Slimes disposal at South African gold mines

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SYNOPSIS

The soil mechanics, civil engineering, and environmental considerations applicable to the construction of slimes dams on the Witwatersrand gold mines are discussed. It is concluded that, though the procedures used in the construction of dam embankments do not accord with the best possible practice, they are entirely adequate in current local circumstances, provided that proper precautions are taken to ensure that the wall foundations are sufficiently permeable and strong, and that the dams are protected against erosion. If current trends towards larger mining and metallurgical complexes continue, it may become necessary to build larger, higher dams, and to adopt slimes embankment-building practices that are inherently more reliable.

SAMEVATTING

Die grondmeganika-, siviele-ingenieurs- en omgewingsfaktore wat op die bou van slykdamme op die Witwatersrandse goudmyne van toepassing is, word bespreek. Daar word tot die slotsom gekom dat, hoewel die metodes waarvolgens die damwalle gebou word nie met die beste moontlike gebruik ooreenstem nie, hulle in die huidige plaaslike omstandighede heeltemal toereikend is, mits behoorlike voorsorgmaatreëls getref word om te verseker dat die muurfondamente voldoende deurtrekbaar en sterk is en dat die damme teen erosie beskerm word. As die huidige tendens tot groter mynbou- en metallurgiese komplekse voortduur, kan dit nodig word om groter, hoër damme te bou en om slykwalboumetodes te volg wat inherent betroubaarder is.

The rapidly rising world demand for minerals, and the need to exploit progressively larger but lower-grade deposits in order to satisfy demand, have led to mining operations being conducted on a truly massive scale, with many metalliferous mines achieving milling rates approaching 100 000 tons per day. Most of these mines are open-cast operations that face not only the problem of disposing of enormous volumes of overburden material both safely and acceptably, but often also of disposing of almost the whole of their milled tonnage as tailings. That there is mounting public concern over the stability and the environmental effects of these very large deposits of mine wastes, and over the possible spoliation by mining of millions of hectares of land, is therefore not surprising, particularly in the light of predictions that the annual production of minerals may increase tenfold by the turn of the century.

Compared with the largest metalliferous mines, individual South African gold mines are modest operations that mill some five to ten thousand tons of ore daily. The typical slimes dams serving these mines each occupy a plan area of 50 ha, rise to an average height of 15 to 20 m, a maximum height of 30 m at the toe-wall, and, when complete, contain about 25 million tonnes of milled tailings. Though average Witwatersrand slimes dams therefore are not exceptionally large by comparison with mine-waste deposits created by the open-cast 'super mines', they certainly are large structures when judged by other standards. For example, the major earth irrigation-dam wall of the Sterkfontein Dam, which will impound half as much water as Vaal Dam, will involve the placement of 12 to 13 million tonnes of material, i.e., only about half the quantity of material contained in an average-sized gold-mine slimes dam. The magnitude of mining operations and of slimes disposal on the Witwatersrand gold fields immediately becomes more impressive when the total production of the forty-odd mines situated along 300 km of the perimeter of the Witwatersrand basin is considered. These mines together mill about 250 000 tonnes of ore daily. The total area under slimes is about 15 000 ha, which provides for the disposal of no less than 3 hundred million tonnes of slimes!

This huge tonnage of milled tailings is situated in a relatively densely populated region, served by and draining principally to only one river, the Vaal, so that the need to ensure that the slimes dams are not only functional but that they are also sufficiently stable to create no 'environmental' difficulties, and even that they are acceptable in terms of aesthetic considerations, is clearly important.

Functional considerations governing the selection of sites for slime disposal and methods of slimes dam construction on the Witwatersrand gold mines have recently been summarized by Adamson[1]. Where possible, dams are sited on ground of good permeability to facilitate drainage and hence to improve their stability; on gently-sloping 'hillside' terrain so as to achieve maximum slime disposal per unit area of land; and as close to, and generally at a lower elevation than, reduction works in order to minimize the costs of slime transport. The area allocated by a mine for slimes disposal is, at any given time, generally arranged to be just sufficient to accommodate the slimes at an acceptably low rate of rise of the dam. Slimes dams also serve as 'balancing tanks' in the recycling of process water to reduction works and for the evaporative disposal of excess water.

The method of slimes-dam construction involves, initially, the excavation of toe trenches, the installation of penstocks, and, where the dam foundation is impermeable, the installation of drains[2]. Slime from one or perhaps two discharge points is allowed to gravitate to slimes races at the outer wall, or, when these are full, to the internal

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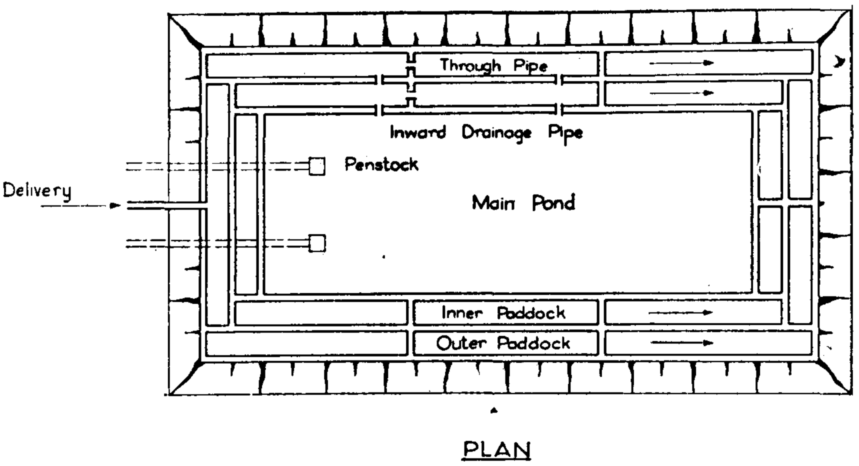

Fig. 1—Slimes-dam paddock system (from Adamson[1])

pond area. Wall building is done by progressive manual packing of slime at the external and internal edges of the outer walls so as to raise them by about 0,25 m at a time. The external edges of the walls are stepped back at vertical intervals of about 0,5 m to establish an overall slope of 30° to 35°. Surplus water is drawn from the internal pond area through penstocks. The general arrangements, including toe dams for the retention of storm water, are shown in Figs. 1 to 3.

These methods have evolved over a period of three-quarters of a century. As currently operated they are relatively cheap, absorb only a small proportion of the capital and working costs of mining, and are functionally adequate. There is thus currently little incentive to depart significantly from established practice unless this should become necessary for other reasons such as the need to improve the structural stability of dams, to reduce any environmental nuisance that they may create, or, perhaps, to reduce even further the manual labour involved in their construction.

Failures of earth structures, including tailings dams, are not uncommon, and some (like the El Cobre tailing dam in Chile in 1965[3], and the Aberfan Colliery slack heap in the United Kingdom in 1966[4]) are catastrophic. Slimes-dam failures on a similarly disastrous scale have not occurred in South Africa, but tailings-dam failures of less severity have, as elsewhere[5], been commonplace, so that slimes dams of any substantial height and age showing no evidence of some failure, or of incipient failure that has required remedial measures, are the exception rather than the rule.

Massive failures of earth structures can occur owing to shear failures in walls or foundations, to liquefactions, to overtopping by floodwaters, or to erosion of walls[5]. The mechanisms of shear failure of the slopes and foundations of earth structures have been the subject of considerable study since the classic investigations of Casagrande[6] and others[7] were first reported, and are now well understood[8, 9]. Amongst the earlier of such investigations relating particularly to mine tailing dams was that of Donaldson[10], who from 1953 to 1959 made a detailed examination of the stability of South African gold-mine slimes dams. Donaldson's results indicate that the shear strength of slimes, after they have been consolidated by drying, is generally sufficient to ensure that these dams are stable within the limits of height, rate of rise, and slope angle to which they are customarily built, provided that the walls are not impaired by erosion. This proviso will be considered below. Blight[11] has subsequently confirmed the above conclusions, and has defined more closely the structural criteria governing the stability of completed slimes dams (see Figs. 4 and 5).

An important assumption made in arriving at the general assessment that gold-mine slimes dams are structurally stable is that the shear strength of the material of the walls, if not of the bulk of the dams, is in fact that of dry consolidated slimes. While this assumption is generally valid, situations can, and do, arise principally where dams are constructed on impervious foundations, when water seeps into the wall so that pore-water pressure is increased and the shear strength of the wall material is greatly reduced. The risk of such a situation developing in South African gold-mine slimes dams is significantly enhanced by the use of what is effectively an 'upstream' method of dam construction (see Fig. 6). This method is less reliable than either the 'downstream' or the 'centreline' methods (see Fig. 6) because, with increasing height, the phreatic surface (i.e., the upper limit of the seepage zone in the dam) tends to move towards the toe. At the same time, the critical failure surface tends to move towards the wetter,

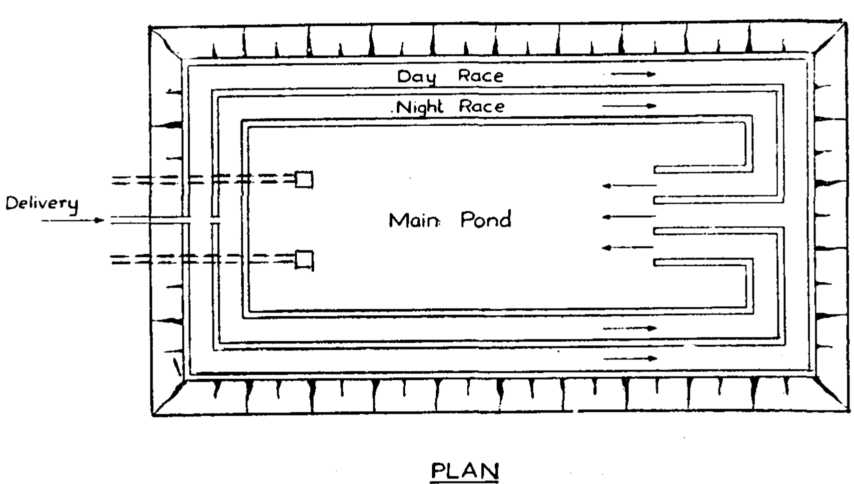

Fig. 2—Slimes-dam race system (from Adamson[1])

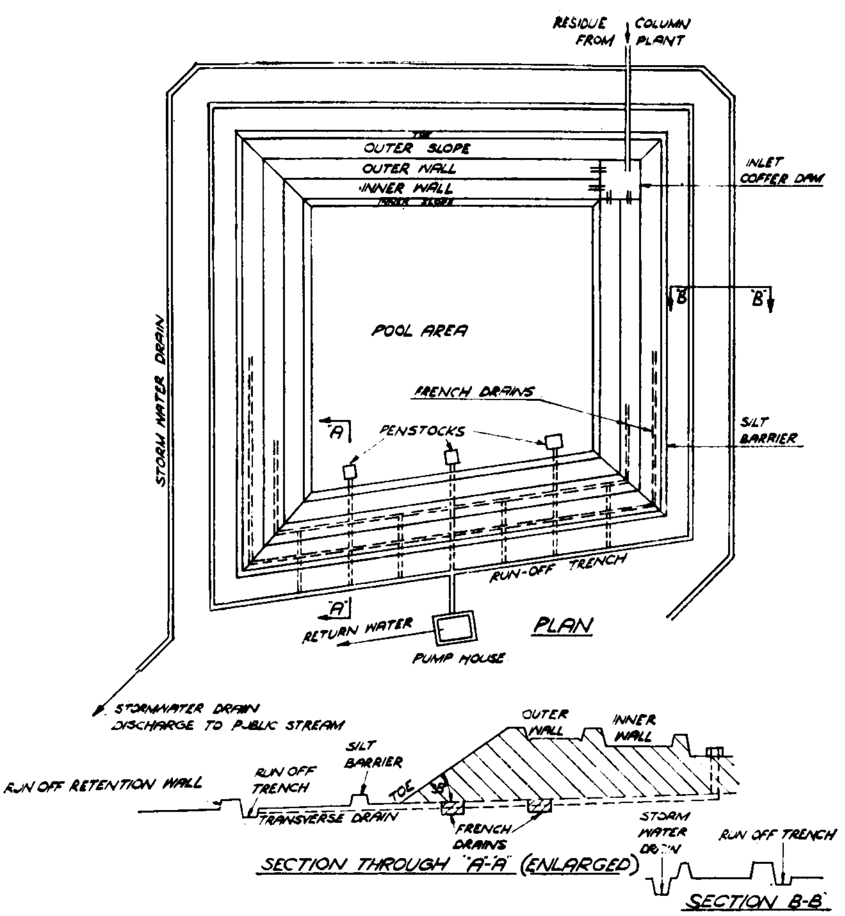

Fig. 3—Plan of a slimes dam and section of a wall (from Adamson[1])

less well-consolidated material of lower shear strength in the pond area[8]. The movement of seepage water into the walls can result in massive shear failures in the slopes. The closer proximity of unconsolidated saturated pond material to the outer slope, and the inability of the weakened wall to support this material especially when, for instance, it is accelerated laterally by earth tremors, can also result in liquefaction failures. Donaldson[10] has reported the occurrence of both shear and liquefaction failures of slimes dams.

Seepage through toe walls of dams built on impervious foundations, and consequent erosion and undercutting of such walls, are additional hazards that can lead to massive failures[10].

Clearly, the role of seepage water in determining the stability of slimes dams is critical. Piezometric determinations of the level of seepage water (i.e., the phreatic surface), particularly in the walls of dams, is thus essential in all cases where the stability of a tailings dam is in doubt[9]. The possibility of shear or liquefaction failures can be avoided in existing dams of doubtful stability by the construction of underdrained buttress walls[10], and in new dams by ensuring before construction commences that the foundations are adequately permeable and strong. There are well-established methods for the determination of the permeability and load-bearing capacity of foundation soils[9], and for the construction of underdrains[10]. It is important to note that a smaller angle of slope will not significantly improve the stability of dams built on impervious foundations.

In summary, therefore, because gold on the Witwatersrand is obtained from narrow, extensive reefs, mining activity is necessarily widely dispersed so that the huge aggregate tonnage mined is milled and processed at many points, and tailings are accordingly disposed of to many dams. Individual slimes dams, generally designed conveniently to accommodate the current tailings output of a single reduction works at an acceptable rate of rise, are not usually therefore inordinately large in area, and are usually abandoned before their height exceeds 30 to 40 m. Reasons for the abandonment include diminished availability of deposition area, increases in slime pumping costs, and the availability of alternative deposition area sufficiently close to reduction works. Slimes dams of these dimensions can be built to acceptable standards of bulk stability by the essentially simple 'upstream' procedures used by local gold mines, provided that adequate attention is given to underdrainage requirements.

The trend towards the consolidation of mines, to larger reduction works, and probably, therefore, to the building of larger and higher slimes dams may in due course lead to the adoption of dam-building practices involving the segregation of coarser slimes fractions by spigoting or cycloning for use in tailings-embankment construction, and the adoption of 'downstream' methods of building embankments, as is done elsewhere in the building of very large tailings dams.

Many failures of various degrees of severity are caused by surface erosion, even in dams that have been well designed to adequate factors of safety. Failures can, for instance, be caused by leaks in the outer embankments of walls during construction that subsequently lead to 'piping' by overfilling of slimes races on walls, by the careless grading of final surfaces of dams towards, instead of away from, the walls. The most usual failures, however, are caused by the erosion of slimes-dam walls and of the tops of completed dams by wind and rainwater, which gives rise to problems of instability, and to air and water pollution.

It has been estimated that on the Witwatersrand, which has a rainfall of 700 mm per annum, the annual loss by rainwater erosion of material from the surface of slimes walls, 30 to 40 m high and having slopes of about 35°, is a layer of average thickness of about 0,10 m. However, the rate of erosion is not uniform over the surface of a wall.

The methods of construction of

South African gold-mine slimes dams provide for relatively little segregation of fines from the wall material, which is therefore particularly erodable and impermeable, compared with the material commonly used elsewhere in the construction of tailings embankments. The rate of erosion of deposited slimes is a function, within limits, of the volume, as well as of the velocity, of the water flowing over its surface. Since, in the case of impermeable slimes, the volume of rainwater flowing over the surface of a slimes-dam wall at any level is the accumulated volume of water precipitated at and above that level, the rate of erosion varies inversely with elevation above ground. The loss of material from the side of a slimes wall is therefore significantly greater towards the bottom of the wall than it is towards the top, so that rainwater erosion can be expected to result in the steepening of slimes-dam slopes, which in turn leads to increasing instability. Thus, for the 30 m high 35° slope considered earlier, if the rate of erosion of the wall varies on average between 0,05 m per annum at the top and 0,15 m at the base, the wall will steepen from 35° to 40° in about 70 years (or from 30° to 35° in 90 years in the case of a 30° slope). The rate of wall steepening, particularly of steep slopes (i.e., slopes of more than 30°), is in practice often increased by a further degree of non-uniformity of surface erosion resulting from the stepped formation of the outer surfaces of walls. The concentration of rainwater spillage at a discrete number of points along each step and its near-vertical fall to points at the back of the next lower step accelerate formation of the vertical erosion gullies that are so common a feature on dams. With increased rainwater run-off flow across the lower surfaces of the wall, gully formation increases in depth and severity (see Fig. 7). There is no quantitative information available on the extent to which the 'undercutting' of walls by this process increases the erosion rate differential between the upper and lower levels of slimes-dam walls, but there is no lack of qualitative information that the effect is very significant. There is some evidence that a hard layer, which often forms on slimes surfaces owing to the cementing of the material by iron oxides produced by pyrite oxidation, may reduce erosion rates. However, the cemented layer, if present at all, is usually thin and discontinuous, and easily lifted by wind or water. It is possible that the presence of cemented layers that would be more easily lifted by increased flow at lower levels may actually increase the erosion rate differential.

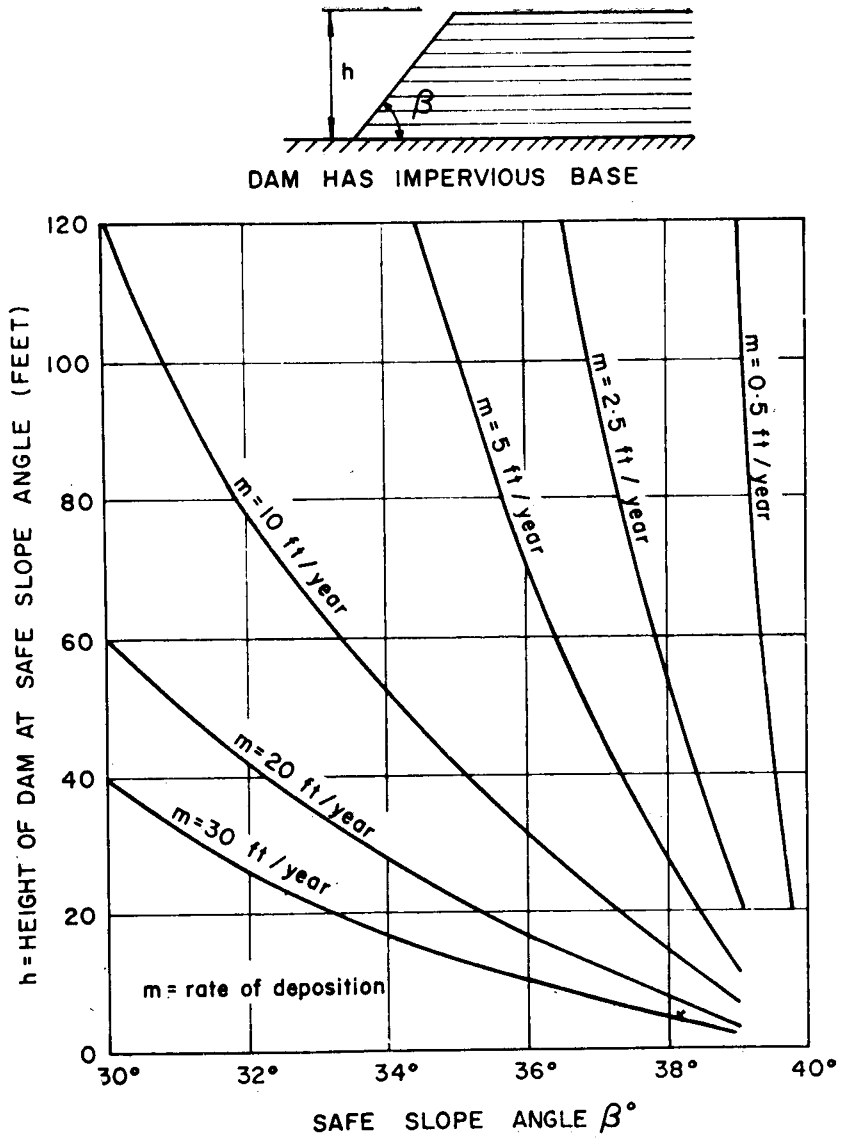

Fig. 4—Design graph for slimes dams having an impervious base (from Blight[11])

Though the steepening of slimes-dam walls by erosion processes is very slow, it clearly can, if left unchecked, result ultimately in the development of dangerous slope instability.

The erosion of slimes dams not only creates potential problems of slope instability in the longer term, but also gives rise to immediate problems of air and river pollution.

The rainwater erosion of completed slimes-dam walls at rates of the order of 0,1 m per annum creates no obvious visual impression of significant annual loss. However, in a typical unprotected dam 50 ha in area and of an average height of 20 m, the loss of wall material may be some 30 000 tonnes per annum. Extrapolation of this assessed quantity to the approximately 300 gold-mine slimes dams, without allowance for any control measures, suggests a huge current annual loss by erosion of embankments of the order of millions of tonnes of slimes. Slumps or breaks in walls can, of course, add dramatically to the total, as can rainwater erosion of material from the tops, particularly, of completed dams if no proper arrangements have been made to establish flat surface grades and either to impound rainwater or to drain off such water through properly constructed and maintained penstocks.

The loss of material from dry slimes-dam surfaces is more generally caused by wind rather than by rainwater erosion. No reliable data are available on the rate of wind erosion of slimes-dam tops, but it seems that this may be of the order of tens of millimetres (i.e., hundreds of tonnes per hectare per annum), giving rise to considerable dust pollution in the vicinity of slimes dams.

The finely milled but inert quartzitic silt of which most of the material eroded from slimes dams consists, if not trapped in specially provided impoundments, is generally redeposited on land in the immediate vicinity of the dams, or, if carried to rivers, is redeposited in the river beds within a few kilometres. The inert silt, though unsightly, is not a significant pollutant. However, significant pollution of streams can be created by the soluble mineral matter associated with slimes. The main contaminants concerned are calcium and magnesium sulphates, together with smaller concentrations of the sulphates and chlorides of sodium and potassium and, sometimes, of iron and aluminium. The small concentrations of other metal ions in slimes-dam drainage are usually of little significance, though in some instances low but unacceptable concentrations of highly undesirable contaminants such as boron may be present.

Soluble calcium and magnesium minerals are not normally present in the gold ore as mined. However, lime added to the milled slime in the course of metallurgical processing and alkali earth minerals in the ore are converted to soluble alkali earth sulphates by the acid iron sulphate formed at and near slimes surfaces by bacterial and/or atmospheric oxidation of the iron pyrites[12], which constitutes some 3 per cent of the mineral content of Witwatersrand gold ores. Some 5 per cent of the material eroded from slimes-dam walls and from the tops of dams is therefore potentially soluble. The available amount of calcium sulphate, which has a limited solubility of about 3 g/l, is generally well in excess of the amount that can be dissolved by rainwater precipitating directly onto a dam, so that the drainage from unprotected dams is always saturated with calcium sulphate. On the Witwatersrand (700 mm annual rainfall), the amount of calcium sulphate removed directly, in solution, by rainwater can be calculated to be about 20 tonnes per hectare of dam underwalls per annum. The overall dissolution of calcium sulphate from unprotected dams has been determined in field measurements to be 10 tonnes per hectare of dam per annum[13]. Excess undissolved sulphates are redeposited in the vicinity of slimes dams and in river beds, together with the inert quartzitic silts, and are subsequently leached from these deposits so that dry-weather stream flows in the vicinity of dams can also be contaminated by calcium and other sulphates in solution.

To avoid the problems of slope instability and of stream pollution created by slimes-dam erosion, it is necessary to reduce considerably the velocity of rainwater run-off from walls by reducing slope angles, by finishing slopes to a smooth instead of a stepped surface, and by planting vegetation. Vegetation is also neces-

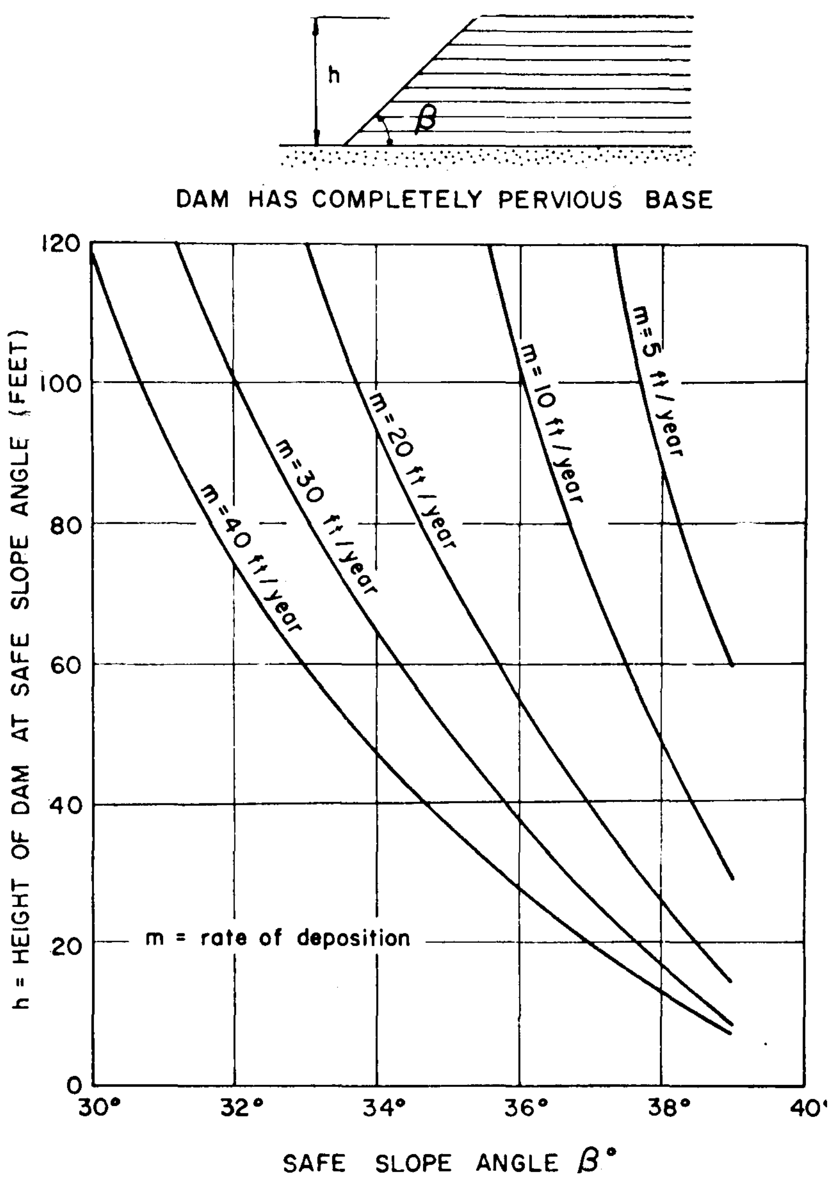

Fig. 5—Design graph for slimes dams having a pervious base (from Blight[11])

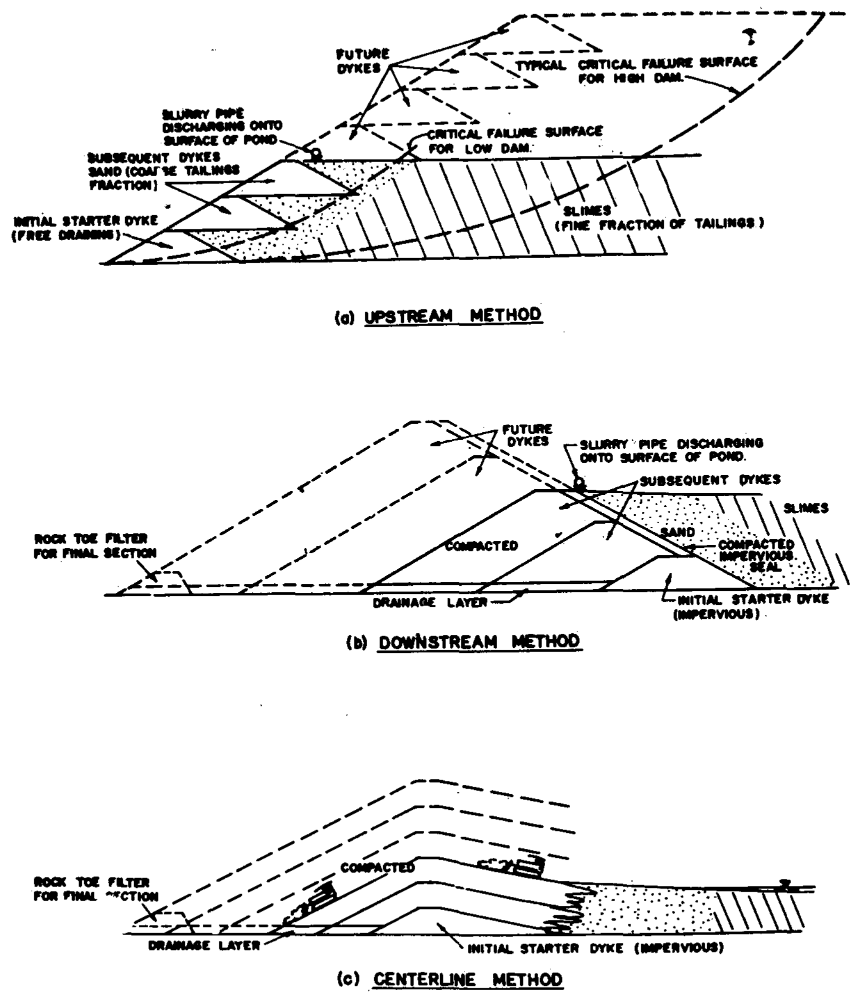

Fig. 6—Methods of tailing-dam construction (from Brawner and Campbell[8])

sary on the tops of dams to control wind erosion and, consequently, air pollution by dust.

The establishment of vegetation on slimes surfaces has been shown[15] to be possible if attention is given, firstly, to ensuring the removal of acidity produced by pyrite oxidation within the one or two metres from the slimes surface to which air has access[12, 15], and, secondly, to retention of the leached material. The most effective means of removing such acidity is to leach the acid into the alkaline material within the dam (see Figs. 8 and 9). For maximum effectiveness, leaching conditions must be maintained as continuously as possible, in order to avoid evaporative conditions during which acidity rises to the slimes surface. Since the permeability of slimes is low—from about 20 to 40 mm per day—continuous leaching is required to be maintained for periods of six weeks or more, and is best effected at low rates of water application by fine sprays. Methods have been developed for the spray leaching of slimes surfaces, for the retention of leached slime by mulching and by the construction of reed windbreaks to protect the material from wind and water erosion and from exposure to unoxidized slime until vegetation is established, and for the seeding and fertilizing of prepared slimes surfaces. These procedures are applied on a large scale by the Vegetation Unit of the Chamber of Mines, and, independently, by mines. The procedures are among the cheapest and most effective that have been developed anywhere[16].

Some difficulty is experienced in the application of the procedures on embankments having a slope of more than 30°, owing probably to less effective leaching and to less effective reduction of rainwater run-off velocity on such slopes, which once again emphasizes the desirability of reducing the angles of slope of slimes embankments.

The foregoing review leads to the following conclusions.

(1) The dispersal of Witwatersrand gold mining has led to slimes disposal on many moderately-sized slimes dams and has therefore led to a relatively large ratio of wall volume to bulk volume. The finely milled gold slimes contain insufficient material of large particle size to provide 'sands' for the construction of the greater wall lengths involved. A simple and cheap upstream method of dam construction is used because, though there is some segregation of sands at the walls, the material of the walls and of the bulk of the dams differs so little in physical properties that the stability of the

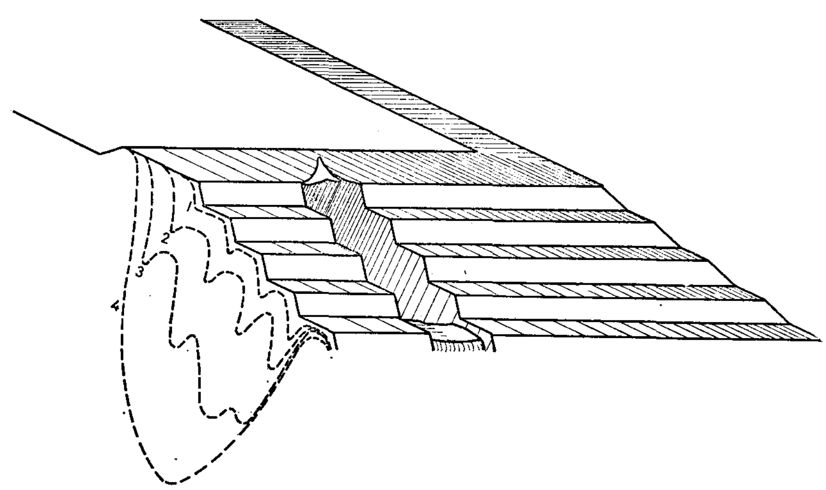

Fig. 7—Successive stages of erosion on a slimes-dam wall

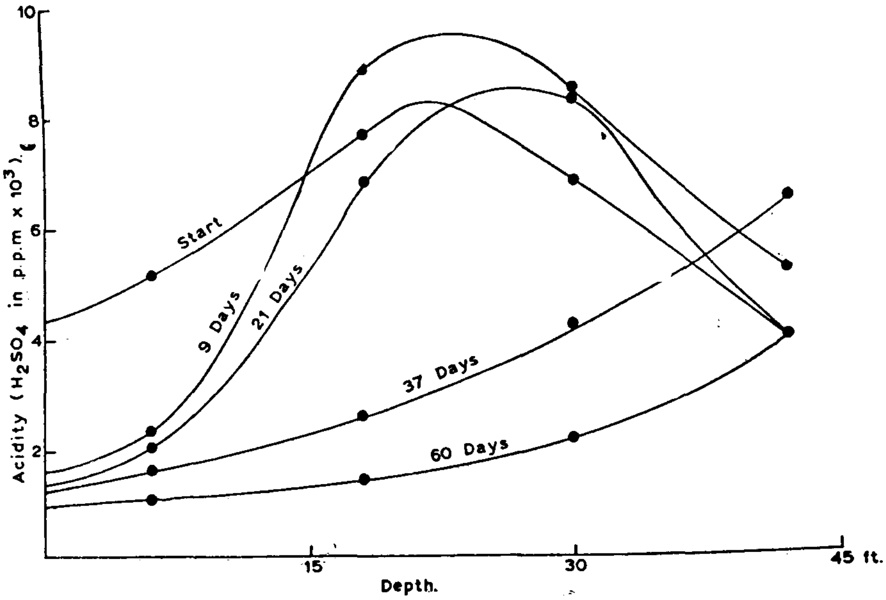

Fig. 8—Slimes-dam leaching—change in acidity at various depths with time (from James and Mrost[12])

dams, at completion, is almost independent of the method of wall building used. Within the limits of height and slope angle at which the relatively smaller dams are built, and with due attention to underdrainage and to consolidation by the limiting of rates of rise, the dams have adequate bulk stability. In principle, however, the use of coarse material, whether 'borrow' or segregated tailings, in downstream methods of construction provides greater embankment stability, particularly for large, high embankments.

(2) An important deficiency of Witwatersrand gold-mine slimes dams, due in large part to the fineness of the material exposed on walls, is their proneness to erosion. This can result, in the long term, in instability of the dams, and in the short term, in air and water pollution. The control of erosion is being achieved by well-developed methods for the establishment of vegetation on slimes surfaces. These methods are at least as effective, and probably, at this stage, in advance of, practice in any other mining areas.

(3) There is a discernible trend towards the operation of larger gold-mining conglomerates, and of reduction works of larger capacity. It may therefore become necessary to build larger and higher slimes dams than those customarily built on the South African gold fields, and to adopt the inherently more reliable methods of tailing-embankment construction used elsewhere. Such dams would be significantly less prone to erosion, and consequently less liable to become unstable or to create problems of river pollution.

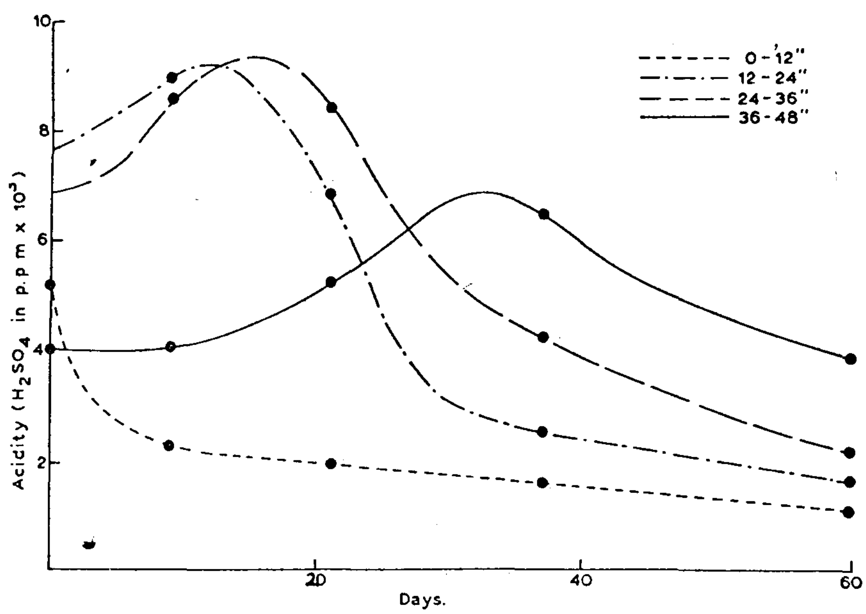

Fig. 9—Slimes-dam leaching—change in acidity profile with time (from James and Mrost[12])

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