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The abatement of pollution from abandoned gold-residue dams

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SYNOPSIS

The metropolitan area of the Witwatersrand has grown up around the Witwatersrand gold mines. Most of the mines have now been abandoned, but deposits of waste material remain and have been surrounded, and in some instances covered, by urban and industrial sprawl.

This paper describes the development of geotechnical measures for the abatement of air and water pollution from abandoned gold-residue dams in the Witwatersrand area. The measures include the stabilization of the surfaces of the dams to prevent wind and water erosion, the terracing of slopes to minimize erosion, and the construction of catchment walls and dams.

The measures were developed in terms of the set of guidelines for environmental protection adopted by the Chamber of Mines of South Africa in 1979.

SAMEVATTING

Die metropolitaanse gebied van die Witwatersrand het om die Witwatersrandse goudmyne gegroei. Die meeste van hierdie myne is tans verlate, maar die afsettings van afvalmateriaal is steeds daar en is deur wydlopige stedelike en industriële uitbreiding omring, en in sommige gevalle selfs daardeur bedek.

Hierdie referaat beskryf die ontwikkeling van geotegniese maatreëls vir die vermindering van lug- en waterbesoedeling afkomstig van verlate goudresidudamme in die Witwatersrand-gebied. Die maatreëls sluit in die stabilisering van die oppervlakte van die damme om wind- en watererosie te voorkom, die aanlê van terrasse teen hellings om erosie tot die minimum te beperk en die bou van keermure en opvangdamme.

Die maatreëls is ontwikkel in terme van die riglyne vir omgewingsbeskerming wat die Kamer van Mynwese van Suid-Afrika in 1979 aanvaar het.

Introduction

Unlike the United States of America and Canada, the Republic of South Africa has no legislation specifically directed towards the protection of the environment from the effects of mining. However, there are a number of statutes that affect the design, operation, and abandonment of residue deposits. These are the Atmospheric Pollution Prevention Act, the Health Act, the Mines and Works Act, the Soil Conservation Act, and the Water Act. To comply with the requirements of these Acts and to achieve effective environmental control over the tailings deposits owned by its members, the Chamber of Mines of South Africa in 1978 commissioned the authors to draft a comprehensive set of guidelines for the design, operation, and closure of tailings deposits[1]. These guidelines were revised in 1983.

After a brief description of the guidelines pertaining to the closure and aftercare of tailings deposits, this paper describes measures put into effect to bring a number of abandoned gold-residue dams in the Witwatersrand area into compliance with the guidelines. The measures incorporate a number of interesting features. First attempts at compliance with the guidelines were based on tried and tested, but conventional, geotechnology. Because of the characteristics of gold slimes, the measures met with mixed success. Apart from describing the protection measures, the paper recounts the difficulties experienced and points to solutions to these difficulties.

It became abundantly obvious during these investigations that no known maintenance-free solution exists to the abatement of pollution from abandoned dams. Maintenance efforts can be minimized by careful design and construction, but the onslaught of the elements ensures that maintenance and aftercare can never be eliminated. The present paper represents an amplification and updating of an earlier paper on the subject[2].

Guidelines for the Closure of Tailings Deposits

The guidelines for the closure of tailings deposits require, prior to the closure of any tailings deposit, an inspection to be made by a professional engineer, who should report on the existing state of the deposit and list all the actions that are needed to ensure that the deposit complies with the provisions of the guidelines. In addition to the state of the tailings deposit itself, the report should note the presence of any adjacent structures or development, and the extent to which they may be affected by abandonment of the deposit. Recommendations to minimize the impact of abandonment or of possible failures of the deposit after abandonment should also be made.

Erosion of Top Surfaces

The Atmospheric Pollution Prevention Act requires that steps be taken to prevent the dust from any waste deposit becoming a nuisance as a result of its dispersion in the atmosphere. Regulations under the Mines and Works Act require that any waste deposit be dealt with in a satisfactory manner so as to prevent the dissemination of dust or sand from it. The Water Act requires all rain water precipitated on a waste deposit to be retained on that deposit, together with any of the waste material that becomes displaced by the action of the precipitation. To comply with these requirements, the guidelines require the best practicable means to be adopted to

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prevent erosion of top surfaces. Among the measures that have been suggested for the control of wind erosion are the following:

(a) the establishment of vegetation on the top of a deposit, either by planting directly into the tailings material or by first covering the surface with a layer of top soil of suitable thickness (the cost of importing topsoil usually rules out the latter alternative);

(b) covering the top of the deposit with a suitable thickness of broken waste rock.

Water erosion on top surfaces, as well as the requirement that all precipitation should be held on the dam, has been taken care of by a system of crest walls that sub-divide the surface of the dam into a series of paddocks. The crest walls also prevent precipitation on the top of the dam from cascading down the outer slopes and increasing the potential for slope erosion. The height of the crest and division walls is designed hydrologically so that the walls contain the maximum probable precipitation over a period of twenty-four hours with a frequency of once in a hundred years*. A freeboard of 0,5 m is required throughout the system above the predicted maximum water level. In the Witwatersrand area, as the annual evaporation from a free-water surface vastly exceeds the annual precipitation, there is usually no need to decant water from the top surface of a deposit.

The paddocks must be carefully shaped to prevent water from standing near the crest wall of a dam. Numerous cases of piping erosion[3] have occurred when water has been held on the surface near to the crest of a dam.

The penstocks used to decant water during the operation of a residue dam are plugged when the dam is closed because they otherwise tend to collapse and provide channels for piping erosion. Old dams often have a number of steel delivery or penstock pipes buried in them at various positions. The steel has usually corroded away and the resulting void been enlarged by erosion. Such a collapsed pipe can result in severe erosion, as illustrated in Fig. 1.

In practice, water and wind erosion are inextricably linked. Material loosened and collected in low spots by water erosion in the wet season may be picked up by the wind and dispersed as dust during the dry season.

Erosion of Slopes

The slopes of old residue dams are extremely steep (usually 35° or more), and the protection of these steep slopes against erosion is very difficult. Sheet erosion of the slopes can be reduced, and gulley erosion virtually eliminated, by the provision of crest walls, which prevent water from cascading off the top and down the slopes of a residue deposit. Slopes can be protected against erosion by being covered with a layer of waste rock. However, this requires a large quantity of rock because the angle of repose of the rock seldom, if ever, equals the slope angle. Vegetation has also been used to provide protection against erosion. This practice has not proved entirely successful: some of the steeper slopes are gradually denuded of grass as erosion progresses.

Fig. 1—Severe erosion caused by the collapse of steel penstock and delivery pipes buried in the residue. Voids left by a number of such pipes are visible

Containment of Precipitation and Eroded Material

Run-off and eroded material are contained by a series of catchment paddocks round the perimeter of a dam. These paddocks are designed hydrologically to ensure a freeboard of at least 0,5 m above the maximum predicted water level, which is based on the average monthly rainfall for the area concerned less the gross mean evaporation for the area plus the maximum precipitation to be expected over a period of twenty-four hours for a frequency of once in a hundred years. To this is added an additional capacity to allow for the siltation resulting from erosion off the slopes. Little information exists on rates of siltation, but it appears that, in extreme cases, a single storm can silt a paddock to the extent of encroaching on the freeboard, whereas more usually the siltation capacity is a number of years. Regardless of the actual siltation rates, provision must always be made for the desiltation of paddocks, or raising of their walls, once the required freeboard is no longer adequate.

Control of Access

It has been found essential to prevent access to abandoned tailings deposits by members of the public,

*On the Highveld, this is equivalent to 250 mm of precipitation.

especially those seeking recreation by horseriding or cross-country motor cycling. The trails left by these activities often reduce the freeboard of paddock walls and result in gulley erosion. It is therefore considered essential that each abandoned tailings deposit should be surrounded by a properly constructed, well-maintained security fence. Cutting of fences, and even the theft of whole sections of fencing, gates, etc., are common. Hence, frequent inspection and maintenance are essential if unauthorized access is to be prevented.

Stability of Slopes

The retention of water on the top surface of a tailings deposit, as well as measures such as erosion protection by the covering of slopes with rock, may lead to instability of the slopes.

The guidelines require an investigation of potential slope instability as part of the closure report.

Fig. 2 shows diagrammatically some of the features mentioned above, while Fig. 3 shows the crest and dividing walls on the top of an abandoned dam. (Note the urban development surrounding the dam and the severe surface erosion in the foreground.)

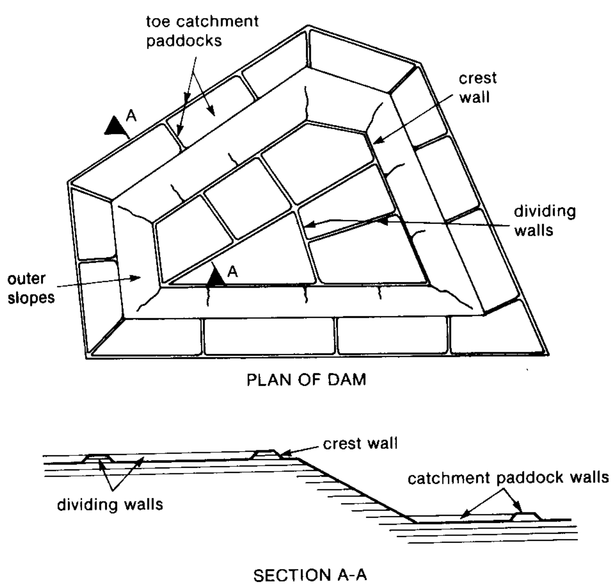

Fig. 2—Diagram showing measures taken to minimize water erosion of abandoned tailings dams

Geotechnical Developments in Pollution Abatement

A considerable number of abandoned gold-residue deposits exist within the Witwatersrand metropolitan area. The area has been almost completely built up, and the tailings deposits in question are surrounded by residential and industrial development. In most instances, the mining companies responsible for the tailings deposits are defunct, and the State has accepted responsibility for the rehabilitation of these dams to comply with the Chamber of Mines guidelines. To date, more than twelve dams have been rehabilitated. During the course of the work, a number of rehabilitation features were developed that differ from those envisaged when the guidelines were prepared. While the authors are convinced that the principles on which these measures were designed are correct, their implementation has not been completely successful, for a number of reasons. These measures and their shortcomings are described below, together with possible remedies.

Cement Stabilization of Top Surfaces

The Chamber of Mines considers the vegetating of the top surfaces of dams to be the best practicable means of stabilization, but this is subject to certain difficulties. The lack of success can be partly ascribed to the low pH of the surface material, and wind action may also undermine the root systems of the vegetation. Estimates by the Chamber of Mines at the time at which the guidelines were being prepared (1978) indicated that vegetating and the associated maintenance was costing upwards of R10 000 per hectare, while the cost of importing soil or waste rock was prohibitive, quite apart from the limited availability of these materials.

For these reasons, the chamber decided to stabilize the top surfaces of a number of dams on an experimental basis, using either slaked lime or Portland cement. Although the gold mine tailings that were being dealt with were highly acidic (pH of 3,5), Eades tests showed that relatively little stabilizer was required to raise the pH to a stable level of approximately 12,5. Fig. 4 shows typical results of Eades tests with ordinary Portland cement. It is also known that, although gold residue contains no clay minerals, it does contain a certain amount of amorphous silica, which can be expected at pH values above 12 to react with hydrated lime to form calcium silicates. The ability of slaked lime to stabilize residue sands had earlier been demonstrated when the surface of an access road to a sand dump near the Johannesburg market was stabilized. The surface remains in a remarkably good condition a decade and a half later, although the lime content of the material is very high. It was considered that stabilization should be even more effective with the gold slimes, which are finer.

In the case of cement stabilization, it was realized that sulphates contained in the residue might attack the products of cement hydration. However, at pH values above 12, the sulphates should be in the form of gypsum which, being sparingly soluble, is not as aggressive as other forms of sulphate. The use of sulphate-resisting cement could not be contemplated owing to its high cost. Because it is essential to keep the costs of rehabilitation as low as possible, and also because the object was the achievement of an erosion-resistant skin on the surfaces of the tailings deposits without the achievement of much strength, it was decided that experiments should be conducted with very small stabilizer contents.

Accordingly, a series of large test panels measuring 30 m in length by 5 m in width and stabilized to a depth of 150 mm were laid out using 2, 3, and 4 per cent by mass of both lime and cement. After the required quantity of stabilizer had been spread on the surface of the tailings deposit, it was mixed in by use of a rotary mixer. The moisture content was then adjusted to the optimum for compaction, and the panels were compacted by pneumatic rolling. The completed stabilized panels were

Fig. 3—Abandoned tailings dam provided with crest and dividing walls

moist-cured for six days by use of water sprays. The erosion resistance of the stabilized tailings surface was assessed with a portable Comet erosion tester, which directs a jet of water 0,8 mm in diameter at the surface from a distance of 25 mm. The pressure behind the jet is increased at a steady rate until the surface breaks up, the pressure at which the disruption occurs being recorded as a measure of the erosion resistance. The authors do not consider the Comet tester to be ideal for the measurement of the erosion resistance of residue surfaces. It gives a point measurement that, in their view, is not representative of the erosion resistance of a surface of large extent. Moreover, the relationship between the Comet index and actual rates of erosion has not yet been established.

Fig. 4 shows the measured erosion resistance plotted against percentage cement at times of 21 days, 42 days, and 2 years after stabilizing. It became apparent from these results that (at least in the early ages) cement was more effective than lime, and it was decided that the top surfaces of a number of tailings dams should be stabilized with cement (3 per cent) to a depth of 75 mm, and that the performance of these surfaces should be observed over a number of years. Twelve tailings deposits were stabilized in this way.

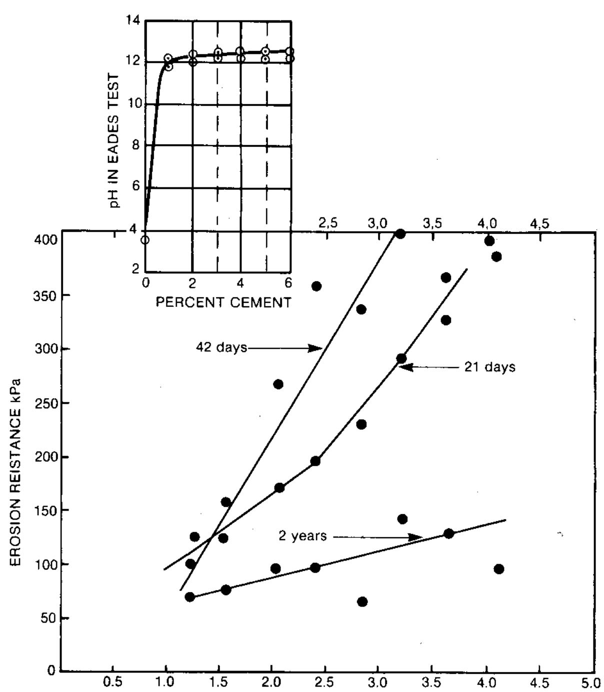

Fig. 4—Results of tests on the stabilization of gold residue with Portland cement

The test results in Fig. 4 show a considerable decrease in Comet readings after 2 years. The decrease can be attributed to at least two causes:

(i) the attack on the cement by sulphates proved to be more severe than expected; and

(ii) soluble salts, drawn to the surface by evaporation gradients and crystallizing out at the surface, disrupted material at the surface.

These effects may reinforce each other. Rising salts and acid may result in a lowering of pH and, hence, an acceleration of the attack by sulphates.

The Comet resistance of lime-stabilized panels showed a similar decrease after two years to that for cement-stabilized panels. As attack by sulphates can be ruled out in the former panels, disruption by salt crystallization and acid attack appear to be the major causes of the deterioration.

A visual assessment of the surface condition of twelve dams that had been stabilized with cement shows that similar deterioration has occurred there. 'Fluffy', raised surface crusts resulting from salt crystallization are much in evidence. The surface finish appears to be more important in maintaining erosion resistance than was previously appreciated. The smooth, almost-glazed surface

Fig. 5—Appearance of test panels of stabilized gold residue three years after laying

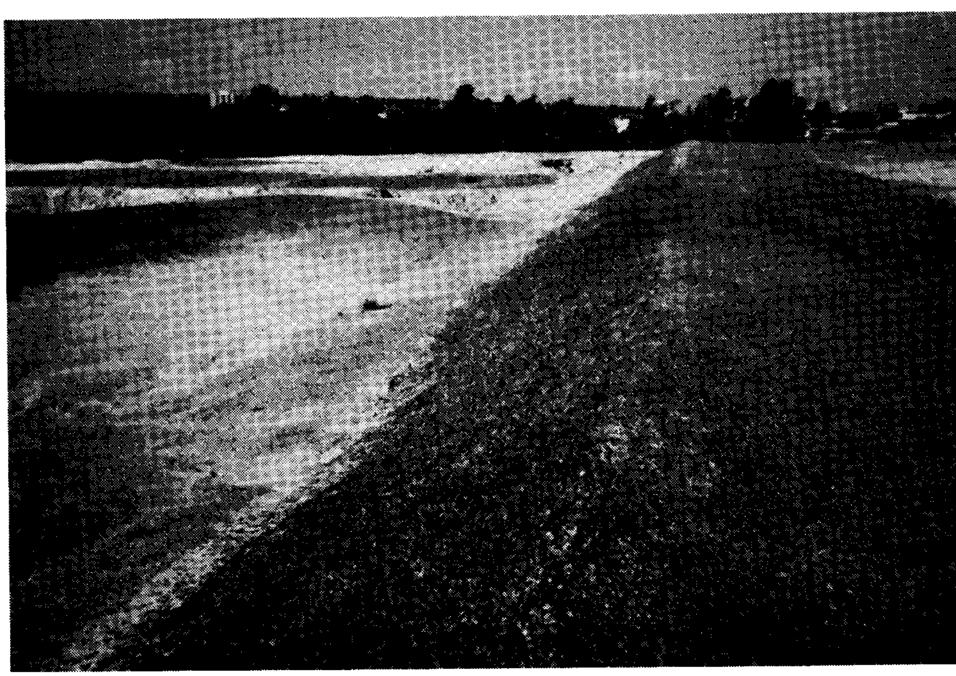

Fig. 6—Appearance of paddock walls protected against wind and water erosion by a single layer of 19 mm of crushed-stone chips. Photograph taken two years after laying

produced by a pneumatic compactor appears to deteriorate less than the rough, indented surface left by a tamping compactor. Fig. 5 shows the surfaces of the original test panels three years after being laid. The unstabilized strips between the panels show up as a result of their lighter colour. Even though the Comet resistance of the panels is low, they now stand proud of their surroundings, showing that they are more erosion-resistant than the unstabilized surfaces.

The effect of the surface deterioration is that loosened material is washed into the low spots of the paddocks during the wet season. Although this material crusts over as it dries, it is potentially available for dispersion by wind during the dry season if the crust is disturbed.

Successful alternatives to stabilization with cement or lime are not obvious. Potentially the most successful alternative is a process that was used for the stabilization of travelling sand dunes outside Walvis Bay. There, a large dune that threatened to move into the town was successfully halted after its surface had been covered with power-station cinders. The layer was thin, only one particle thick, but successfully prevented the wind from picking up the underlying sand, thus halting the movement of the dune. This technique was tried on the slopes of the paddock walls of one of the twelve treated dams. There, a single-particle layer of 19 mm crushed-stone chips was spread on the slopes. Two years later, the treatment appears to have been very successful, with little evidence of the displacement of the stone or the underlying slimes by water or wind. Fig. 6 shows the appearance of this treatment two years after its application.

Grassing of Residue Deposits

Greig[4], from a study of the vegetation established on 27 slimes dams in the Central Witwatersrand area, concluded that, in general, the ratio of grass cover to slime exposure is 1 to 2 or greater, and that this cover ratio approaches that of the natural veld. He notes that there is no evidence that wind or water erosion from horizontal surfaces grassed up to fifteen years ago is a problem. The cost per hectare of grassing, leaching, and maintaining the top of a slimes dam where only the perimeter and contour wall are leached varied at that time from R3836 for a 40 ha site to R9321 for a 4 ha site. When the whole surface was leached, these costs increased to R10 024 and R14 859 respectively.

The average cost of cement stabilization at the twelve deposits so treated varied from R5000 to R8000 per hectare.Thus, the costs for the two types of treatment were similar at that time.

Terracing of Slopes

At a number of locations, the authors had observed that, where vertical faces had been cut in the slopes of tailings deposits; these faces appeared to be unaffected by erosion. The same phenomenon has been observed in natural vertical slopes. It was therefore decided that an experiment should be carried out in which the slope of a tailings deposit is terraced into a series of vertical faces separated by approximately horizontal steps or berms. To retain the precipitation, the berms are sloped back towards the dam, and are sub-divided at intervals by cross-walls so that all the precipitation on the berms is held and allowed to evaporate. Fig. 7 gives a design section of a terraced slope, and Fig. 8 shows an experimental terraced slope three years after the terraces were cut.

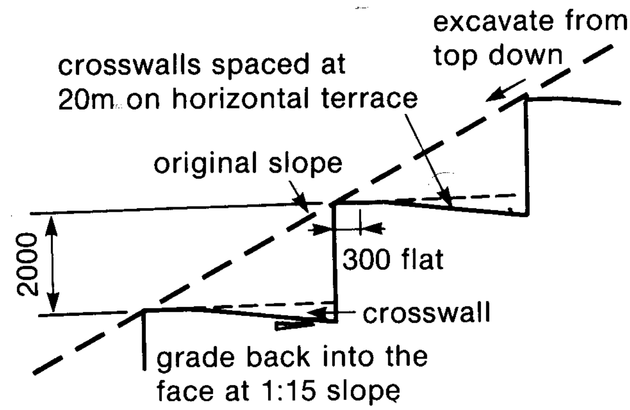

Fig. 7—Design section for terraced slope shown in Fig. 8

The state of these terraces is extremely good. In all cases very little erosion of the vertical faces has occurred, and in many cases a hard, dry crust has formed on the vertical face. Some eroded slime has accumulated in the paddocks formed by the back-sloping benches, and in a few instances exceptionally heavy rain has resulted in

Fig. 8—Experimental terraced slope three years after the terraces were cut

Fig. 9—Vertical face of a terrace taken three years after the terrace was cut

overtopping of the benches. Fig. 9 is a close-up view of the vertical face of a terrace, showing the excellent condition of the surface.

On the basis of the observed behaviour of the terraces, it is concluded that terracing is a very effective way of reducing erosion from the slopes of residue dams.

Filter Dams

Run-off from tailings deposits that is polluted by material eroded from the deposit is retained at strategic positions by dams designed to retain the silt content of the run-off while allowing clear water to seep away. Although this water is clear, it contains dissolved solids, and only one component of pollution is removed. Fig. 10 shows typical details of such a filter dam. The upstream slope of the dam is underlain by a filter blanket that acts as a collection drain and filter for the polluted water retained behind the dam. After entering the filter blanket, the water gravitates to the central collecter drain and is allowed to escape downstream. Fig. 11 shows one of these dams, together with its emergency spillway, protected from erosion by means of a gabion mattress.

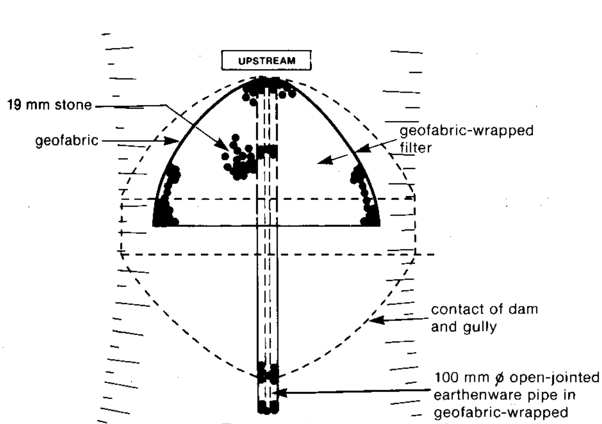

Fig. 10—Plan showing details of a filter dam

Fig. 11—Appearance of a filter dam with an emergency spillway

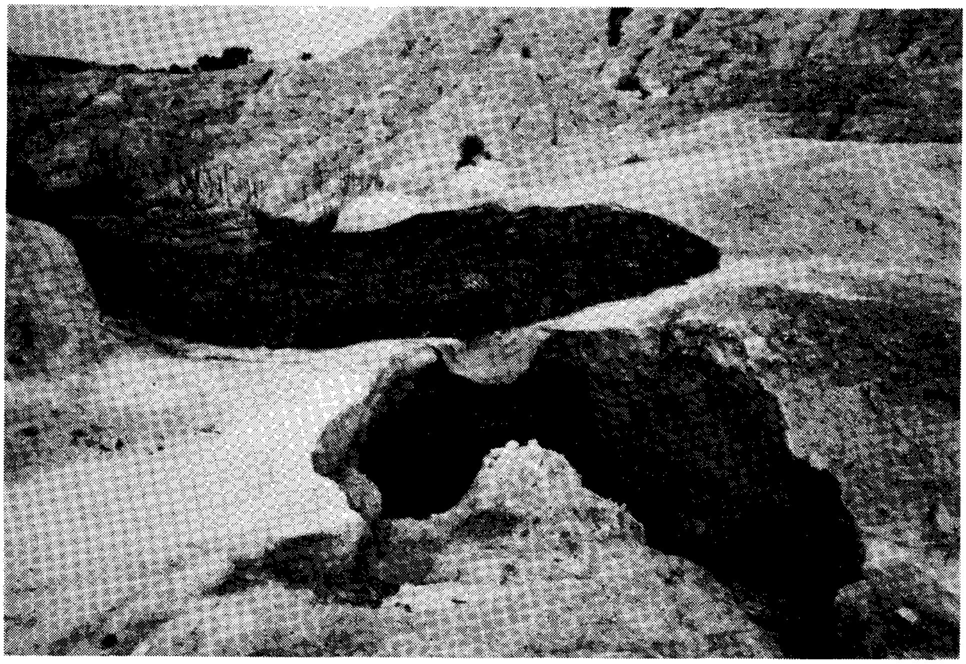

Fig. 12—Failure by piping erosion of a filter dam constructed of gold slimes and built on a slimes foundation

No problems have been experienced with these dams where it was possible for them to be constructed of natural soil. However, when constructed of gold slimes, especially when built on a foundation of slimes, numerous problems have been experienced with piping erosion. Erosion pipes have formed in the slimes under the dams, at the contact between the dam and the abutment, and at the interface between the embankment material and the geofabric-wrapped filter. Laboratory tests have shown that the erodibility of slimes is much reduced if the pH is raised to above 12 and the material cemented by the addition of lime. Future embankments should be constructed of lime-treated material. In addition, the embankment must be keyed into its abutments and foundation to lengthen the seepage path of potential pipes. Fig. 12 shows typical piping-erosion damage to a filter dam constructed of gold slimes and having slimes abutments.

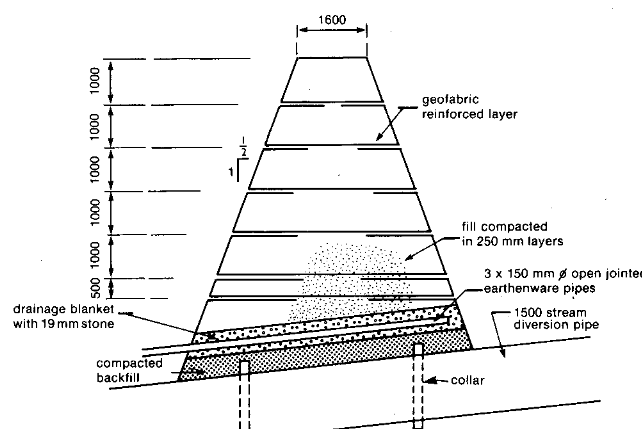

Fig. 13—Section through geofabric-reinforced gravity-section filter dam

Fabric-reinforced or Cement-stabilized Dams

In rehabilation work on tailings dams, it often occurs that a narrow valley with a limited capacity has to be crossed by a filter dam. If a conventional dam of compacted tailings is constructed, too much of the capacity of the valley is occupied by the filter-dam embankment. In situations like this, it is advantageous for the dams to have steeper slopes and, in fact, a gravity section is ideal in such instances. A gravity-section dam can be built either of cement-stabilized tailings or of fabric-reinforced tailings.

Fig. 13 shows the design of a fabric-reinforced gravity-section embankment. This embankment has been built and is illustrated by Fig. 14. The dam spans a valley between two tailings deposits down which a natural stream flows. The stream has been by-passed through a culvert that runs down the valley and under the gravity-section dam, while the gravity-section dam itself acts as a filter dam for precipitation running off the slopes of the tailings dams on either side of the valley.

When first filled, an erosion pipe large enough for a man to crawl through formed through the lower part of the dam abutment. The entry to the pipe is clearly visible in Fig. 14. The fabric-wrapped embankment bridged over the pipe with some deformation but was otherwise undamaged, as the photograph shows. The failure was repaired by the placing of a filter blanket over the hole on the upstream side and plugging of the hole with compacted tailings from the downstream side. The authors consider that any less flexible construction would have failed completely.

Aftercare of Tailings Dams

It must be recognized that the environmental protection measures specified by the guidelines of the Chamber of Mines require continual inspection and maintenance if they are to remain effective. There is no maintenance-free solution to the environmental protection of tailings dams.

(1) Any erosion damage to crest or dividing walls, filter dams, or catchment paddocks must be repaired.

(2) Catchment paddocks and filter dams must be desilted periodically, or must be raised in order to maintain their capacity.

(3) Continual inspection must take place lest problems of slope stability, the collapse of old drainage conduits, or penstock outfalls and similar degeneration should cause breaches in the anti-pollution defences of the protected dam.

(4) Access by animals and the public must be prevented. This last requirement contains something of a sociological problem. The existence of the large, abandoned, inaccessible areas represented by environmentally protected tailings dams within urban environments makes them attractive, not only as playgrounds for early-teenage children, but also as hiding places for the lawless element of the community.

(5) Dumping of litter adjacent to abandoned tailings dams is another social problem to which there appears to be no solution at present but periodic clean-ups.

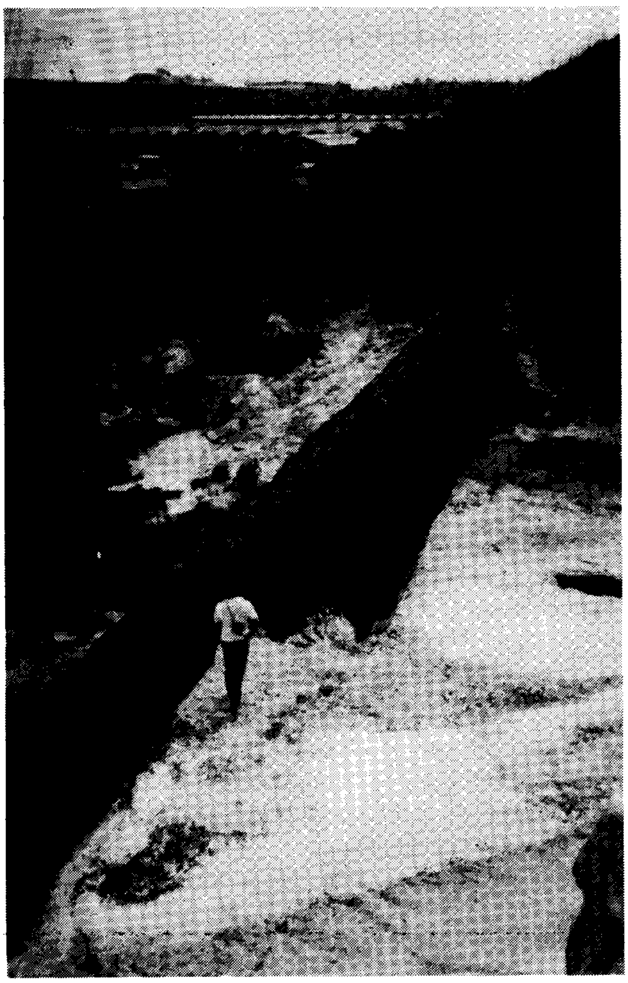

Fig. 14—Geofabric-reinforced dam after the formation of a pipe through the foundation. The entrance to the pipe can be seen to the right of the dam

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References

1. CHAMBER OF MINES OF SOUTH AFRICA. *Guidelines for environmental protection*, vol. 1/1979, *The design, operation and closure of residue deposits*. Johannesburg, the Chamber, 1979.
2. BLIGHT, G. E., REA, C. E., CALDWELL, J. A., and DAVIDSON, K. W. Environmental protection of abandoned tailings dams. *Proceedings, 10th International Conference on Soil Mechanics and Foundation Engineering*, Stockholm, 1981. vol. 2, pp. 303–308.
3. BLIGHT, G. E., and BENTEL, G. M. The behaviour of mine tailings during hydraulic deposition. *J. S. Afr. Inst. Min. Metall.*, vol. 83, no. 4. 1983. pp. 73–88.
4. GREIG, J. A. A review of grassing as a means of minimizing air and water pollution from sand dumps and slimes dams. Johannesburg, Chamber of Mines of South Africa, *Research Report no. 40/81*. 1981.