 1974). With an insufficiently rapid dissipation of the pore pressure, a flowslide can develop. This sequence of events accounts for what happened at the Arcturus dump.

Consequences of Dump Failure

Had the failure of the west wall of the dump involved only shear failure of the wall, it would not have resulted in a fatality and it is unlikely that it would have attracted much attention outside the mine. In fact, however, a liquefaction slide developed in which the normal stress was largely transferred on to pore water filling the pore spaces (Bishop 1973). Such slides move very rapidly, and this is supported by the report from mine workers living in houses near the site that the failure occurred with a "loud bang."

A five-phase sequence in the failure of the west wall and development of the flowslide has been reconstructed on the basis of documentary evidence, fieldwork, and laboratory data (Fig. 10). In view of the development of an arcuate scar some six years prior to the collapse in the central part of the west wall, it is likely that this was the point of greatest weakness in the dump (phase one, Fig. 10). Once failure of the wall had occurred, this would have triggered liquefaction of the saturated tailings in the dam. As movement of this highly mobile sediment began, tension cracks would have formed around the scar zone and extended on to the dump surface (phase two, Fig. 10). Once the breach was opened up, the semifluid sediment would have flowed very rapidly downslope away from the west wall.

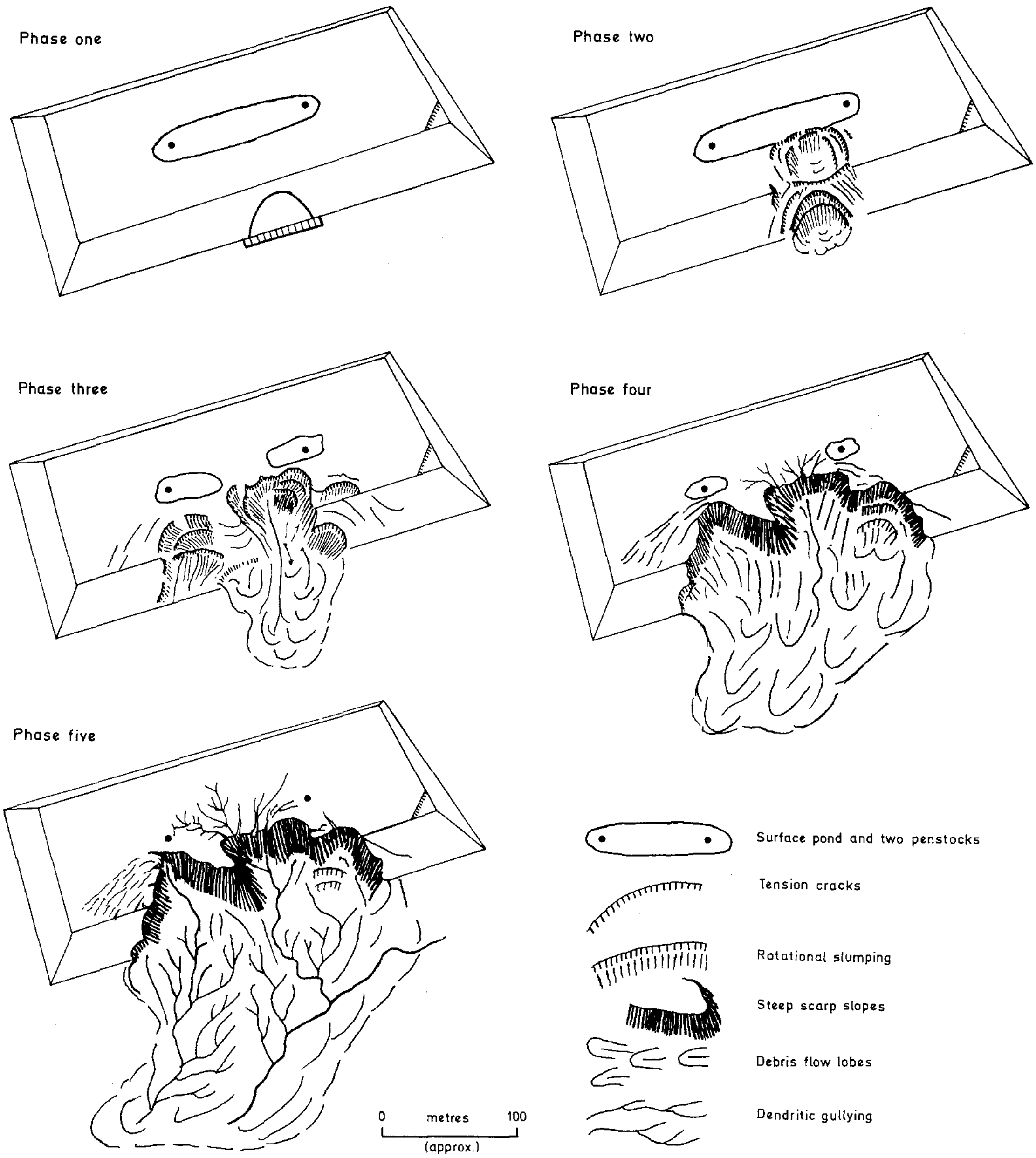

Figure 10. Five-phase reconstruction of failure of the west wall of the waste dump and subsequent development of the flowslide.

As it did so, it would have undermined the overlying, slightly coarser, more stable tailings, causing further tension cracking and eventual collapse through rotational slipping along these cracks (Fig. 11). Thus, large slabs of sediment would have moved downslope together with the extension of the flowslide at the base.

The development of tension cracks and rotational slumping would have extended back rapidly towards the surface pond, thereby commencing drainage of this part of the dump (phase three, Fig. 10). At this time, stresses on areas of the west wall either side of the breach would have increased to such an extent that they too collapsed. This would have promoted further flowage of basal sediment, enlarging the main breach and two smaller embayments either side of this central cavity as shown in phase four (Fig. 10). In addition, rapid drainage of the surface pond resulted in the formation of a dendritic gully network in the wet tailings (Fig. 12).

By this stage the flowslide would have reached the small stream below the dump and been diverted down valley towards the first of two small dams constructed to prevent seepage waters from the dump entering the

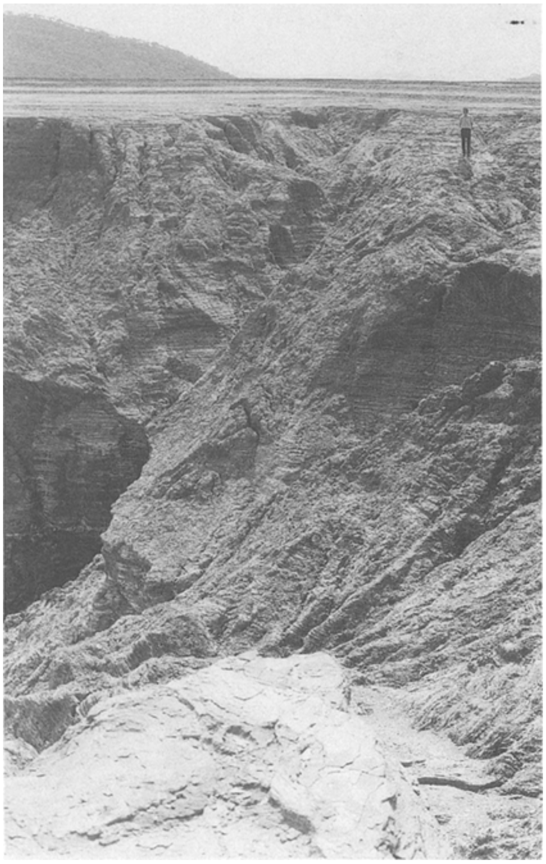

Figure 11. Steep slip faces and slumps in the central part of the collapsed area of the waste dump.

Figure 12. Deep gully that formed at the time of failure in wet tailings. The slumping of the originally wet tailings on the margins of the gully can be seen.

lower reaches of the stream (phase five, Fig. 10). A considerable volume of excess water accompanied the flowslide. This is demonstrated by the wash apron (Fig. 4), which extended some distance up the slope opposite the dump towards the mine workers' dwellings. With continued heavy rains in the 48-h period following collapse, the flowslide sediments were affected by gully incision and further gullying occurred on the surface of the main dump.

The entire flowslide was approximately 300 m in length with an average slope of 2° (Fig. 13). Its width varied between 60 and 75 m in its lower part. The main complex comprised most of the debris removed from the dump, forming a jumbled mass of debris that stretched across the entire 175-m width of the breach in the west wall and extended some 190 m down valley. Intact lumps of sediment up to 1 ton in weight were found as far as 150 m away from the breach. The fringing wash apron apparently left a thin covering of sediment with occasional larger agglomerations of material. This extended about 35 m on the western edge of the main complex and about 110 m beyond the limit of this complex in a down-valley direction.

Apart from loss of life and injury, the dump failure disrupted mining operations until arrangements could be made to utilize another dump site for tailings disposal. It also led to pollution problems downstream, contaminating a farm reservoir and depositing sediment over approximately 8 ha of soya beans (letter by farmer to Ministry of Mines, 16 February 1978). It involved direct costs to the mine since the lower part of the flowslide had to be bulldozed flat to avoid further pollution downstream and a new dump site had to be prepared sooner than anticipated. In addition, a system of retaining bunds had to be built on the intact surface of the collapsed dump to encourage infiltration of rainwater and reduce the chances of further erosion.

Summary and Conclusions

Despite the elapse of about ten years since failure, field observations together with documentary and other sources indicated the main factors involved in the failure of the Arcturus dump and associated destructive flowslide. It is suggested that a combination of factors was involved: most important were the underlying relief tending to direct basal drainage towards the base of the central and highest part of the west wall, poor provision of basal drainage, steep perimeter walls, saturation of the dump walls and basal sediments through continued spigoting of slurry onto the dump and through heavy rainfall, and the effect of this saturation on the behavior of the tailings. Although the steep perimeter walls were highlighted by the official inquiry as the important dump construction factor leading to the disaster, this is viewed here as one of several contributory factors. The stability of a nearby dump with equally steep perimeter walls supports this view.

The lessons to be learned from the Arcturus dump failure would appear to be that, in addition to building

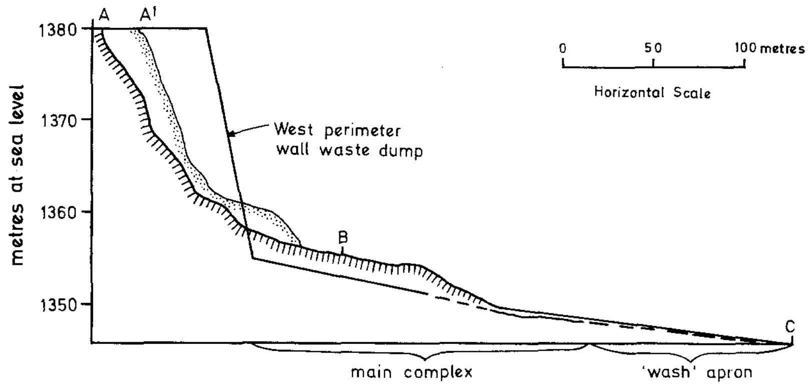

Figure 13. Long profile of flowslide.

the perimeter walls at low angles, particular attention should be paid to: (1) careful siting of dams, taking into account pedogeomorphological characteristics of potential dam sites; (2) regular monitoring of the engineering properties of tailings; (3) the relationship between shear strength, slope, and factor of safety (Donaldson 1960); (4) the position of the worst failure arc, to determine a satisfactory wall width; and (5) gaining the maximum shear strength from the material by keeping it as dry as possible. One cheap way of maintaining a low water content in the tailings is to restrict its use to the driest times of the year so that the sun and wind can promote high rates of evaporation (Okagbue 1987). Another way would be to restrict both the thickness of continuously deposited tailings and the time interval between periods of deposition.

In the absence of effective legislation, economics will tend to result in limited attention being paid to waste disposal in mining operations, particularly in developing countries such as Zimbabwe. The costly consequences of the failure of the Arcturus waste dump demonstrate that a better understanding of the causes, monitoring of the state of dump materials, knowledge of suitable remedial measures, and an appreciation of the likely consequences of dump failure would be not only highly desirable to avoid loss of life and property, but also cost-effective in the medium and long term.

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