Some Aspects Of The Behaviour Of Hydraulically Deposited Tailings

G.M. Bentel.

techniques are really only used (in South Africa) for the construction of tailings dams, developments in this field are limited in their applicability, being beneficial only to the design and construction of tailings dams. The extent of further research is thus dependent on the further requirements of dam builders and designers who must consider whether an overall general understanding will be sufficient, or will the generalized variables need to be quantified?

It is felt however, that the overall general understanding is not entirely adequate, especially when the theory is extrapolated to very different boundary conditions such as very long beaches. In this particular case, there is doubt that the beaching parameters observed for short beaches will be applicable to very long beaches.

Thus the need will probably arise for the investigation and possible quantification of the beaching parameters under varying boundary or system conditions. Since, due to the large scale of tailings disposal operations, difficulties will be experienced in attempting to achieve control over the variables in the field and in measuring the flow characteristics, it is felt that this further investigation will best be conducted using laboratory modelling techniques.

At the outset of this project, a laboratory model was proposed as a means of investigating the beach development process. However it was generally felt that, in addition to being redundant due to the availability of operational dams, modelling in a laboratory flume would not be feasible unless the particle size distribution of the solid material was also scaled down.

However from the observations in this study, it can be seen that the flow along the beach adjusts itself according to the boundary conditions, resulting in very similar dimensionless beach profiles for varying beach lengths, the beaching parameters (n and i_{av}) varying because of different initial flow conditions and material properties.

SOME ASPECTS OF THE BEHAVIOUR OF HYDRAULICALLY DEPOSITED TAILINGS

Gary Michael Bentel, BSc.Eng.(Witwatersrand)(Civil)

A Dissertation Submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the Degree of Master of Science in Engineering.

Johannesburg, 1981.

Considering this similitude between beaches of various lengths, we can thus visualize a 40m beach as being a one in four scale model of a beach of 160m length. In other words, one can most probably design a laboratory model without theoretical flow considerations, but by merely scaling down the linear dimensions of the beach and the initial flow conditions, as noted above.

It is thus felt that the use of a laboratory model in further investigations is entirely feasible, and will provide a quick and simple means of investigating the various unquantified variables, with the added benefit of visual observations only possible with such a model.

DECLARATION

I, Gary Michael Bentel, hereby declare that this is my own unaided work and that I have not submitted this dissertation to any other University for degree purposes.

APPENDIX

Appendix A_1 The Theory of Clay Flocculation and Deflocculation

A.1.1 Electrical Charges in Soil Particles

(Note: The following theory is a simplified summary of theory extracted from the quoted references. These references should be consulted should a more detailed explanation be required.)

Every soil particle carries an electrical charge, theoretically either negative or positive, although only negative charges have been measured. The net electrical charge may arise from a number of factors of which isomorphous substitution may be considered the most important (Lamb and Whitman 1969). Isomorphous substitution is the substitution of ions of one kind by ions of another type, with the same or different valence, but with retention of the same crystal structure. In reality, replacement does not occur, and the mineral is initially formed with its present proportions of different cations in the structure (Mitchell 1976).

The magnitude of the electrical charge is directly related to the particle surface area, thus the influence of the charge on the behaviour of the particle relative to the influence of mass forces (weight) will be directly related to the specific surface (surface area per mass). The smaller a particle, the larger its specific surface - silt size particles and larger have a specific surface less than $1m^2/g$ compared to kaolinite (10 to $20m^2/g$) and montmorillonite ($800m^2/g$) - and thus the larger the influence of the charge on the behaviour of the clay particle.

Clay particles can thus be called "colloids" since their

ABSTRACT

Tailings dams are constructed using hydraulic fill techniques where fine solid wastes (tailings) are pumped to the tailings dam using water as the transporting medium. This construction technique utilizes the 'beaching' property of the deposited slurry to obtain separation of the solids into coarse and fine fractions, the coarse material remaining at the dam perimeter where it is used to construct the 'wall' of the dam.

Since very little information is available on the mechanisms of the development of a beach, this study was undertaken to investigate some aspects of the beach development, namely, the beach profile and the variation of material properties along the beach. The observations were conducted on beaches formed by gold, platinum and diamond tailings.

It was found that, due to a progressive decrease in the flow velocity along the beach, the beach profile has a parabolic shape, with the slope a maximum at the deposition point and a minimum at the pool. The same equation can be used to describe the profile for all the types of tailings, the constant and exponent in this equation (the beach parameters) varying according to the particle size distribution of the deposited tailings and the deposition flowrate.

Particle size separation along the beach occurs as a result of the continuous velocity reduction, whereby the size of particle which the stream can transport also decreases. The results of tests conducted on samples extracted at various positions along the beach show that, in general; the sand content decreases, the silt content increases, and the clay content remains fairly constant with increasing distance from the point of deposition to the edge of the pool.

The results seem to indicate that the degree of separation is inversely proportional to the uniformity of the deposited tailings. Also, one will find, in general, that the flatter the

behaviour is controlled by surface-derived forces (electrical) rather than mass-derived forces.

When the clay particle carries a net negative charge, cations (M^+) are adsorbed to the structure to neutralize the charge. Since these cations are usually weakly held on the particle surface, they can easily be replaced by other ions and are thus termed 'exchangeable cations'.

A.1.2 Clay in the Presence of Water - The 'Double Layer'

In the presence of water, both the mineral surface and the exchangeable cations hydrate with the following general effects:

i. The exchangeable ions increase in size (upon hydration, the radius of the sodium ion Na^+ increases approximately sevenfold) and move away from the particle surface since their increased size does not permit them to fit into a monoionic layer on the particle surface (Lambe and Whitman 1969). The ions, attracted to the particle surface to satisfy the negative charge on the surface, move to positions of equilibrium, with a high concentration of ions near to the clay surface due to the high concentration of negative electrical charge at the clay surface. The concentration falls off with increasing distance from the surface (Figure A1)

ii. The exact nature of the water immediately next to the mineral surface is not known although it is generally accepted that, due to the fact that water molecules are polar, at least the first few molecular layers of water are orientated and strongly attracted to the particle surface. As the distance from the particle surface increases, the degree of orientation and the rigidity with which the water molecules are held, decrease (Figure A1).

beach slope (for a specific type of tailings), the less is the degree of separation along the beach, since both are strongly influenced by the deposition flow rate and the content of coarse material in the total tailings.

Hand shear vane tests show that the undrained shear strength decreases with increasing distance from the deposition point. This variation results from a variation in the rate of consolidation along the beach, the more permeable material near the deposition point consolidating far quicker than the less permeable material near the pool. The more permeable material is also influenced by the development of capillary tensions in the pore water which tend to overconsolidate this material. The overconsolidated material dilates strongly when sheared, exhibiting a greater shear strength than the normally consolidated material further along the beach.

A major problem encountered in the construction of tailings dams is the occurrence of impermeable 'clay' layers that create an anisotropic system which encourages horizontal flow. This is thought to promote 'piping' which may in turn result in breaching of the dam. Furthermore, the anisotropic system causes a raised phreatic surface (or a series of perched phreatic surfaces), thereby reducing the factor of safety against a shear failure of the slope.

It was concluded that the major cause of these clay layers is the overflow of fines (held in suspension) from concentrated rivulets of flow, onto areas adjacent to the section of beach being slimed. It is thus suggested that the use of training walls (parallel to the direction of flow) be investigated as a means of directing the flow, thus minimizing the formation of the clay layers.

It was initially felt, in the case of diamond tailings which contains a large quantity of flocculated clay (montmorillonite), that the degree of separation could be improved by adding deflocculating agents to disperse the clay content and thus allow gravitational sorting to occur, with the clay and silt sized

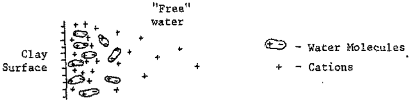


Figure A 1 : Adsorbed Water Molecules and Exchangeable Cations in a Clay-Water system.
(After Ryan (1978))

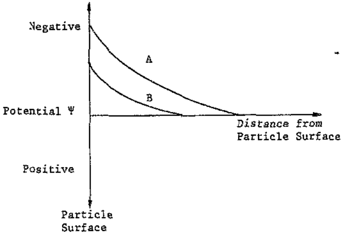


Figure A 2 : Variation of Electrical Potential with distance from Clay Particle Surface
(After Ryan (1978))

particles remaining in suspension. The addition of deflocculating agents also aims at improving the flow properties of the suspension by reducing the viscosity of the suspension. The increased velocity of flow will allow a greater degree of separation and will ensure that a larger quantity of fines is transported to the pool. Although fairly promising results were obtained, the high costs of the deflocculants and the cyclic process required to ensure a clear water draw-off, make the feasibility of this method doubtful as a means of achieving the desired results.

For the flocculated diamond tailings, the use of hydrocyclones which mechanically separate the flocculated material into coarse and fine fractions, is suggested as the best means of acquiring a material with properties suitable for the construction of the wall. Since the mechanical separation reduces the quantity of material available for beaching at the dam perimeter, a deposition system is suggested whereby the coarse underflow is retained in 'paddocks' while the fines are deposited in the body of the dam.

This layer formed by the exchangeable ions and the water molecules is known as the 'double layer'. (Mitchell (1976) gives a detailed description of the double layer and the theoretical prediction of the double layer thickness.) This double layer extends to a point where the concentration of exchangeable ions is equal to that in the 'pore' or 'free' water, or in other words, to a point where the electrical potential is zero.

Figure A2 shows the variation of electrical potential with increasing distance from the clay surface. As the distance increases, the negative charge becomes more and more reduced, being neutralized by the cations in the double layer.

Figure A2 also shows that the double layer thickness is directly related to the electropositivity of the exchangeable cation since, when the exchangeable cation is highly electropositive (A), it ionizes well and the electrical potential at the particle surface is high. When the cation is not so electropositive (B), ionization is limited, the potential at the particle surface is comparatively small and the charge is reduced to zero at a lesser distance from the particle surface (Ryan 1978).

For the cations involved in clay minerals, electropositivity varies as follows:

$$H^+ < Mg^{2+} < Ca^{2+} \leq Li^+ < Na^+ < K^+$$

A.1.3 The Double Layer and Interparticle Forces

When two clay particles are brought towards each other, they are subjected to two types of interparticle forces.

Since each particle carries a net negative charge, the two particles repel each other because of the Coulombic electrical force between like charges (R'). Since the net negative charge is balanced by the cations in the double layer, the two advancing particles begin to repel each other when their double layers come into contact with one another. Thus any change in the

ACKNOWLEDGEMENTS

I would like to express my appreciation to the following:

My supervisor, Prof. G.E. Blight, whose assistance and advice I gratefully acknowledge.

Dr. O.K.H. Steffen, Dr. D. van Zyl, Mr. G. McPhail (Steffen, Robertson and Kirsten Inc.) and Mr. M. Gowan (Fraser F. Alexander and Co. (Pty) Ltd.) for their assistance and interest in this research project.

The Council for Scientific and Industrial Research,
The University of the Witwatersrand,
Steffen, Robertson and Kirsten Inc. and
Fraser F. Alexander and Co. (Pty) Ltd.,
for financial assistance during this project.

The managements of:
Premier Diamond Mine,
Wesselton (Kimberley) Diamond Mine,
Rustenburg Platinum Mines,
Impala Platinum Mine (Bafokeng),
President Steyn Gold Mine and
President Brand Gold Mine,
for allowing me access to the various tailings dams on which the research was conducted.

Prof. J.R. Mc Iver (Department of Geology) for the X-Ray analysis of the clay in diamond tailings.

Prof. .B. Watt (Department of Surveying) for the use of survey equipment.

James Robertson, who kindly allowed me to use his 'word processor' to type this dissertation.

characteristics of the soil-water system that reduces the thickness of the double layers, reduces the repulsive force for the same interparticle spacing (Figure A3 - Lamb and Whitman 1969).

In addition to a repulsive force, the approaching particles are subjected to a component of attractive force (A'), being the van der Waal's force, or secondary bonding force, which acts between all adjacent pieces of matter.

If the net effect of the attractive and repulsive forces between the clay particles is attractive (Figure A4(a)),the particles tend to move towards each other and become attached i.e. flocculated (Figure A5(a)). If the net effect is a repulsive force (Figure A4(b)), the particles tend to move away i.e. dispersed or deflocculated (Figure A5(b)).

Since the repulsive force is dependent on the characteristics of the system (variation of the double layer thickness), and the attractive component is not, a tendency towards deflocculation is usually caused by decreasing one of the following:

Electrolyte concentration
Ion valence
Concentration of the solids in the suspension
Temperature

or increasing one of the following:

Dielectric constant
Size of hydrated ion
Electropositivity of exchangeable ion
pH of the suspension
(After Lambe and Whitman 1969)

Deflocculants containing Sodium (Na^+) or Lithium (Li^+) satisfy most of these requirements and are thus the most succesful and common deflocculants in use.

Mark Axelrod and Tom Rumpelt for their friendship and help.

David and Barbara Bentel for all their help during my visits to Welkom.

Special thanks to my parents for all the support they have given me throughout my academic career.

Thank you all,
Gary Bentel
13 August 1981.

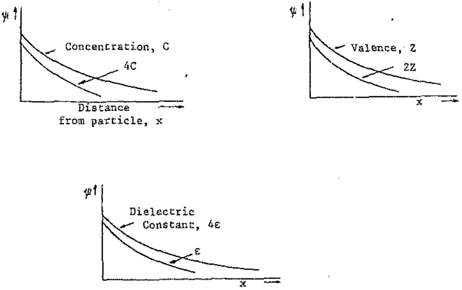
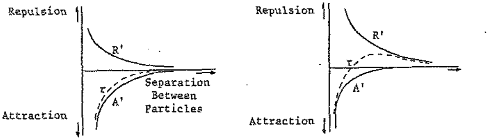


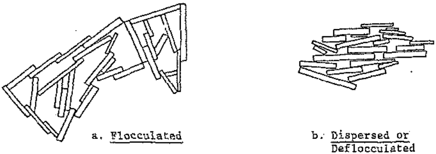
Figure A 3 : The Effects of Changes in System Properties on the Electrical Potential, Ψ, and hence the Double Layer Thickness and R: (After Lambe and Whitman (1969))



a. Flocculated Suspension

b. Deflocculated Suspension

Figure A 4 : Variation of Interparticle Forces with decreasing Concentration of suspension (After Ryan (1978))



a. Flocculated

b. Dispersed or Deflocculated

Figure A 5 : Flocculated and Dispersed Clay Particles (After Lambe and Whitman (1969))

Table of Contents

On deflocculating a flocculated suspension, various changes in the system properties are effected by increasing the repulsive force between particles, the most important in the case of the flocculation of diamond tailings being:

i. a decrease in viscosity resulting in an increase in flow velocity, and

ii. a decrease in the rate of sedimentation of the clay particles from the suspension.

Appendix A_2 Brief Review of the Structure of Smectite Minerals

The smectite group consists essentially of two-to-one layered structures consisting of two silicon-oxygen sheets $(Si_4O_{10})^{4-}$ sandwitching between them either gibbsite ($Al(OH)_3$) or brucite ($Mg(OH)_2$) (Figure A6).

When gibbsite is the central sheet, 'condensation' of a silicon oxygen sheet on either side of it leads to the formula

$$Al_2Si_4O_{10}(OH)_2$$

which is the ideal formula for pyrophyllite.

Montmorillonite (a member of the smectite group) has a structure similar to pyrophyllite with the exception that there has been isomorphous substitution of magnesium for aluminium in the gibbsite sheet resulting in the formula:

$$(Al_{1,67}Mg_{0,33})Si_4O_{10}(OH)_{10} \qquad \text{(Figure A7).}$$

Other members of the group are formed in a similar manner, e.g. saponite is formed by isomorphous substitution of Al^{3+} for Si^{2+}, brucite being the central sheet

We have seen that montmorillonite has undergone isomorphous substitution of one Mg^{2+} cation for every sixth Al^{3+}, resulting in a net charge deficiency per substitution. The negatively charged structure is neutralized by adsorption externally to the structure of some cation M^{1+}, which is some monovalent cation such as Na^+ or H^+ etc. (M^{1+} is the exchangeable cation). Should the adsorbed cation be divalent e.g. Ca^{2+}, then only half the quantity would be required to balance the charge.

Thus the formula for montmorillonite is written:

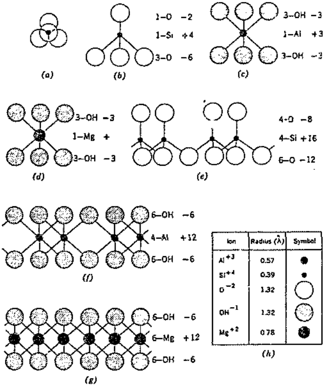


Figure A 6 :

Basic Silicate Units

a. and b. Silicon Tetrahedron

c. Aluminium Octahedron

d. Magnesium Octanedron

e. Silica

f. Gibbsite

g. Brucite

(After Lambe and Whitman (1969))

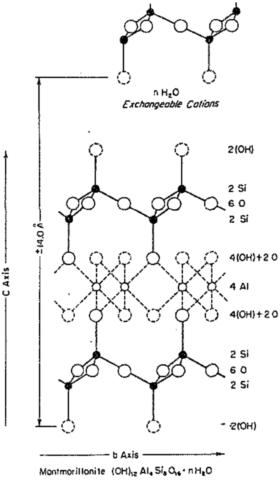


Figure A 7 :

Schematic Representation of The Structure of Smectite

(Suggested by Edelman and Favejee)

(From Grim (1968))

List of Figures

Thus the formula for montmorillonite is written:

$$\begin{array}{c} (Al_{1,67}Mg_{0,33})Si_4O_{10}(OH)_2 \\ \downarrow \\ M_{0,33}^{1+} \end{array}$$

M^{1+} is a monovalent cation

or

$$\begin{array}{c} (Al_{1,67}Mg_{0,33})Si_4O_{10}(OH)_2 \\ \downarrow \\ M_{1/6}^{2+} \end{array}$$

M^{2+} is a divalent cation

Appendix A_3 The Behaviour of Clay in the Presence of a Salt Solution

It is conventional to refer to a clay that has adsorbed cations of type M as 'M clay', and since some ionization of the clay occurs in water, it is possible to replace the M^+ cation by some other cation say N^+, by treating the clay with a solution of N^+ salt, say NA (Ryan 1978), i.e.:

$$\text{M clay} + N^+A^-\text{(in solution)} \rightleftharpoons \text{N clay} + \text{MA}$$

The quantity of exchangeable cations required to balance the charge deficiency of a clay is termed the 'cation exchange capacity' (c.e.c.) of the clay, usually expressed as milli-equivalents per 100 gm of dry clay (typical values are quoted in Table 5.1).

However the amount of M^+ which is actually replaced by N^+ will depend on the concentration of the NA solution, the sizes of the two cations, the valencies of the two cations and the solubility of the product MA.

An approximate order of preferred cation adsorbtion in clays is:

$$H^+ > Mg^{2+} > Ca^{2+} > Li^+ > Na^+ > K^+$$

where H^+, Mg^{2+} and Ca^{2+} tend to flocculate clays, while Li^+, Na^+ and K^+ tend to deflocculate clays, the most common method of deflocculating a clay being the formation of sodium clay.

From this it can be envisaged that a problem arises when the products formed are of high solubility i.e.

$$\text{M clay} + \text{NA} \rightleftharpoons \text{N clay} + \underset{\substack{\downarrow \\ M^+ + A^-}}{\text{MA}} \text{ (highly soluble)}$$

The M^+ ions produced are free to compete with the N^+ ions for

adsorption on the clay, and if they are 'preferred' cations, they will compete successfully i.e. the reaction lies to the left (indicated by the solid arrow), unless the N^+ concentration is high.

The ideal deflocculant will thus form a product of low solubility which will then precipitate out i.e.

$$M\ \ \text{lay} + NA \rightleftharpoons N\ \text{clay} + MA\downarrow \ \ \text{(low solubility)}$$

and the reaction proceeds to the right.

List of Tables

List of Plates

Appendix A_4 Calculation of the Mass of Deflocculant for a Specified Overall Concentration

To simplify the calculation it has been assumed that the deflocculant is added in Z% solution form to 1,0Kg tailings consisting of 45% by mass solid material and 55% by mass water.

Let xg be the mass of solid deflocculant in the added solution. Let yg be the mass of the water in this solution.

For a Z% solution: $\frac{x}{x+y} = \frac{Z}{100}$ - A_1

Expressing the concentration of solid deflocculant as a percentage of the total solution, we can write:

$$\left(\frac{x+y}{1000+x+y}\right)\cdot\left(\frac{x}{x+y}\right).100 = C\%$$ where C% is the specified overall concentration.

which can be simplified to:

$$\left(\frac{x}{1000+x+y}\right) . 100 = C\% \qquad - \quad A_2$$

i.e. the concentration of solid deflocculant (xg) in total solution (1kg tailings + xg deflocculant + yg water).

The quantity of solid deflocculant required will be obtained by the simultaneous solution of Equations A_1 and A_2.

1.0 INTRODUCTION

This dissertation deals with a specific aspect of tailings dam construction, namely the behaviour of a free flowing slurry deposited on the dam.

The principles of tailings dam construction are dealt with to some extent, but should this provide insufficient background on the subject, the reader is advised to consult the Chamber of Mines Handbook of Guidelines (Volume 1 - 1979) which covers, in detail, the design and operation of tailings dams.

1.1 The Need for Further Research into the Behaviour of Hydraulically Deposited Tailings

Tailings dams are extremely large structures and if not carefully and correctly designed, constructed and monitored, may pose a significant threat to human safety, as well as being potentially serious environmental hazards.

Legislation has been introduced and Handbooks (e.g. Chamber of Mines Handbooks - Volumes 1 and 2) are available to assist in the correct design and operation of tailings dams, to ensure a maximum factor of safety against failure as well as minimum damage to the environment, should a failure occur.

To make this possible, a great deal of research concentrating on the stability and environmental aspects of tailings dams has been carried out.

However, there exist a number of aspects of tailings dam construction, all basically related to the behaviour of the hydraulically deposited tailings on the beach, in which

Example

Water Glass (Sodium Silicate) is added in 5% solution to 1Kg tailings to give an overall concentration of 0,1%.

Eqn. A_1 yields : $\frac{x}{x+y} = \frac{5}{100}$ i.e. $y = 19x$

Eqn. A_2 yields : $\left(\frac{x}{1000+x+19x}\right).100 = 0{,}1\%$

Solving A_1 and A_2 we find that we need:

$x = 1{,}02$g of deflocculant per 1Kg tailings,

or 1,02Kg deflocculant per 1 ton of tailings.

Thus for 222 000 tons of tailings at a cost of R 0-35 per Kg for the deflocculant:

Cost of deflocculant=(222 000).(1,02).(0,35)

i.e. R79 400-00 per 222 000 tons of tailings knowledge is lacking. Furthermore, some fairly serious problems are being encountered in the construction of the dams, for which solutions are required.

Firstly, a number of tailings dams, considered to be structurally stable, have failed, in some instances with disastrous consequences. Some of these failures have been attributed to the fact that, resulting from the deposition process, a layering effect occurs where consecutive layers of deposition are separated by thin layers of fine, relatively impermeable material.

This layering may cause the horizontal permeability of the system to become far greater than the vertical permeability since the relatively impermeable fine layers reduce vertical permeation through the system.

Such an anisotropic system is undesirable since the phreatic surface may rise significantly, and 'horizontal' flow may be concentrated in the coarser material between the fine layers. These effects may result in piping through the wall or a shear failure (followed possibly by a flow slide), and it is thus desirable to find a solution which will either minimize the formation of the layers, or completely eliminate their formation.

Tailings dam designers have also recognised the need to be able to predict the variation of particle size distribution, as well as the engineering properties of the dry material along the beach. This information would be extremely valuable in assessing the overall stability of the dam.

Past attempts (eg. Van Zyl (1976)) to predict the variation of particle size distribution along the beach have used the components of velocity due to the transporting medium (drag) and the weight of a particle, to calculate the distance that a suspended particle of a given size will move along the beach (similar to Camp's theory for settling basins).

REFERENCES

BLIGHT, G.E. (1979). Kimberley Diamond Tailings Dam - Investigation of Particle Size Separation of Tailings. Report No.S.721/2, Steffen, Robertson and Kirsten Inc., Johannesburg.

BLIGHT, G.E. (1980). Kimberley Diamond Tailings Dam - Investigation of Particle Size Separation of Tailings. Report No.S.721/3, Steffen, Robertson and Kirsten Inc., Johannesburg.

BLIGHT, G.E. and STEFFEN, O.K.H. (1979). Geotechnics of Gold Mine Waste Disposal. Current Geotechnical Practice in Mine Waste Disposal - Papers Collected by the Committee on Embankment Dams and Slopes of the Geotechnical Engineering Division. American Society of Civil Engineers: New York.

BRADLEY, D. (1965). The Hydrocyclone. London; Pergamon Press.

CHAMBER OF MINES HANDBOOK (1/1979). Handbook of Guidelines for Environmental Protection: The Design, Operation and Closure of Residue Deposits. Volume 1/1979, Johannesburg: Chamber of Mines of South Africa.

GRAF, W.H. (1971). Hydraulics of Sediment Transport. Mc Graw Hill.

GRIM, R.E. (1968). Clay Mineralogy. New York: Mc Graw Hill.

JENNINGS, J.E. (1979). The Failure of a Slimes Dam at Bafokeng - Mechanisms of Failure and Associated Design Considerations. The Civil Engineer in South Africa, Volume 21, No.26, pages 135 to 141, June 1979.

KRESTEN. P. (1973). Differential Thermal Analysis of Kimberlites. Lesotho Kimberlites, edited by P.H. Nixon. Lesotho National Development Corporation.

LAMBE, T.W. and WHITMAN, R.V. (1969). Soil Mechanics. New York: John Wiley and Sons, Inc.

In a slurry stream, where the solids concentration is very high and the depth of flow very small, the behaviour of the particles in the stream becomes extremely complex, with the movement of larger particles occuring due to rolling and pushing along the bed, and saltation (Melent'ev et al. 1973). The above theory (gravitational settlement according to Stoke's law) is thus more applicable to the behaviour of finer particles settling through the slurry stream as it moves along the beach.

Tailings dam designers (e.g. Van Zyl) have also expressed the need for an analytical method of predicting the profile (shape) of a developed beach. The ability to predict the profile is very useful snce it aids in determining design factors such as the length of the beach, the available freeboard (hydrological), the volume of material deposited and the rate of rise of the dam (rise in height with time) at any stage of its 'life'. These factors are all important to the designer who must be able to predict the shear strength of the material and the position of the phreatic surface etc. for stability calculations.

The primary aim of this project was thus to study the behaviour of the free flowing slurry on the beach, and the resulting properties of the dry material.

In achieving this, the dissertation will hopefully provide a useful design tool which will allow the designer a more flexible design approach since variations in the profile and the properties of the beach material which can be expected, should any changes in the system occur (e.g. deposition flow rate), can then be predicted.

In conducting this study, a great deal of time was spent on the visual examination of existing construction techniques in order to assess their efficiency and in order to identify the probable causes of 'clay' layering.

MELENT'EV, V.A., KOLPASHNIKOV, N.P. and VOLNIN, B.A. (1973). Hydraulic Fill Structures. 'Energy', Moscow. Translated by Mrs B. Nowak (University of the Witwatersrand) and Edited by D. van Zyl.

MITCHELL, J.K. (1976). Fundamentals of Soil Behaviour. New York: John Wiley and Sons, Inc.

RIETEMA, K. and VERVER, C.G. (1961). Editors: Cyclones in Industry: A collection of Papers on the Principles and Utilization of Industrial Cyclones. Amsterdam: Elsevier.

RYAN, W. (1978). Ceramics of Raw Materials. London: Pergamon Press.

STEPHENSON, D. (1979). Rockfill in Hydraulic Engineering. Amsterdam: Elsevier.

VAN ZYL, D. (1976). The Sedimentation of Particles on Mine Tailings Dams. Sediment Transport Engineering - Term Paper. Purdue University: Department of Civil Engineering.

Further problems, such as the behaviour of a slurry containing flocculated clay (eg. diamond tailings), were also investigated with a view to improving the degree of particle separation resulting from the flow of such a stream.

Being the first research project of this nature, it was not possible to investigate all of the operational dam types and their respective materials. The results obtained can thus only be applied to the 'systems' for which they were observed.

However in selecting the three tailings types discussed, the research aims at providing an overview of the subject, which will hopefully simplify further research undertaken into either these materials or other material types.

1.2 Terminology and Material Properties

1.2.1 Tailings Deposits

The following definitions are given in the Chamber of Mines Handbook (1979):

Residue - includes 'Tailings', the part of a material that remains or results after processing to extract those constituents or parts which it is profitable to extract at the time; as well as 'waste rock' which, not being ore itself, is rock removed from the mine in order to allow extraction of the ore ....etc.

Deposit - a dump, heap, pile or filling which usually projects above the natural ground surface ... . Deposits may be formed by mechanical or hydraulic deposition of material....etc.

At this stage it is important to note that there are two distinct types of tailings, namely:

1. Coarse tailings (or 'overburden' or 'waste rock') which is mechanically deposited on 'tailings dumps',

and

2. Fine tailings (or 'slimes'), which is comparatively fine material deposited hydraulically on tailings (or slimes) dams.

This dissertation deals only with fine tailings (referred to as tailings or slimes) and the behaviour of this material once it has been deposited on the tailings dam.

1.2.2 Types of Tailings

Throughout this dissertation, for the sake of clarity, the types of tailings are referred to by the major precious mineral extracted in the mining process.

For example, although diamonds are extracted from kimberlite 'pipes', the tailings are referred to as 'diamond tailings'.

The three types of tailings dealt with in this dissertation are diamond, gold and platinum tailings. Typical particle size distributions of these tailings are shown in Figure 1.1. Other properties of the tailings are given in Table 1.1.

1.2.3 General Terms

Figure 1.2 shows a generalized cross-section of the fundamental tailings dam system.

The following terms are commonly used:

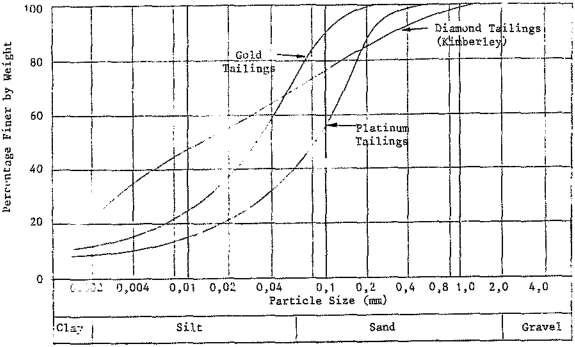


Figure 1.1 : *Typical Particle Grading Distributions of the Tailings Types Investigated*

Table 1.1: Some Properties of Gold, Platinum and Diamond Tailings

Tailings Type	Classification	Strength Parameters		Specific Gravity	Coefficient of Consolidation	Permeabilities
		$\bar{\phi}$	$\bar{C}$ (kN/m^2)	(S.G)	(C_v) (m^2/y)	(k) (m/y)
Gold	Silt	35°	0 – 30	2,7 – 2,9	50	$\bar{k} = 15$ k_h/k_v = 1,5 to 3,0
Platinum	cohesionless silty sand	35°	0	SG_1 3,0 – 3,1 SG_2 2,7 – 3,0	$C_{v1}=45$ $C_{v2}=10$	$k_1 = 67$ $k_2 = 2$ k_1/k_2 = 30 to 1000
Diamond	Clayey silt	24°	0 – 20	SG_1 2,8 SG_2 2,8	$C_{v1}=1070$ $C_{v2}=0,11$	$k_1=170$ $k_2=3.10^{-3}$ $k_h=160$ $k_v=55.10^{-3}$

(After: Chamber of Mines Handbook (1/1979), Blight (1979), Jennings (1979) and records of laboratory tests conducted by Steffen, Robertson and Kirsten Inc.

Note: The subscripts 1 and 2 refer to the coarse and fine materials respectively, while k_h and k_v denote the coefficients of permeability in the horizontal and vertical directions respectively.

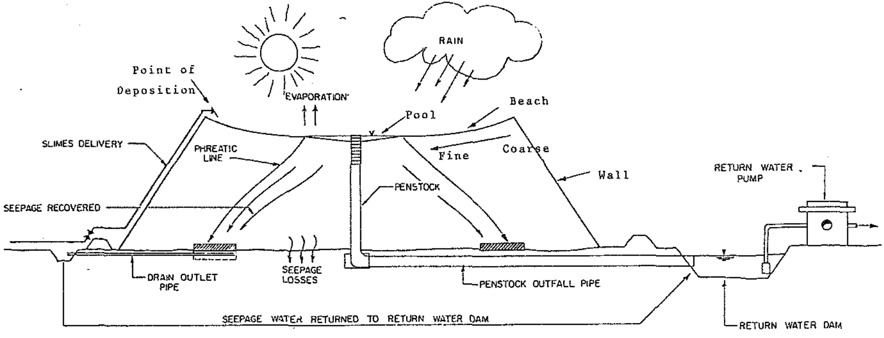


Figure 1.2: Generalized Cross-Section of the Tailings Dam System

1. Point of deposition

The point of deposition is the point where the slurry leaves the delivery line and is deposited on the 'beach'.

2. The Beach and the Pool

The design of tailings dams relies on the fact that the deposited tailings forms a natural downgrade from the point of deposition onwards. This is called the beach.

The surface of the dam, being bowl shaped, can thus be used to retain some water on the dam to allow the settlement of fines before clear water can be drawn off. This region is called the 'pool'.

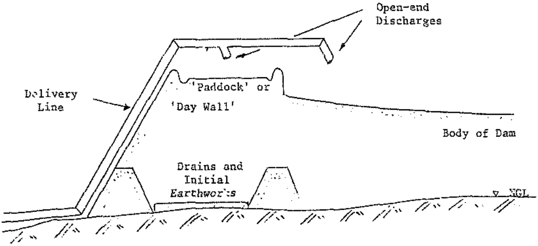
The principles of deposition are different for above water and below water deposition, and for the present purpose which is to study above water deposition, the 'beach' extends from the point of deposition to the edge of the pool.

3. Deposition Methods

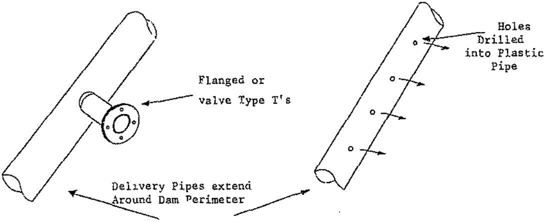
Tailings are generally pumped to the tailings dam through a delivery line. However various methods of deposition are used for the different tailings types, these being:

i. Open-ending

Gold tailings is deposited into the body of the dam through open ended pipes (Figure 1.3(a)), situated at various points around the dam. These points are located so as to achieve the maximum possible beach length and thus minimize the amount of material that reaches the pool. This study is only concerned with the beach formed by this open-ended deposition, and not with the deposition in the paddocks that form the outer wall of the dam.



a. Typical Gold Tailings Dam System



b. and c.

'Spigot' Deposition Methods

Figure 1.3 : Deposition Methods

ii. Spigotting

Platinum and diamond tailings are generally deposited from a ring main extending around the perimeter of the dam.

The outlets on the pipe, i.e. the spigots, may take the form of T's (Figure 1.3(b)) which can be partially or fully opened by means of gate valves, or they may simply be holes drilled into the pipe (Figure 1.3(c)) which are closed using wooden plugs.

The spacing of the spigots varies, the actual spacings measured being 3 to 4,5m for platinum tailings (T's) and 1m for diamond tailings (holes).

4. Coarse and Fine Tailings

The particle size distributions shown in Figure 1.4 illustrate the various terms used to describe the beach material.

The 'coarser' tailings (A) is generally found close to the deposition point, while the 'finer' tailings (B) is deposited further along the beach.

Figure 1.4 shows a typical particle distribution curve for the 'total tailings' (C) which is the product pumped from the extraction plant.

Reference is often made to 'clay layers' and to the 'fines carried to the pool'. This material may be very different from the general material found on the beach and usually consists almost entirely of silt and clay sized particles with little sand sized material (D).

Throughout this dissertation, the thin, relatively impermeable layers are referred to as 'clay layers' even though in the case of some tailings types, clay minerals may not actually be present,

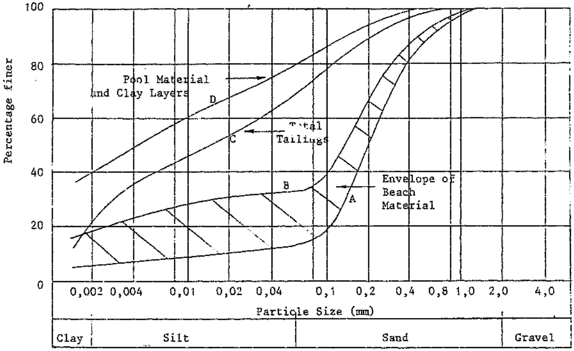


Figure 1.4 : Comparison of Total Tailings and Tailings Found on the Beach

(Kimberley Tailings Dam - Blight 1979)

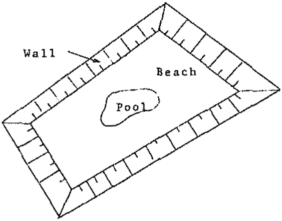
the layers consisting of clay-sized particles.

5. Dam Types

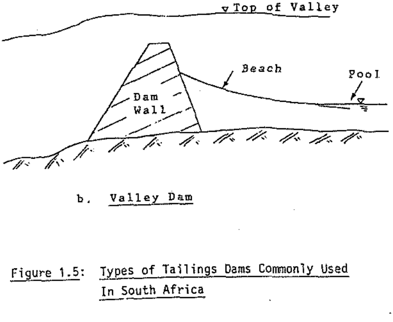
Two types of tailings dams are used in South Africa.

Figure 1.5(a) shows the ring-dyke dam which is normally constructed in areas with a flat topography. Except for a small amount of initial earthworks, the entire dam is constructed using the tailings that is deposited on the dam.

Figure 1.5(b) shows the valley dam which is constructed where a natural valley exists. The Premier Diamond Mine tailings dam is a valley dam, the wall being constructed of mine waste rock, while all the other dams discussed are dyke dams.



a. Ring Dyke Dam



b. Valley Dam

Figure 1.5: Types of Tailings Dams Commonly Used In South Africa

2.0 BEACHING CHARACTERISTICS OF A SLURRY

2.1 Introduction

Characteristic of all tailings deposited as a slurry, is the tendency of the solid material to beach, that is, to form a natural downgrade from the point of deposition to the pool.

This beaching characteristic is benefically utilized by dam designers in a number of ways including the following:

i. Since the velocity of flow is highest at the point of deposition, the coarser material is deposited near the deposition point, and the finer material is deposited further along the beach or carried to the pool (Chapter 3). The result of the separation of particles is that the material in the outer regions of the dam, once this material has been allowed to dry, has better drainage and strength properties than the material further along the beach. This material can thus be used to construct the 'wall' of the dam which must be well drained for stability purposes.

ii. The surface of the dam, being bowl shaped, is used to retain some water to allow the settlement of fines transported in suspension, in order to obtain clear water draw-off for re-use in the extraction plant. The size of the pool is dependent on the time required for the settlement of these fines before a clear water draw-off can be obtained. However, since the level of the pool may rise quite rapidly during periods of heavy rainfall, resulting in a raised phreatic surface, the quantity of water retained on the dam is kept to a minimum so that the required hydrological freeboard can always be maintained.

In order to investigate the possible relationships between the properties of the deposited material (total tailings), the resulting beach profile and the resulting properties of the beach material, numerous observations were conducted on various tailings dams. The results of the field observations and the subsequent analyses of the beach profiles are presented below, while the variation of the material properties of the beach material are dealt with in Chapter 3.

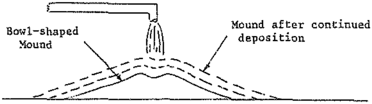
2.2 The Development of a Beach - A Qualitive Explanation

As an analogy to the development of a beach, consider the deposition of a slurry on flat ground as shown in Figure 2.1(a). Due to the dissipation of kinetic energy through impact and turbulence, the velocity of the deposited slurry is far less than the velocity in the delivery line, and coarser material which could be transported in the pipe will be deposited at this point, forming a bowl-shaped mound (analogous to a plunge pool).

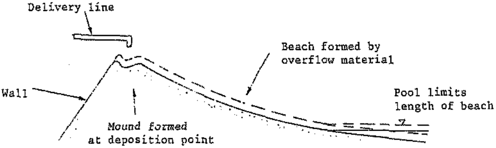
The excess slurry (solids and water), overflows the edge of the bowl, flowing radially outwards. With continued deposition, as the top of the mound rises, so the lengths of the sides of the mound increase (Figure 2.1(a)), unless some restriction is placed in the path of the flow.

The same principles apply to the development of a beach, except that due to the presence of the wall behind the deposition point, flow can only proceed into the body of the dam (Figure 2.1(b)). Furthermore, the length of the beach is limited by the presence of the pool, so that even though the top of the beach rises, the beach length will remain approximately constant if the level of the pool is raised (by raising the level of the penstock inlet) at the same rate as the deposition point rises. This is in fact normally the case with tailings dam operation where the level of the pool is raised at the same rate as the top of the beach in order to maintain a constant pool size.

It is thus fairly simple to conceive of how the downgrade of the



a. Deposition on Flat Ground



b. Development of a Beach on a Tailings Dam

Figure 2.1: Descriptive Sketches of Beach Development

beach is initiated since the deposition point always rises before the rest of the beach.

However, for different deposition flow rates and particle grading distributions, one would expect that for beaches of the same length, the difference in elevation between the end-points would vary, as would the shape of the beach between these points.

In order to understand the influences of such variations on the beach profile, it is necessary to study both the hydraulic behaviour of the slurry as it flows along the beach, as well as the resulting beach profile.

Unfortunately, except for a rather vague description given by Melent'ev et al. (1973), no other description of the behaviour of a free flowing slurry could be found. This section thus includes a short description of the behaviour of free-flowing slurry on the beach as observed during this study.

The observations made are generally visual observations necessitated by the practical difficulties experienced in measuring the properties of the flow on a wet beach (re-wetted tailings cannot be walked on). An idea of the variation of the velocity of flow was obtained through the rather crude method of observing the speed with which confetti was carried by the stream.

2.2.1 Description of the Flow along the Beach.

During the studies conducted on the various dam types, the following general flow characteristics were observed, these characteristics being common to all the deposition methods.

Just after the deposition point, the velocity of the slurry flow is high (supercritical), and the slurry flows in individual scoured rivulets in which numerous 'hydraulic jumps' can be observed (Plate A). These jumps result from the scouring of 'furrows' (Figure 2.2) that cause a local instability of flow, and are

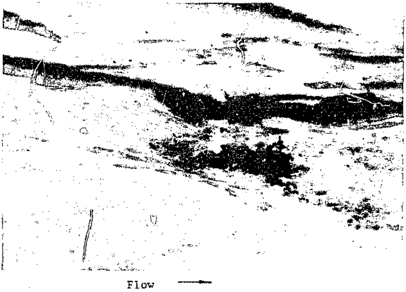


Plate A - Hydraulic Jump   Rivulet of Concentrated Flow

Plate B - Lower Region of Beach Showing Increased Spacing of Jumps and Sheet Flow at End of Reach

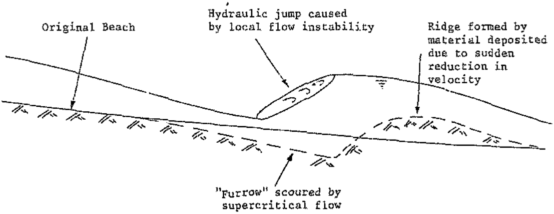


Figure 2.2 : Hydraulic Jump - Sketch Illustrating Furrows and Ridges

Plate C - Rippled Bed at End of Beach

accompanied by a decrease in the velocity of flow due to the energy lost in the jump. 'Ridges' are formed after the jumps, where material is deposited due to the sudden decrease in the velocity.

These jumps become less numerous and spaced further apart as the flow proceeds along the slope (Plate B), the velocity decreases and the slope becomes more gentle. Further along the slope, the rivulets begin to meander and widen, and eventually join up, the flow proceeding as 'sheet flow' over the previously deposited material, with little evidence of scour.

At the end of the beach, the velocity of flow is low (subcritical), and this low velocity is generally associated with a 'rippled' bed (Plate C).

It was also observed that, after the high velocity supercritical region in which the flow proceeds along a straight path, the width of the stream increases progressively along the beach due to the fact that the sliming region is higher than the surrounding areas. Thus, although the velocity of flow at the end of the beach is subcritical, the depth of flow may be less than the depth of flow at the top of the beach, depending on the extent to which the stream broadens.

The velocity thus decreases along the beach, and bedforms, as described in sediment transport theory are established. These bedforms and associated flow regimes are summarized in Figure 2.3.

It is interesting to note the change in beach slope at the edge of the pool, resulting from the difference between the development processes for above water and submerged beaches. Although the profile in Figure 2.3 was measured on a dry dam, the edge of the pool could easily be located by this abrupt change in slope and the change in the grading of the deposited material (almost no coarse material is transported beyond the edge of the pool - see Chapter 3).

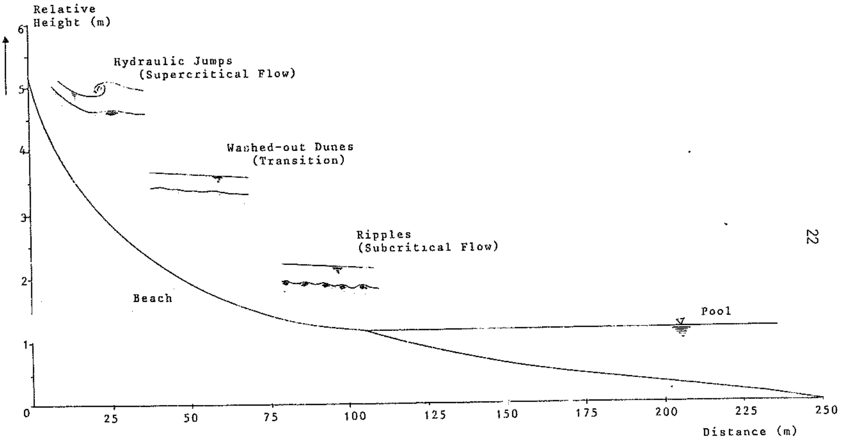


Figure 2.3 : Illustration of Measured Beach Profile and Typical Bedforms

2.2.2 The Resulting Beach Profile.

On all the types of dams investigated, the observed beach profile was of a parabolic shape, with the slope decreasing from a maximum at the point of deposition to a minimum at the edge of the pool (Figure 2.3).

For flow in non-erodable channels, the velocity of flow is dependent on the bed slope, the velocity of flow being high for large slopes and vice versa. For the development of a beach however, being a process of sedimentation, the dependence of the velocity on the beach slope cannot be assumed, i.e., we cannot say that the velocity of the stream decreases along the beach because the beach slope decreases.

However it is logical to say that the beach slope decreases as a result of the reduction in the stream velocity along the beach. In a broad sense, let us consider the reasons for the decrease in velocity along the beach, and thereafter the resulting beach profile.

Firstly, consider the hydraulics of the flow and the influences of the boundary conditions. In terms of open channel hydraulics principles, there are two control points, namely:

1. The edge of the mound at the point of deposition, at which the flow approximates to the critical flow condition, and after which, since supercritical flow is upstream controlled, the flow is supercritical.
2. The pool, being a downstream control, which has a 'backwater' effect that causes the flow upstream to be subcritical.

Thus at some stage along the beach, partially due to the boundary conditions, the flow changes from supercritical to sub-critical flow. This change occurs due to the dissipation of energy as a result of various influences including:

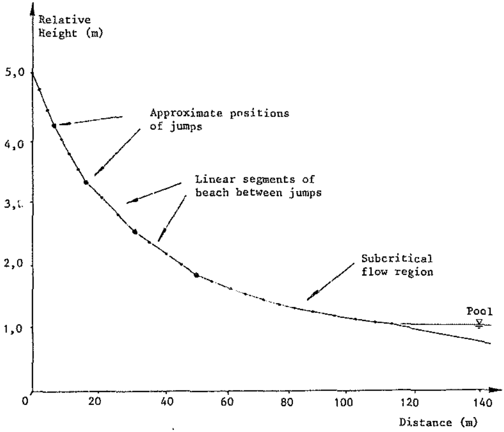


Figure 2.4 : Actual Profile Showing Linear Sections of Beach between Jumps

i. bed friction,

ii. bedforms e.g. hydraulic jumps,

iii. meandering and broadening of the stream.

It is difficult or impossible to quantify these energy losses due to the fact that in some regions, the flow is non-uniform and unsteady. Furthermore, losses, such as those due to bedforms, may vary significantly over the length of the beach.

However, the observed beach profile provides the evidence that these losses result in a progressive decrease in the stream velocity, which in turn results in a progressive decrease in the slope of the beach.

As shown in Figure 2.4 (which is the actual plot of the profile shown in Figure 2.3), the profile can be more accurately represented by a series of straight lines, each section representing the length of the beach between the hydraulic jumps. The slope of each section is less than the slope of the previous section, since the average velocity decreases due to the energy lost in the hydraulic jump formed at the end of the previous section.

The beach development between the end-points is thus a self-establishment process where the slurry stream and the deposited material influence one another in such a way that the flow velocity decreases progressively along the beach, resulting in an overall parabolic profile.

2.3 Observed Beach Profiles

Presented in this section are the measured profiles of various beaches, followed by an analysis of these profiles based on the observations made in the previous sections.

These profiles were measured by observing the levels of the beach at numerous points along a line from the deposition point to the edge of the pool.

In selecting the line to be levelled, it was necessary, in order to observe the natural beach profile, to avoid cross flows, from other sides of the dam, which produce discontinuities in the beach profile. Cross flow and lateral flow (parallel to the wall) occur extensively on beaches where open ended deposition is used. The observations thus concentrated on platinum tailings dams (spigot system) where the beach development is influenced by cross flow only at the corners of the dam. With these dams, the observed profile was thus situated approximately midway between two dam corners.

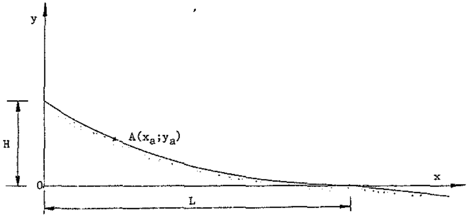
2.3.1 Observed Profiles on Platinum Tailings Dams

The profiles observed on the various platinum dams are presented in Figure 2.6.

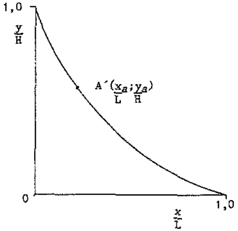
In this form, the similarities between the curves are masked. In order to compare the profiles, it is necessary to make them dimensionless, both with respect to height and length. Referring to the parameters defined in Figure 2.5, the dimensionless plot for a particular beach is obtained by dividing the x and y co-ordinates of a point on the actual beach (e.g. point $A(x_a;y_a)$), by the total length (L) and total drop (H) respectively, of that beach so that:

at $x= L$, $x_o= 1,0$ and $y/H= 0$
at $x= 0$, $x_o= 0$ and $y/H= 1,0$

Figure 2.7 shows the dimensionless plots of all the curves shown in Figure 2.6. These dimensionless plots give a vastly different picture in that all the curves are very similar, with the scatter of



a. Co-ordinate System for Measured Profile



b. Dimensionless Profile

Figure 2.5 : Definition Sketches of the Beach Profile

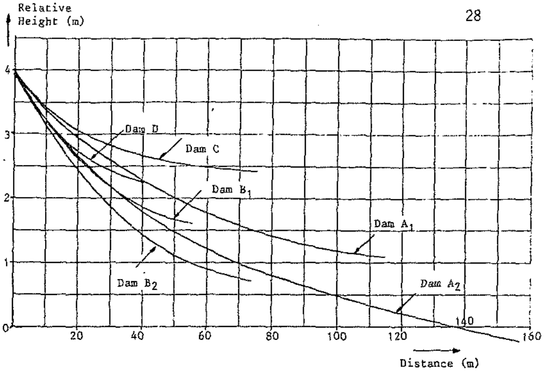


Figure 2.6: Measured Beach Profiles (Platinum)

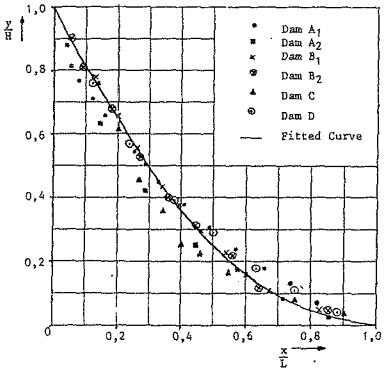


Figure 2.7: Dimensionless Beach Profiles (Platinum)

the results around the 'fitted' curve being small.

The fitted curve shown has the equation:

$$\frac{y}{H} = \left(1 - \frac{x}{L}\right)^2 \qquad 2.1$$

Although a polynomial of a higher degree may give a curve of a better fit, the above approximation was chosen for simplicity in the practical application of this theory (e.g for use in computer programmes), and for comparison with other dam types. Furthermore, it was felt unnecessary to be exact in a situation where further 'errors' are introduced by unpredictable variations such as cross-flows.

The above form of equation was found to agree with the observations of Melent'ev et al. (1973) who found that the beach profile can be represented by an equation of the form:

$$y = i_{av}\, L\, (1-x_o)^n \qquad 2.2$$

where $i_{av} = H/L$ is the average slope of the beach,
$x_o = x/L$,
and n is a parameter dependent on the particle size distribution of the deposited material.

Manipulation of this equation yields:

$$\frac{y}{H} = \left(1 - \frac{x}{L}\right)^n \qquad 2.3$$

which is the same as Eq.(2.1) when n is taken as being 2,0.

For the various dams, the magnitudes of the 'parameters' n and i_{av} are summarized in Table 2.2. These parameters will be discussed in more detail at a later stage in this chapter.

Table 2.1: Values of Average Slope (i_{av}) for Various Platinum Tailings Dams

Dam	Average Slope (i_{av})
A_1	1:39
A_2	1:42
B_1	1:23
B_2	1:23
C	1:47
D	1:26

Notes: 1. A_1 and A_2 imply measurements were taken on the same dam.
2. The low i_{av} value for Dam C results from beaching against an upgrade (new dam).

Table 2.2: Summary of Beach Profile Parameters

Tailings	Grade indicator (n)	Average Slope (i_{av})
Platinum	2,0	1:23 - 1:42
Diamond	1,5	1:52
Gold	4,0	1:390

2.3.2 The Beach Profiles for Diamond and Gold Tailings Dams

Figure 2.8(a) shows the observed beach profiles for the various dams in terms of the typical lengths encountered on each dam type.

Figure 2.8(b) shows the dimensionless plots, with the grade indicators (n) and the average slopes (i_{av}) summarized in Table 2.2.

These results are not as accurate as the results obtained for platinum tailings for the following reasons:

1. For the diamond tailings (observations on Premier tailings dam), the open-ended deposition method in use creates a great deal of cross-flow due to the sliming region being at a different level to the surrounding areas. Thus the unavoidable irregularities in the measured beach profile were attributed to deposition from the cross-flow, and were ignored in attempting to predict the natural profile of the beach.

2. For the gold tailings, the observations were conducted on the President Steyn Gold Mine tailings dam, since this dam had been out of operation for approximately three weeks, and was the only dam dry enough to walk on. Nevertheless, it was only possible to take observations over part of the length of the beach, and thus the results had to be extrapolated over an approximated beach length to the level of the pool.

These results do however show that the beach develops in a similar way on all the types of tailings dams, resulting in a parabolic beach profile. However, the profiles of the beaches of the different tailings types vary due to a number of factors such as the initial flow velocity and the properties of the deposited material. The influences of variations in the system variables on the beach profile are discussed below.

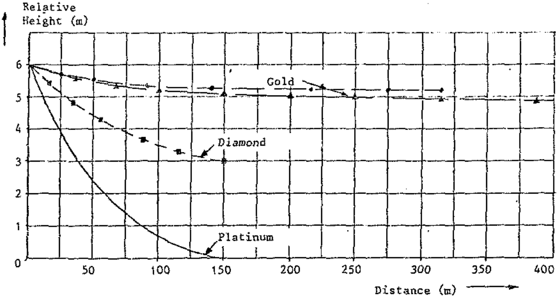


Figure 2.8 (a): Comparison of Typical Measured Beach Profiles

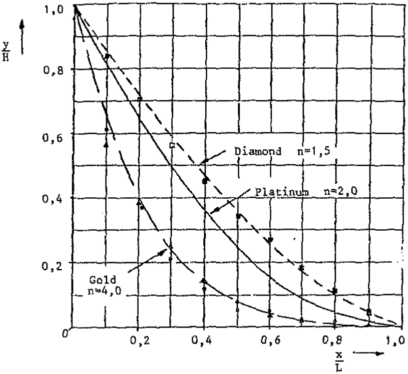


Figure 2.8 (b): Dimensionless Beach Profiles for the Various Types of Tailings

2.3.3 Discussion of the Presented Beach Profiles

The dimensionless beach profiles presented in Sections 2.3.1 and 2.3.2 show that the beach profile for a specific type of deposited tailings can be fairly accurately expressed as:

$$y = i_{av} L(1 - x_o)^n$$

where the parameters i_{av} and n depend on the 'system' properties.

Consider the similarity between the dimensionless plots for the platinum tailings dams for which the properties of the deposited material are very similar at each dam. We can logically conclude that if the the flow velocity and the particle grading distribution at the deposition point were the same at each dam, then beaches of the same length would have the same profiles.

This agrees with the analysis of the profile (Sec. 2.2) since, for the same initial flow conditions, and the same slurry properties:

i. The top of the beach would rise are equal amount due to the same suppression of kinetic energy at this point.

ii. Since the beach material and the hydraulic properties of the stream are similar, the self-establishment process would also be similar, resulting in the same beach profile.

It is thus felt that there are two major variables that influence the beach profile and these are:

i. The particle size distribution of the deposited material.

ii. The flow velocity at the top of the beach.

Let us now consider how these variables influence the beach profile.

Note that in the following discussion of the beach parameters, the results for the gold tailings dams have not been included as it was felt that since these beaches have such great lengths, they were not directly comparable with the diamond and platinum beaches. The possible influences of the beach length on the beach profile are discussed in Section 2.3.3.3.

2.3.3.1 The parameter n

From the description of the beach development in Section 2.2, one can visualize that the parameter 'i_{av}' describes the relative positions of the end points i.e. the average slope of the beach, while the parameter 'n' describes the shape of the beach between the end points.

The n parameter thus depends to a large extent on the interdependent influences of the slurry and the bed on one another since these determine the shape of the beach between the end points. Since it was impractical to quantify these variables on the tailings dams, it is as such not possible to determine conclusively the variables that influence the magnitude of n.

However from the results presented in Section 2.3.2, it seems likely that the n parameter is not influenced by the deposition flow rate (i.e. by the velocity at the top of the beach) since, although the deposition flow rates varied from dam to dam, an approximately constant value of n was found to apply to all the dams.

Furthermore, it seems that (ignoring gold tailings) the magnitude of n increases with increasing d_{50}, the mean particle size of the total tailings, as shown by the magnitude of n for platinum tailings ($n = 2,0$ - $d_{50} = 0,08$mm) as opposed to diamond tailings ($n = 1,5$ - $d_{50} = 0,012$mm).

This observation agrees with the work conducted by Melent'ev et al. (1973) who define n merely as a 'grade indicator', dependent on the particle distribution of the deposited tailings. Their study showed that n increases as d_{50} increases, but does not vary with a variation in the deposition flow rate.

It is felt that in order to quantify the variables which influence the n parameter, studies will need to be conducted in model flumes (see Chapter 6), where control over the variables such as flow rate, sediment concentration and particle size distribution can be exercised easily and over a short period of time.

2.3.3.2 The Parameter i_{av}

Note that for simplicity in the following analyses, whenever the influence of one variable is considered (e.g. variation in u_o, the initial velocity), then the magnitudes of each of the other variables (beach length, particle size distribution etc.) are all kept constant.

A. The Influence of the Deposition Flow Rate on the Average Slope

Consider again the analogous situation of the deposition of slurry on a flat surface, and for this situation, let us examine the effects of varying the flow rate of deposited material. Note that an increase in the flow rate logically implies an increase in the velocity at the top of the beach.

At very low flow rates, the mound will rise quickly, since most of the solids will be deposited at this point due to the low carrying capacity of the overflowing water.

As the flow rate is increased, so the carrying capacity of the overflow increases (with an increase in the velocity - see Section 3.1) and more solids will be carried over the edge of the mound to be deposited on the sides. Thus for the same quantity of deposited material, the mound will rise faster for a lower velocity.

Applying this concept to beaches of the same length, we can conclude that the average slope (i_{av}) thus decreases for an increase in the flow velocity.

This influence is often utilized by platinum tailings dam operators in order to 'push' more material out towards the pool, thus achieving a more efficient usage of the deposition area by flattening the beach. The deposition process thus has two cycles:

1. High velocity flow, obtained by opening fewer spigots, which prevents the build up of the beach at the deposition point and allows more material to be carried towards the centre of the dam, resulting in a flat beach.

2. A large number of spigots are opened up, resulting in a low velocity at the top of the beach which in turn results in the build-up of the beach in this region. This is necessary to obtain sufficient material to build the wall.

There appears to be no justification for the use of this method of deposition since deposition at a velocity between the high and low velocities would probably produce the same results, i.e. an overall flatter beach.

B. The Influence of the Particle Grading Distribution of the Deposited Material.

Consider two beaches of the same length, with the same deposition flow rate, but different particle grading distributions in that the one product has a larger content of coarse material.

It is logical, using the same reasoning as in (A) above, that since the overflow in each case has the same carrying capacity, the mound formed by the coarser material will rise more quickly for the same quantity of deposited material, since less material will be carried away in the overflow.

Thus we can say that the average beach slope will increase for an increase in the content of coarse material.

The above observations are in general agreement with the work carried out by Melent'ev et al. (1973) who found (from a large number of field and laboratory observations on hydraulic fills) that the average slope can be expressed by:

$$i_{av} = \frac{H}{L} = a_1 \, C_{so}^{\frac{1}{3}} \left(\frac{d_{50}}{h^*} \right)^{\frac{1}{6}} \qquad 2.4$$

where a_1 is a constant ($a_1 = 0,15$)
C_{so} is the initial sediment concentration ($C_{so}=Q_{so}/Q_w$)
d_{50} is the median particle size
and h^* is the stream depth associated with the scour velocity of clean water.

Unfortunately, although further empirical equations which they develop are based on this equation, the authors do not elaborate on this equation except to quote the reference from which the equation was obtained, and that Equation (2.4) is the transformation of the following equation:

$$i_{av} = a_1 C_{so}^{\frac{1}{3}} \left(\frac{q_{wh}}{q_w} \quad \frac{d_{50}}{d^*} \right)^{\frac{1}{5}} \qquad 2.5$$

where q_{wh} is the minimal bedform rate of water (a scour criterion)
q_w is the flow rate of water in the stream
and $d^* = 0,1mm$

In other words, the average slope is proportional to the initial sediment concentration and the particle grading distribution of the deposited material, and is inversely proportional to the velocity of the stream.

In this study, the sediment concentration was not considered to have an individual influence on the average slope, since the initial sediment concentration can be related to the velocity at the top of the beach as follows:

Since $Q_{slo} = Q_{wo} + Q_{so}$,

> where Q_{slo}, Q_{wo} and Q_{so} are the initial flow rates of the slurry, the water and the solids, respectively,

an increase in Q_{so}, while keeping Q_{slo} constant, implies a decrease in Q_{wo}, and hence a decrease in the velocity, (u_o) at the top of the beach.

Since the average slope is dependent on the inverse of the velocity at the top of the slope, the average slope is thus logically dependent on the initial sediment concentration, C_{so}, but not necessarily as an individual influence.

It is also felt that, since the average slope is not dependent on the entire particle distribution, but rather on the content of coarse material, the magnitude of i_{av} is not dependent on the d_{50} particle size, but more likely on a larger particle size, say d_{85}.

Again, it is felt that these effects will only be successfully quantified through the use of a model, with which the desired control can be obtained.

2.3.3.3 The Possible Influence of Beach Length on the Average Slope (i_{av}) and n

The validity of the above equation (Eq. (2.4)) for all beach lengths, is however doubtful, since the observations leading to the development of the equation, were generally conducted on 'short' beaches (embankments for hydro-electric power stations), these lengths being similar to the range of beach lengths considered in this study. The shortfall of this equation is that it implies that no matter what the length of a beach is, the relationship between the total drop and the length of the beach is constant, that is, the magnitude of i_{av} is constant.

For the range of beach lengths considered in this study, it is evident that the average slope of the beach for a particular system can be assumed constant, without introducing a significant error.

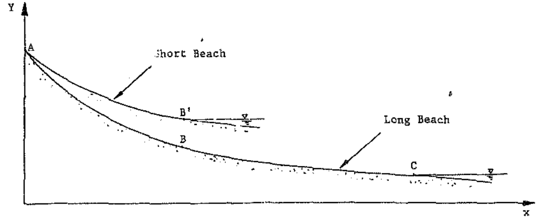
A problem is however encountered when extrapolating these results to beaches of far greater length, if it is assumed that the parameters i_{av} and n remain constant.

For example, let us compare the overall drop of a platinum beach of 100m length to that of a beach of 1000m length. Using an i_{av} value of 1/25, the 100m beach has a drop of 4m, while the 1000m beach would have an overall drop of 40m, which would clearly be unacceptable. (An actual case exists of such a tailings dam for which the operational beach length will eventually reach approximately 1000m.)

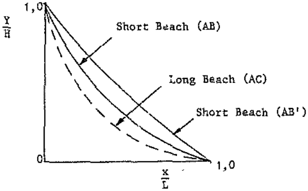
It is felt however, that it is unlikely that this situation will occur, this opinion being based on the fact that at no section along the short beach does uniform flow occur. Considering the profile for long gold tailings beaches, one will notice that the major proportion of the drop occurs over only a small length of the beach (associated with the supercritical flow condition) after which the the profile becomes flatter and can in fact be assumed a linear function of distance, i.e. the beach has an approximately constant slope which can be associated with a uniform flow condition.

Applying this hypothesis to the platinum beaches, it is thus probable that a similar flow pattern will occur for the long platinum beaches, that is, although the length of the supercritical region may increase due to the downstream control being effectively absent, this increase will not be very large, and if the beach is sufficiently long, flow will tend to a uniform subcritical flow condition, resulting in a flatter beach profile.

Figure 2.9 illustrates the above concept from which it can be



a. Suggested Profile for Long Platinum Beach



b. *Dimensionless Profile*

Figure 2.9 : Sketches Illustrating Probable Profile for very Long Beach

concluded that if the i_{av} value decreases in this way, then the magnitude of n will increase as illustrated by the dimensionless plots.

This change in n probably explains the observation that although gold tailings is finer than platinum tailings, the n value is greater for the gold tailings which is contrary to the analysis of the variation of n in Section 2.3.3.1.

Consider the beach profile in Figure 2.9 to be that of the profile for the gold tailings dam presented in Figure 2.8(a). If we assume that the above explanation holds true, and ignore the constant slope i.e. the uniform flow region, we obtain the beach of length AB in Figure 2.9. In this case, the value of i_{av} decreases from 1/390 to 1/160, while the parameter n changes to a value of approximately n = 1,85.

2.4 Summary of the Influences on the Beach profile

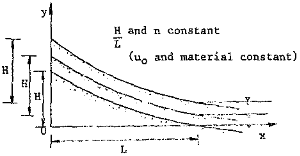
Summarized in Figure 2.10 are the variations of the beach profile which can be expected if variations in the basic system variables occur.

For constant system variables, i.e. i_{av} and n remain constant, Figure 2.10(a) shows the incremental beach rise for a constant beach length, while Figure 2.10(b) shows the beach profile for varying lengths of beach.

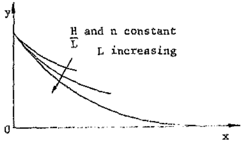
Figure 2.10(c) shows the variation in the profile with a variation in the particle size distribution of the deposited tailings where the magnitude of n increases with an increase in d_{50}, while the magnitude of i_{av} increases with an increase in the quantity of coarse material. In the illustration, i_{av} is shown to be proportional to d_{85} as discussed in Section 2.3.3.2.

Figure 2.10(d) shows the variation in the average beach slope with a variation in the deposition flowrate. In this case, the

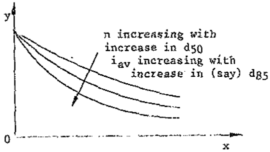
Figure 2.10: Summary of Influences on the Beach Profile



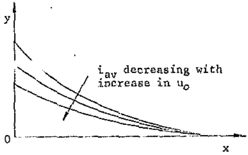
a. Profiles for constant set of system conditions showing incremental rise of beach



b. Profiles for constant set of system conditions but varying beach lengths



c. Profiles for variation in deposited tailings (u_o constant and L constant



d. Profiles for variation in deposition flowrate, i.e. u_o (initial velocity) (d_{50} constant and L constant) magnitude of i_{av} decreases for an increase in the deposition flowrate, or alternatively, for an increase in the flow velocity at the top of the beach (u_o).

2.5 Notes on the Use of the Beach Profile Equation

It was noted in Section 2.3 that the form of the beach profile equation i.e.

$$y = i_{av} L (1 - x_o)^n$$

was chosen for simplicity in the practical application of the equation, since this equation can be used for any tailings type by substituting the correct parameters for that material.

With the aid of a computer, this equation is very useful for modelling the surface of a tailings dam and in calculating volumes of deposited material. However, in order to use this equation, an approximation of the beach length must be made, and this can be done in two ways.

Firstly, the beach length can be approximated by assuming the size of the pool, the position of the pool being known since the position of the penstock inlet is known.

A problem is however encountered in using this approximation since the pool is generally not symmetrically located on the dam surface, due to elevation differences of the tops of the walls. Hence it is felt that a better approximation may be made by assuming the elevation of the pool, calculating the drop (H) from the top of each wall, and, by the indirect use of the i_{av} parameter (H/L), calculating the lengths of the beaches on each side of the pool.

At this stage, there is very little information about the profile of the material deposited in the pool, and thus a further approximation is required for this profile. Melent'ev et al.(1973)

suggest an exponential underwater profile of the form:

$$y = h(1 - e^{-ax/L}) \quad ,$$

where h is the total depth of the pool, and 'a' is a dimensionless coefficient. (In this equation, the y axis is positive downwards with the origin of the axes at the top of the underwater slope.)

This equation was however developed for underwater fills of a fairly large ratio of drop to beach length (i.e. steep slopes). The pools on ring-dyke dams were generally observed to be fairly shallow, and based on the profile presented in Figure 2.3, (observations taken on a dry dam) it is felt that it will be sufficiently accurate to use a straight line approximation from the end of the 'dry' beach to the low point at the penstock. The two equations can be combined by simply extending the dry beach from its maximum length, at a constant slope.

Although a number of approximations are necessary, the equation of the beach profile nevertheless provides a simple and fairly accurate method of modelling the surface of a tailings dam, requiring the input of only a small number of variables, these being the relative elevations of the end-points of the beach, and the beach profile parameters for the 'dry' and underwater beaches.

This equation can be easily incorporated in a computer programme to simulate the progress of a tailings dam, and thus predict the volume of deposited material and hence the rate of rise of the dam at any stage of its 'life'.

3.0 THE VARIATION OF MATERIAL PROPERTIES ALONG A BEACH

In order to be able to assess the overall stability of a tailings dam, it is necessary for the designer to have some idea of how the material properties vary along the beach from the wall to the edge of the pool.

One of the results of using hydraulic fill techniques, is that one obtains the separation of particles in the original material into coarse and progressively finer fractions.

Since the coarse material, once it has been allowed to consolidate, has better drainage, and hence strength properties, than the finer material further along the beach, the material deposited at the top of the beach can thus be used to construct the wall, which should be well drained for stability.

This chapter discusses the basic principles of particle separation (in terms of size) in a slurry stream, after which the results of the studies on the variation of the particle size distribution (fractionation), and the variation of some properties of the dry material along the beach, are discussed.

3.1 The Variation of Particle Size Along The Beach ('Fractionation')

Since the velocity of the slurry stream varies along the length of the beach, one can thus expect that this variation will result in a variation of the particle size distribution along the beach.

In this section, a simplified analysis of how the variation in the velocity gives rise to particle size separation is presented, after which the results of observations conducted on various tailings dams are presented.

3.1.1 The Basic Principles of Particle Size Separation

Consider a particle resting on a bed of slope i, with flow in the direction of the slope.

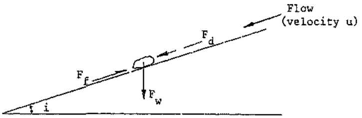


Figure 3.1: Definition Sketch for Critical Velocity Equation

The drag force F_d is expressed by:

$$F_d = C_d K_1 d^2 \frac{\gamma_w U_b^2}{2g} \qquad 3.1$$

The weight of the particle is:

$$F_w = K_2 \gamma_w (G - 1) d^3 \qquad 3.2$$

and the force resisting motion F_f is:

$$F_f = F_w \cos i \tan\phi \qquad 3.3$$

where:

C_d is the coefficient of drag,

k_1 and k_2 are constants,

u_b is the bottom component of the stream velocity,

G is the specific weight of the soil skeleton,
d is the particle diameter,
and ϕ is the angle of friction of the material.

In general, a granular particle will slide before it rolls (Stephenson (1979)) since:

For sliding equilibrium,

$$F_{ds} \leq F_f = K_2 \gamma_w (G-1) d^3 \cos i \tan \phi \qquad 3.4$$

For overturning,

$$F_{do} \frac{d}{2} \leq K_2 \gamma_w (G-1) d^3 \cos i \frac{d}{2}$$

(where d is a representative dimension of the particle.)

whence,

$$F_{do} \leq K_2 \gamma_w (G-1) d^3 \cos i \qquad 3.5$$

Since $\tan \phi < 1$, $F_{ds} < F_{do}$, and the particle will slide before it rolls.

Considering sliding equilibrium, the condition of incipient motion of a particle can be described by:

$$\tan \phi = \frac{\text{Forces parallel to bed}}{\text{Forces normal to bed}}$$

whence

$$\tan \phi = \frac{F_d + F_w \sin i}{F_w \cos i} \qquad 3.6$$

Substituting for F_d and F_w yields

$$\frac{(u_b)_{cr}}{g\, d\, (G-1)} = 2 \frac{K_2}{K_1 C_d} (\cos i \tan \phi - \sin i) \qquad 3.7$$

where $(u_b)_{cr}$ is the critical bottom velocity at which incipient motion takes place. (Equation (3.7) is known as a critical velocity equation.)

The quantity of the right hand side in Eq.(3.7) is referred to as the sediment coefficient A' which depends on;

1. the particles, their size, uniformity, shape, size distribution, texture etc.,
2. the dynamics of flow, since this determines C_d,
3. the channel slope (i),

and 4. the angle of friction of the material (ϕ).

Following on this principle, a number of empirical equations *predicting incipient motion* have been developed. Figure 3.2 shows one such analysis by Hjulström (1935) of data obtained for "monodisperse material on a bed of loose material of the same size of particles". Thus, depending on the size of a particle and the velocity of the stream, the particle *will* either be *deposited*, transported, or lifted from the bed (erosion).

For the slurry stream on the beach, fractionation thus occurs as a result of the decrease in the velocity along the beach, as discussed in Chapter 2. That is, at the top of the beach, where the velocity of flow is high, only the coarser particles are deposited. As the flow proceeds along the beach, the forces causing particle motion (drag) decrease, with the result that progressively smaller particles can be deposited.

A *problem* is however encountered with the slurry flow in attempting to predict the particle size which will be deposited at a point, since the behaviour of the particles is extremely complex.

As in sediment transport theory, the solids in the slurry stream can be considered to be transported in two states (see Figure (3.3), these states resulting from gravitational sorting of the particles at the point of deposition.

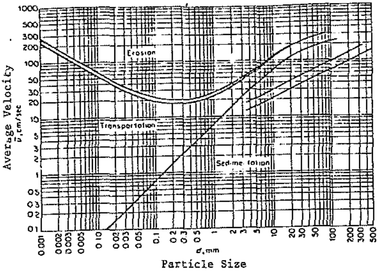


Figure 3.2 : Erosion-Deposition Criteria for Uniform Particles

(After Hjulström)

(From Graf (1971))

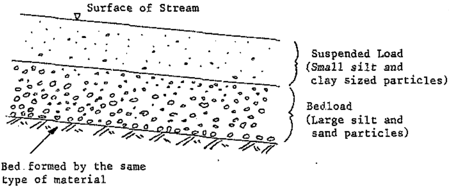


Figure 3.3 : Idealized States of Solids Transportation in a Slurry Stream

i. Coarser particles are transported in the region of the stream adjacent to the bed, mainly by rolling, pushing and saltation (jumping). This state is normally referred to as the 'bedload' of a stream.

ii. Fine particles are transported in a state of suspension, these particles constituting the 'suspended load'. (Although this may not be immediately apparent, evidence will be provided at a later stage for this occurance.) Note that with increasing distance along the beach, particles that are initially carried in suspension settle gravitationally (according to Stoke's law) and if not 'hindered' may eventually become part of the bedload.

Since the depth of flow is generally small, (<100mm) and the number of particles in the stream is very large, it is fairly obvious that in the slurry stream, where flow is generally turbulent, these two states will not be well defined, and that fine particles may be trapped within the bedload, while coarse particles may be held in suspension due to 'hindered' settling.

For this reason, the fractionation is not as definitive as one might expect, and one will find fine particles deposited at the top of the beach, and coarse particles deposited at the end of the beach.

Thus, at all points along the beach, one will not find a sample containing particles of a single size, but rather a distribution of particle sizes with the particles at the end points of the distributions being approximately similar, the contents of the fractions between the end points varying along the beach (see Figures 1.4 and 3.4). Thus in Equation 3.5, d cannot be defined as a single particle size, resulting in the need to define a characteristic particle size.

Melent'ev et al. (1973) noticed that if grading analyses are conducted at various points along the length of a beach, then at any one specific point, there is a fraction within the sample which contains a greater quantity (by mass) of particles, than each of the other individual fractions, and that this fraction corresponds with *the median particle size* d_{50} of the entire sample at that point (called the dominant fraction).

The fact that the dominant fraction corresponds with the d_{50} size is not merely coincidental, but can be explained as follows:

Firstly, the primary influence on transportation of particles is the hydraulics of the stream, i.e. drag etc., which determines the distance a particle will travel before it is deposited. At a point along the beach, this primary influence is of such a magnitude that a certain size of particle is deposited, this logically being the dominant fraction at that point.

In addition to the stream forces, secondary influences affect the deposition of particles, these being the trapping of fine particles *in the bedload and hindrance of settling of large* particles in suspension. Thus at a point, smaller quantities (by mass) of particles both greater and smaller in size than the dominant particle size, will be present in the beach material.

The dominant fraction is thus a 'central' fraction in terms of size, and if one considers a sample being made up of a central fraction that has a greater mass than the individual fractions on either side of it (in terms of size), then this central fraction will generally correspond with the d_{50} particle size of the entire fraction. (See example in Figure 3.4 and Table 3.1.)

Thus in terms of the incipient motion criteria, we can probably use the d_{50} particle size as the representative particle size at a point i.e. in Eq.(3.7), $d = d_{50}$, since deposition of particles greater and less *than this size results from secondary* influences resulting from the turbulence and solids concentration of the stream and not from the bed forces resisting motion.

3.1.2. Observed Variations In Particle Size Along The Beach

3.1.2.1 Sampling

At various points along the beach, samples of the beach material were extracted for particle grading analyses.

In attempting to obtain representative samples, the following sampling procedure was used:

i. Since each layer of deposition may be overlain by a thin layer of fines, (see Chapter 4), and since it was felt that material in these layers was not representative of the beaching process, it was attempted to avoid these layers by removing the surface material. Since the fine layers below the surface cannot be easily avoided, these layers may thus still cause an 'error' in the results.

ii. In order to obtain 'similar' samples at each point, a plastic sampling cylinder (ϕ-100mm x 100mm length) was pushed into the beach. The cylinder was then carefully extracted by cutting away the surrounding beach material, the samples being stored in plastic bags.

3.1.2.2 Particle Grading Analysis

Due to the presence of fines which adhere to the coarser particles on drying, the analyses required both wet and dry sieving as well as hydrometer analyses. Since a large number of samples were to be analysed, the following 'simplified' but accurate technique was used.

Each sample was firstly oven dried for 24 hours at a temperature of 105°C. The dried soil was then broken down into individual particles using a rubber tipped pestle, after which the sample was thoroughly mixed. A representative sample of approximately 350g was then sieved (dry) to a minimum sieve size of 300 µm.

Since the fines tend to adhere to the coarse particles, the material retained on each sieve (greater than 300µm) was again carefully broken down with the pestle until the coarse grains appeared clean and free of fines, after which the material retained on each sieve was weighed to 0,1g.

50g of the -300µm material was then placed in 125ml of a 4% solution of Sodium Hexametaphosphate (a commonly used laboratory deflocculant), and thoroughly mixed (for 15 minutes) using a mechanical mixer.

This material was then placed in a graduated cylinder to which distilled water was added until a 1 litre solution was present.

A hydrometer analysis was then carried out on this material using a 'percentage passing' hydrometer which is calibrated in such a way that a reading taken at a specified time after the beginning of the test, will give a direct result of the percentage material finer than a specified (predetermined) particle size. This method thus saves a great deal of time since it does away with the calculations normally required when using a 'specific gravity' hydrometer, as well as allowing up to three tests to be conducted simultaneously.

Once the hydrometer analysis had been concluded, the material used in this test was then washed through the remaining sieves, i.e. 150µm and 75 µm . The material retained on these sieves was then dried and weighed.

The results of a set of te [illegible] ucted on samples from a platinum beach, (Dam A) are tabulate [illegible] . Table 3.1, while the same results are presented graphically in Figure 3.4.

Two points are evident from these results, namely:

Table 3.1 : Example of Results of Particle Grading Analyses (Platinum Tailings - Dam A)

Distance	Pool		0m		9m		18m		36m		72m		90m	
Sieve Size (mm)	M_{ret}	%Pass	M_{ret}	%Pass	M_{ret}	%Pass	M_{ret}	%Pass	M_{ret}	%Pass	M_{ret}	%Pass	M_{ret}	%Pass
Dry Sieves														
0,6	0,0	100,0	1,5	99,5	0,5	99,8	0,6	99,8	0,0	100,0	0,0	100,0	0,0	100,0
0,3	0,0	100,0	66,5	77,9	25,3	91,6	37,1	87,6	4,9	98,4	0,2	9,9	0,2	99,9
Wet Sieving														
0,15	0,3	99,9	$\boxed{152,0}$	27,2	$\boxed{136,8}$	46,0	$\boxed{152,3}$	36,9	64,3	76,9	18,0	94,0	24,6	91,7
0,075	1,5	99,4	50,7	10,3	90,1	15,9	63,1	15,8	71,4	54,8	$\boxed{130,8}$	50,4	$\boxed{111,5}$	54,6
Hydrometer														
0,056	4,2	98,0	7,5	7,8	9,3	12,8	15,6	10,6	$\boxed{87,6}$	25,6	52,2	33,0	46,8	39,0
0,020	25,2	89,6	4,8	6,2	10,8	9,2	10,5	7,1	47,6	9,9	66,0	11,0	81,0	12,0
0,006	$\boxed{157,8}$	37,0	2,4	5,4	5,7	7,3	4,3	5,7	6,0	7,9	15,0	6,0	13,2	7,6
0,0017	75,0	12,0	4,5	3,9	5,4	5,5	6,6	3,5	9,0	4,9	2,4	5,2	5,4	5,8
d_{50}	0,0081		0,20		0,16		0,18		0,070		0,076		0,072	

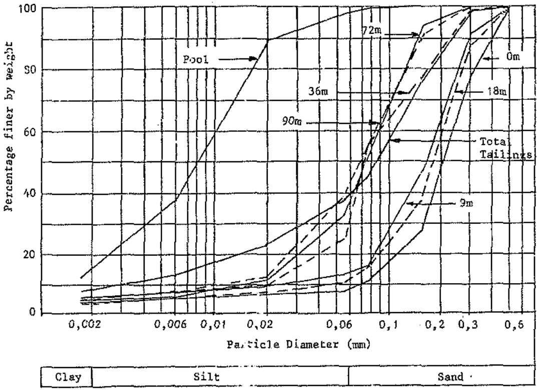


Figure 3.4 : Typical Set of Grading Curves Showing the Variation in Particle Size Distribution along a Beach
(Platinum Tailings – Dam A_1)

i. The fraction that contains the largest quantity of material, is centralized in the size distribution, and generally corresponds well with the d_{50} size of the sample.

ii. Although the maximum and minimum particle sizes are approximately the same at each point, the d_{50} size decreases with increasing distance along the beach.

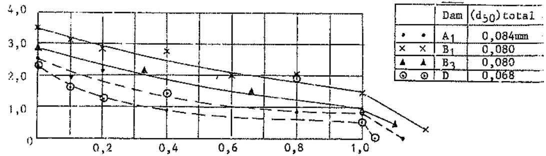
Although not evident in the presented results, it was however noticed while conducting the tests, that the coarsest particles (e.g. >600µm in this case) were present only at the deposition point, (i.e. 0m), and were not found at any other point along the beach. This illustrates the suppression of energy at the deposition point which results in the deposition of the coarser particles at this point, while the overflow still has sufficient potential to transport the remaining material.

For the comparison with other tailings types, and for practical use of the results obtained, i.e. for design purposes, it was felt that a standard form of presenting the results was necessary, and this can be done in two ways:

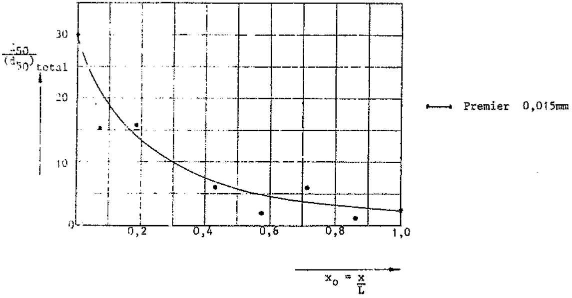
i. The results can be represented by plotting the variation of d_{50} with length along the beach. The results of the tests on all the tailings dams are presented in Figure 3.5 where $d_{50}/(d(50)_{total}$ is plotted against the dimensionless beach length (x_o). For comparison, the particle size d_{50} is made dimensionless by dividing each d_{50} size by the d_{50} size of the total tailings.

However, since the above representation does not show the variation of the individual fractions, (i.e. sand, silt and clay) the following representation (used by Melent'ev et al. (1973)) can also be used together with the above representation, giving a clear overall picture of the fractionation along the beach:

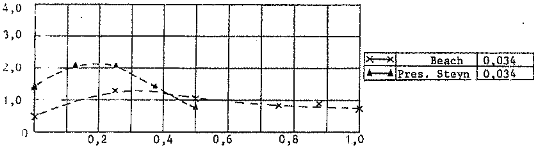
ii. As shown in Figure 3.6, the sample is divided into the various fractions (sand, silt and clay). The content of material is



a. Platinum Tailings

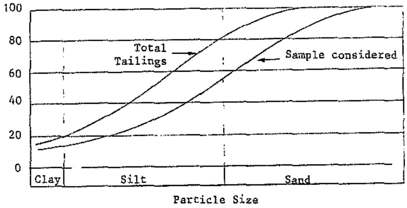


b. Diamond Tailings



c. Gold Tailings

Figure 3.5: Plots of $d_{50}/d_{50total}$ versus x_0 for the Various Types of Tailings



The parameter of fractionation is :

$$\phi_o = \frac{\phi_i}{\phi_{oi}}$$

where

ϕ_i is the percentage (by weight) of a specific fraction (e.g.clay) in the sample considered.

ϕ_{oi} is the percentage (by weight) of the same fraction as present in the total (deposited) tailings.

Thus for the sample considered above :

$$\phi_o\text{sand} = \frac{45}{20} = 2,25 \qquad \phi_o\text{silt} = \frac{40}{60} = 0,67 \qquad \phi_o\text{clay} = \frac{15}{20} = 0,75$$

Figure 3.6 : Definition Sketch of the Fractionation Parameter ϕ_o

then related to the total tailings by expressing the content of a fraction at a point as a percentage of the same fraction in the total tailings. The parameter ϕ_o so obtained is then plotted against the dimensionless beach length, thus illustrating the variation in the content of a specific fraction along the beach.

The results of the grading analyses are presented in this way in Figure 3.7.

3.1.3 Discussion of the Results

While examining the results presented in Figures 3.5 and 3.7 one must firstly recognize that 'errors' may be introduced by:

i. The inclusion of fines from 'clay' layers in the sample.

ii. The possible sampling of points where 'bedforms' may have caused a sudden decrease in the flow velocity.

iii. The fact that, for example on platinum dams, two stages of deposition i.e., high and low velocity, may be used by the dam operator.

These factors can influence the results in that some samples may contain unrepresentative proportions of fine or coarse material.

For the variation of particle size distributions along the beach, it is therefore feasible to examine the trends of the results, ignoring, to some extent, those results that seem likely to have resulted from any of the above influences.

The curves show the following trends:

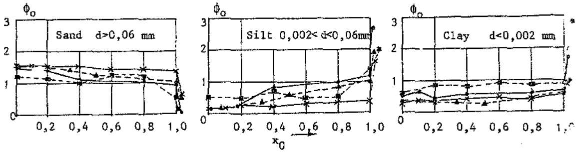


Figure 3.7 (a): Fractionation of Platinum Tailings

■---■ Dam D

●—● Dam A_1 ✗--✗ Dam B_1 ▲—▲ Dam C

Note: Points plotted at $x_o > 1,0$ represent samples from pool.

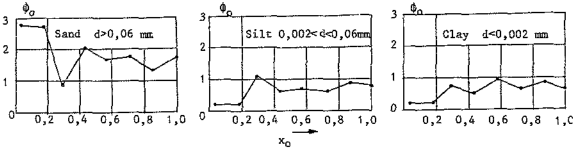


Figure 3.7 (b): Fractionation of Diamond Tailings

●—● Premier Diamond Mine

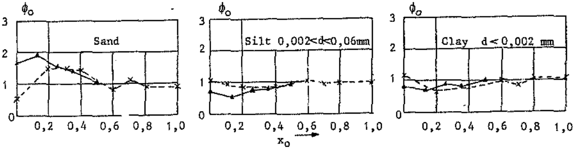


Figure 3.7 (c): Fractionation of Gold Tailings

✗--✗ Beach (420m)
(After Blight and Steffen)

▲—▲ This Study
(Pres. Steyn)

3.1.3.1 Variation of d_{50} Along the Beach

Except for the gold tailings, d_{50} decreases from a maximum at the point of deposition to a minimum at the end of the beach, the decrease in d_{50} associated with the decrease in velocity along the beach.

Although only approximate 'fits', the curves seem to have parabolic shapes. This can be associated with the fact that since the beach profile has a parabolic shape, we can assume that the average velocity along the beach (that resulted in this slope), varies in a similar way. Since d_{50} at a point along the beach is dependent on the velocity at that point, the distribution of d_{50} along the beach can also be expected to be parabolic.

Considering the platinum curves, [illegible] curves do not coincide with each other due to difference in the system properties (e.g.u_o) as well as due to the abovementioned influences that produce 'errors'. There does however seem to be a correlation between the slopes of the curves and the average beach slopes (i_{av}).

If we consider that the manner in which the plots are obtained (Figure 3.5) gives us a good indication of the degree of particle size separation along the beach, the degrees of separation on two or more similar beaches can be thus compared by comparing the slopes of the plots of $d_{50}/(d_{50})_{total}$ versus x_o. (It is felt that this is in fact a good method of representing the degree of particle separation which can otherwise not be quantified.)

Table 3.2 summarizes the slopes of the curves and the i_{av} values for the respective platinum beaches. From these results, we can conclude that, in general, the flatter the average beach slope, the less is the degree of particle separation along the beach.

This can be explained as follows:

Firstly, recall the influences which affect the magnitude of i_{av}, i.e. the velocity at the top of the beach (u_o) and the content of

Table 3.2 : Comparison of Degree of Separation with Average Slope (i_{av}) (Platinum Tailings)

Dam	Slope of $d_{50}/(d_{50})_{total}$ versus x_u	i_{av}
A	1:0,65	1:40
B_1	1:0,5	1:23
B_2	1:0,51	1:23
D	1:0,56	1:26

coarse material in the total tailings.

Considering variations in these influence individually, we can conclude that:

i. An increase in u_0 will result in a decrease in the degree of separation since coarse material which would have been deposited at the deposition point will be carried in the overflow to be deposited further along the beach. This will also result in a flatter beach.

ii. For constant u_0, i.e. the same carrying capacity of the overflow, a reduction in the coarse content would also result in a flatter beach as well as a decrease in the degree of separation since more material would be carried in the overflow to be distributed along the beach.

It seems also, that the degree of particle separation is inversely proportional to the uniformity of the deposited tailings, which is in fact logical since one cannot expect a large degree of separation to occur for a uniform material.

Thus the diamond tailings (Premier) shows a larger degree of particle separation than the more uniform platinum tailings.

For the gold tailings, the d_{50} size tends to remain fairly constant along the beach, with little evidence of particle size separation. This can be attributed to the fact that the deposited tailings is a uniform material ('single sized').

3.1.3.2 Variation Of Fractions Along The Beach

The 'curves of distributions' (Figure 3.7) show the following trends: (again excluding gold tailings)

i. The sand content decreases with increasing distance along the beach.

ii. The silt content increases with increasing distance.

These two curves illustrate the particle separation along the beach in that at high velocities, only the coarse material is deposited. As the stream proceeds along the beach and the velocity decreases, more and more finer material which settles through the suspension, is deposited on the bed.

iii. For the platinum beaches, the clay content remains fairly constant along the beach, the clay particles being trapped and forced out of suspension by the larger particles.

For the diamond tailings, there is evidence of an increase in the clay content along the beach, this increase attributable to the fact that the clay is flocculated, and thus individual clay particles tend to form 'flocs' which are larger than the individual clay particles. These 'flocs' will be trapped more readily than the individual clay particles and may even behave more like silt size particles thus resulting in an increase in the clay content along the beach (this behaviour is discussed in Chapter 5).

iv. There is an instantaneous decrease in the sand content as the slurry reaches the pool (from samples taken 0,5m into the pool). The clay and silt contents of the pool material are very large compared with the contents of these fractions on the beach.

This illustrates two previous statements, i.e:

a. There is a definite discontinuity between the beach and the pool, i.e. the processes of deposition are different.

b. The majority of the silt and clay particles are transported in suspension (i.e. as the suspended load), and are carried to the pool.

3.2 The Variation in Shear Strength along the Beach

A knowledge of the variation in the particle size distribution along the beach is particularly useful, since the drainage and consolidation properties are strongly influenced by the particle size distribution, and hence so is the shear strength.

Considering the 'normally' deposited material just after a deposition cycle (i.e. ignoring the presence of clay layers), one can expect a significant decrease in the coefficient of permeability along the beach, associated with the increase in the proportion of fine material along the beach.

This can be illustrated using Hazen's equation, i.e.:

$k = 100d_{10}^2$ k is the coefficient of permeability (cm/s)

d_{10} in cm

Figure 3.4 shows that, in this particular case, d_{10} decreases from 0,07mm at the top of the beach, to 0,01mm at the edge of the pool, and the application of the above equation implies a significant decrease (two powers of ten) in the magnitude of the coefficient of permeability.

This variation in the permeability implies that once the deposited material is allowed to dry, there will be a variation along the beach in the rate of drainage and hence in the rate of consolidation, resulting in a variation in the rate of gain in shear strength.

The process of consolidation is influenced by both sundrying and the seepage of pore water towards regions of lower total head. The material at the top of the beach, being more permeable, will thus consolidate far more rapidly than the less permeable material near the pool.

The rate of consolidation of the material near the pool is also influenced by the proximity of the pool and the water table (i.e.

by the hydraulic gradient), and the quantity of seepage from this material is very much less than that from the material at the top of the beach. Furthermore, due to the downgrade of the beach and the presence of clay layers, pore water will also tend to migrate from higher up the beach towards the pool, replenishing the pore water lost through evaporation and seepage.

Presented in Table 3.3 are the variations along the beach in the density, void ratio, moisture content and degree of saturation, from which one can notice the significant variation in the rate of consolidation along the beach.

Figure 3.8 shows the variation in measured shear strength along the beaches of four platinum dams, Dam E being inoperational (dry for approximately 6 months) while all the other dams were fully operational.

The shear strengths were measured using a hand shear vane, all measurements being taken with the blades at an average depth of 0,5m. The tests were performed at a quick rate, the measured strengths thus representing *'peak' undrained strengths*. (The use of undrained strength in a stability analysis is based on the probability that a sudden failure will not allow the dissipation of excess pore pressures that may exist in the material, or that may develop during shearing of the material.)

Again it was necessary to present the results in a dimensionless form so that a comparison of the variation in strengths between the various dams could be made. As a result of different 'drying times' on different dams, there is little possibility of obtaining a similar set of results for any two dams.

The shear resistance of a soil mass is dependent on the void ratio of the material, since the smaller the void ratio, the greater the degree of interlocking between soil particles, and the more the soil must 'dilate' in order for the particles to move up and over one another, implying an increase in the shear resistance.

Table 3.3: *Variation in Moisture Content, Density, Void Ratio and Degree of Saturation.*

x_o	M.C. (%)	Field Density (kg/m^3)	Dry Density (kg/m^3)	Void Ratio	Degree of Saturation (%)
0	15	2081	1809	0,52	79
0,33	21	2029	1677	0,64	90
0,66	23	2002	1627	0,69	92
1,0	32	1931	1463	0,89	99

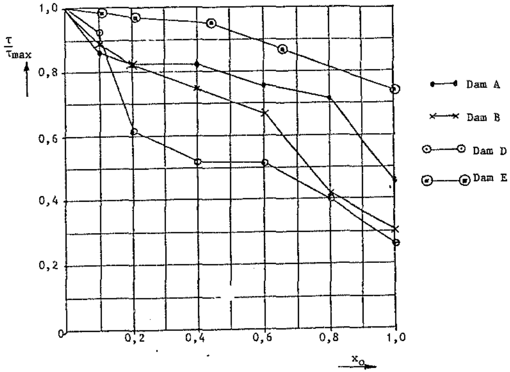


Figure 3.8 : Dimensionless Plots of Shear Strength vs. Distance from Deposition Point (Platinum Tailings)

Thus, associated with the increase in the void ratio along the beach, one can expect a decrease in the shear strength due to the decrease in the degree of interlocking between the soil grains.

The fact that the variation in the shear strength is so large can be attributed (Blight - personal communication) to the development of capillary stresses in the partially saturated material at the top of the beach, resulting from desiccation. The sundrying causes pore water tensions, which increase the stress between the soil particles, tending to overconsolidate the material.

The dilatancy of the overconsolidated material at the top of the beach increases the shear strength of this material significantly, relative to the 'loose' normally consolidated material further along the beach, when sheared at the same overburden pressure.

4.0 THE LAYERING PROBLEM ENCOUNTERED ON TAILINGS DAMS

As mentioned in Chapter 1, a layering effect is encountered on most tailings dams, where consecutive layers of deposition are separated by thin layers of fine, relatively impermeable material (clay layers). (See Figures 4.4 and 5.1.)

Since this occurrence is problematic in that it may ultimately lead to the failure of a dam, it was attempted during this study, to define the major causes of the layers in order to propose a solution which would minimize their formation.

This chapter deals with the effects of an anisotropic permeability on the position of the phreatic surface and the possible resulting influences on the stability of the dam, the causes of clay layering and the suggested solution to the problem of minimizing the formation of these fine layers.

4.1 The Effect of Anisotropic Permeability on the Position of the Phreatic Surface and the Stability of the Wall

For a layered system, where the permeabilities of the alternate layers are significantly different, one can logically conclude that the principal movement of water in such a system will occur in the material with the greater permeability.

If we denote the coefficients of permeability of the alternate layers as k_1 (normally deposited coarse material) and k_2 (clay layers), and the coefficients of permeability of the 'system' as k_h (for horizontal permeation), and k_v (for vertical permeation), we can make the following conclusions:

i. If the magnitude of the ratio k_1/k_2 is close to unity i.e. the system approximates to an isotropic system, the ratio k_h/k_v will also be close to unity.

ii. If the magnitude of the ratio k_1/k_2 is large (i.e. anisotropic), then the permeability of the system will be affected as follows:

A. Due to the presence of the impermeable layers, the vertical permeation through the system will be reduced, i.e. k_v will be small.

B. The reduction in vertical permeation results in a tendency for the water to flow in the material between the clay layers, the direction of the flow depending on the magnitude of the ratio k_h/k_v which varies as the ratio k_1/k_2 varies, i.e the greater the difference in the permeabilities of the layers, the greater the tendency towards horizontal flow.

Figure 4.1 illustrates the effect of the anisotropic permeability of the tailings, which has little effect on the position of the phreatic surface for low values of k_h/k_v. Table 4.1 shows some typical measured values of the ratio of the permeabilities of the coarse (k_1) and fine (k_2) fractions.

The ratio of horizontal to vertical permeabilities depends on the thickness of the relative layers, and Blight (1979) calculated that for diamond tailings (Kimberley - $k_1/k_2 = 60\,700$), the ratio of horizontal to vertical permeabilities was approximately: $k_h/k_v = 2900$

Blight says that this high value of k_h/k_v is "sufficiently large to force the phreatic surface to become almost horizontal, which is in fact the case at Kimberley".

The possible results of the layering are:

i. The phreatic surface is raised, causing seepage through the sides of the dam. This seepage may also occur due to a series

Table 4.1: Measured Values of k_I/k_2

Tailings	k_1/l_2
Gold	3 - 10
Diamond	60 700
Platinum	300 - 1000

(After Blight and Steffen (1979) and Jennings (1979))

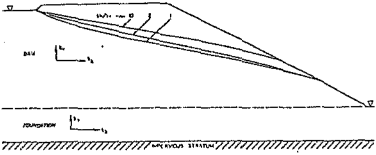


Figure 4.1 : Effect of Anisotropic Permeability on the Position of the Phreatic Line
(After Blight and Steffen (1979))

of perched phreatic surfaces caused by the clay layers.

ii. The wall stability is reduced due to the raised phreatic surface and the resulting high pore pressures set up in the wall material.

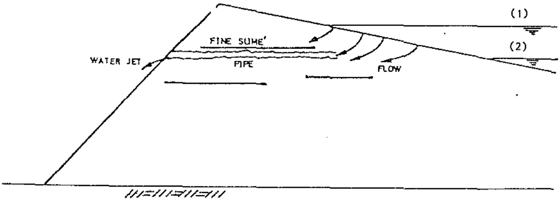
iii. The resulting horizontal permeation may initiate 'piping' and subsequent erosion through the body of the tailings, which may eventually result in a breach of the wall (Jennings 1979).

Investigations following the disastrous failure of Bafokeng Slimes Dam No.1 led to the conclusion that the failure was actually initiated by 'piping' through the layered wall (Jennings 1979). Figure 4.2 shows the mechanisms of piping suggested by Jennings.

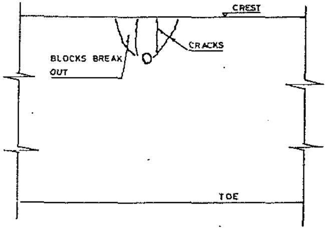
In Fig.4.2, the water level in the pool rises suddenly (e.g. during a heavy rainfall) from level (2) to level (1).

> "Water will flow quickly into the slime of the wall which will probably be partly saturated in the vicinity of the wall. The water encounters layers of fine slime. It tends to run along the tops of these layers and fairly quickly saturates the coarser material sandwiched between the fine layers.
>
> Under the influence of the additional superimposed load as the dam was raised higher, the coarse material tends to take up a smaller volume. If conditions such as thicknesses of layers are not homogeneous and uniform, a local open passage can develop beneath a fine slime layer. In this way a pipe can be started and in due course a jet of water may emerge from the face of the dam, as in Fig.4.2(b). As the pipe quickly expands wedges of soil break out to create an open channel and ultimately the dam fails."

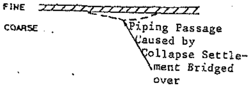
Flow slides (slope failures followed by the flow of liquified



(a) SECTION



(b) ELEVATION OF DAM



(c) DETAIL OF COLLAPSE PASSAGE

Figure 4.2 : Mechanism of Piping Suggested By Jennings
(After Jennings (1979))

tailings), thought to be associated with the raised phreatic surface, have occured at Kimberley tailings dam and more recently at a platinum dam, thus stressing the need for further investigation of the layering problem.

4.2 Brief Assessment of the Layering Problem for the Various Dam Types

From the values quoted in Table 4.1 and from the fact that failures have occured at both platinum and diamond tailings dams, the problem is unquestionably in need of a solution.

However gold tailings differs from diamond and platinum tailings in that it generally has a small coarse fraction and consists almost entirely of silt and clay sized particles (Fig.1.1). Because the material is fine-grained and single sized, and there is little evidence of any particle size separation even over very large distances (Chapter 3), gold tailings is deposited in a different manner, resulting in different design principles.

The *deposition procedure* is as follows:

> During the nights, the tailings is deposited into the body of the dam, thus allowing the development of a beach (Fig. 1.3)
>
> During the day, the tailings is deposited into 'paddocks' enclosed by inner and outer crosswalls (Fig. 1.3 - 'day wall'). After deposition, the tailings is allowed to dry for 2 to 3 weeks by evaporation and seepage, after which the dykes and crosswalls are raised by hand-packing moist material, resulting in a strong 'shell' as the wall of the dam.

The solids thus settle out gravitationally resulting in a situation opposite to that desired for platinum and diamond tailings, i.e. each layer of deposition is overlain by a thin layer of fine, less permeable material.

The occurrence of these fine layers in the paddocks is desirable since their presence prevents the re-entry of substantial quantities of water during subsequent deposition and during prolonged periods of rainfall (Chamber of Mines Handbook 1979). However the same reference accepts that the above situation is only acceptable if k_h/k_v remains low so that there is little possibility of the formation of channels of concentrated flow, during periods of prolonged rainfall, which may result in piping.

Although piping is commonly observed in gold tailings, the piping appears to be associated with shrinkage cracks, and has not yet led to disastrous failures. Thus there is little justification for any changes to the system.

Unfortunately the same deposition method cannot be used for diamond and platinum tailings for the following reasons:

i. Since only gravitational sorting occurs, the values of k_h/k_v in the paddocks would certainly be higher than those quoted in Table 4.1, these values already being far greater than the acceptable values.

ii. Along the length of the wall (i.e. into the page in Figure 1.3(a)), the paddocks must be graded to allow for the natural beaching gradient of the material. This natural gradient is far greater for diamond and platinum tailings due to the presence of a larger quantity of coarse particles in these materials. The paddocks would thus be steep in the direction of the wall, and this would lead to problems in achieving the required freeboard around the entire dam.

Thus it can be concluded that the gold 'paddock' system is unsuitable for platinum and diamond tailings, and that the solution to the layering problem must be sought elsewhere.

In attempting to reduce the effect of the fine layers on platinum tailings dams, a construction method has been adopted whereby the dry tailings in the proximity of the wall is mechanically pushed back and used to raise the wall (*Figure 4.3*). In this way, the layers near the wall are destroyed to some extent.

It is felt however, that this method possibly worsens the situation, since the cutting-back of the beach allows the formation of horizontal layers along which seepage towards the wall can take place (see later discussion).

Blight (1979) concluded that the layering problem in diamond tailings is worsened by the fact that the clay content of the tailings is strongly flocculated and that an attempt should be made to deflocculate the clay and thus improve the situation. The deflocculation of diamond tailings and the use of hydrocyclones are discussed in Chapter 5.

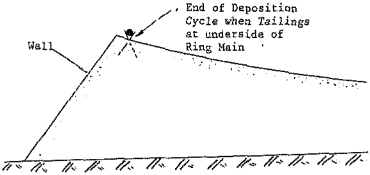
4.3 The Formation of Clay Layers

During the visual studies of the slurry flow and the beach development process, it was observed that the formation of clay layers occured on all the types of tailings dams. Since in most cases, it is difficult to delineate accurately between the fine and coarse layers, the observations are presented in a qualitative form.

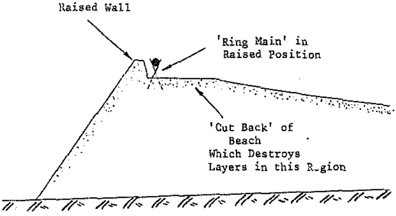
(Note: The term 'clay layer' is used throughout although in the case of some tailings types, clay minerals may not be present and the layers consist of clay-sized particles (i.e. less than 0,002mm).)

4.3.1 *The Modes of Formation of Clay Layers*

On all the types of tailings dams, one can observe clay layers overlying various regions of the dam surface. The layers vary in depth and area according to the mode of formation.



a. <u>End of Deposition Cycle</u>



b. <u>After Wall Building</u>

Figure 4.3 : 'Wall Building' on Platinum Tailings Dam.

The various modes of formation are:

1. Layers resulting from gravitational settlement

Clay layers are generally found in areas where gravitational settlement occurs after a deposition cycle. Examples of this type of formation are:

i. In the space between the constructed wall and the 'mound' where stagnant tailings collects during the deposition cycle.

ii. In the basin of the mound itself which is filled with stagnant tailings.

iii. In scoured rivulets where a change of direction occurs resulting in a furrow which retains tailings after the deposition cycle.

iv. Due to the cutting back of the beach during wall building, reverse slopes might occur on which the tailings can settle gravitationally.

2. Inefficient closure of spigots

At the end of a deposition cycle, the spigots (or valves) are seldom shut off properly, and as a result, fine material that can pass through the small openings is deposited on the beach. After a while, the slurry in the pipe blocks up the openings and no more material can pass through the openings.

This situation can obviously only be rectified by ensuring the proper closure of the spigots at the end of the deposition cycle.

3. Overflow from rivulets of concentrated flow

In order to understand this mode of formation, recall firstly the distribution of particles in the slurry stream, i.e. the coarse particles (constituting the bedload) are transported close to the previously deposited bed, while the silt and clay sized particles are transported in suspension.

It can thus be concluded that, should overflow from rivulets occur, then this overflow will consist almost entirely of silt and clay sized particles. Should coarse particles be present in the overflow, they will be deposited immediately due to the low carrying capacity of the overflow stream.

This overflow from rivulets of concentrated flow does occur on a fairly large scale, the overflow resulting from:

i. Surges in the flow.
ii. Sudden increases in the flow depth after hydraulic jumps.
iii. Collapses of parts of the 'banks' of the rivulets due to underscouring.
iv. Overflow at the ends of the 'trough' scoured parallel to the ring main by the deposited tailings.

Plate D shows a length of a platinum beach on which deposition is taking place. One can see from this photograph that the deposition area is higher than the surrounding areas, and thus any overflow will tend to flow towards the areas surrounding the sliming section, with little possibility of the overflow being washed away into the pool. (Note that, for at least part of the length of the beach, the concentrated flow is contained within the sliming region since the supercritical flow tends to proceed along a straight path.) One can also notice that the entire foreground area in this photograph is wet, although fairly well removed from the sliming area.

This 'moisture' is in fact overflow material from the main sliming area and was observed to consist of very fine material, the depth

Moist area consists almost entirely of clay material

Plate D - Overflow of Fines onto Regions Adjacent to Sliming Area of the layer varying from 5-10mm (approximately).

This layer covers a large area of the surrounds of the sliming area, and the continuity of the layer thus leads to this mode of formation being considered the major contributing factor to the anisotropy of the system.

It should be noted that the cutting-back of the beach, in combination with this mode of formation, may result in horizontal layers, or even layers sloping towards the outside of the dam (Figure 4.4), which are felt to be very undesirable for the following reason:

If one considers that for seepage towards the wall to occur, and hence for piping (as suggested by Jennings) to occur, then horizontal or negatively sloping layers are more likely to result in such flow. (Note that Jenning's analysis was based on the presence of horizontal layers formed by gravitational settlement.)

If the naturally formed beach profile was left as formed, then the slope of the layers at the top of the beach would be steep, since the slope of the beach is a maximum in this region. Therefore, seepage towards the wall would be unlikely due to the high gradient that would be required to cause upward flow.

However, once the beach is cut back, the much shallower or negative slopes may allow seepage towards the wall to occur. Furthermore, these layers, being at some depth after a deposition cycle, will not be destroyed during the next wall building step, although the majority of the steep sloping layers which prevent seepage towards the wall, will be destroyed.

4.3.2 Suggested Solution to the Layering Problem

The above description (overflow) of the formation of clay layers differs from other suggested modes of formation in that the layers

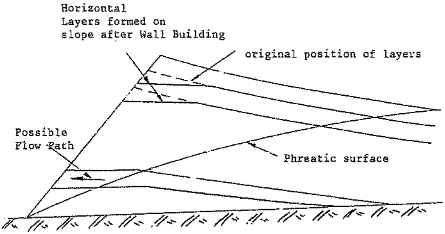


Figure 4.4 : Horizontal and Negatively Sloping Clay Layers due to Wall Building

are formed outside the sliming area.

From this fact, the solution to this problem is fairly obvious, and involves the construction of training walls (parallel to the direction of flow), which contain the flow within the sliming area (Figure 4.5). (The solution is only applicable to spigot systems that actually require such a solution.)

It was observed that training walls have in fact been used on platinum tailings dams. These walls were however spaced approximately 100m apart, resulting in the deposition cycle probably covering only part of the region between the walls, and thus the above described formation could still occur.

The efficiency of the walls in minimizing the formation of clay layers depends on the following factors which should be considered in the design of the walls:

i. The spacing of the walls must correspond with the width of the beach normally slimed during a deposition cycle, i.e. no area of the beach between the training walls should be partially slimed.

ii. Since subcritical flow results partially due to the widening of the stream, the length of the walls should be as long as or longer than the supercritical region, thus forcing the supercritical flow to occur over a longer distance. The higher velocity so obtained will ensure that a larger amount of fines will be transported to the pool.

iii. The ideal wall spacing and length would, in combination with the normal flowrate, produce 'sheet flow' covering the entire area between the cross-walls. Since the flowrate (Q/b) is dependent on the number of spigots opened during the deposition cycle, it is envisaged that a trial and error approach will be used to determine the ideal flow rate and thus wall spacing for a specific dam. The trials will thus need to be carried out for a number of wall spacings until the

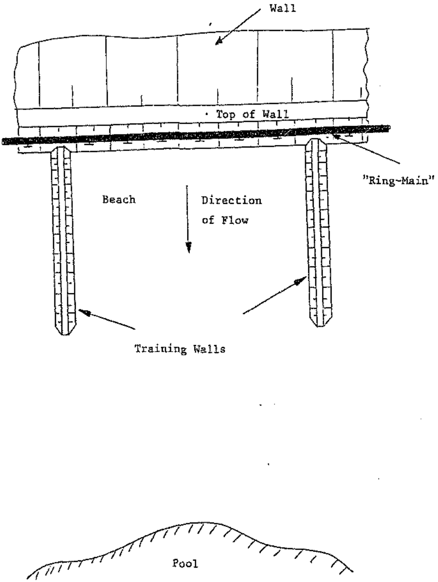


Figure 4.5: Plan View of Beach Showing Position of Training Walls used to Minimize Formation of Clay Layers

desired effect is achieved.

iv. Jennings (1979) recognised that when training walls were used, the front-end loader would often form depressions in the beach in which gravitational settlement, and hence the formation of layers could occur. In the construction of these walls, it is thus very necessary to avoid the creation of such irregularities in order to avoid the formation of layers.

v. The creation of horizontal or negative slopes by the wall building process must be avoided as far as possible. This can be done by borrowing material over a longer length of beach, instead of borrowing to a depth in the immediate vicinity of the wall. In this case, the beach slope and hence the slope of the layers will ensure that seepage will not readily take place towards the wall, and that the potential of the layers to become slip surfaces will be minimized.

As mentioned above, the ideal flow condition will be high velocity sheet flow, since this flow will allow very little settlement of fines held in suspension, as well as 'transporting' a greater proportion of the fines into the pool.

It is felt that, by using this simple and fairly inexpensive solution correctly and efficiently, in addition to the fines content on the beach being reduced, the formation of clay layers will be minimized, thus increasing the factor of safety against the possibility of piping through the wall and against possible slip failures.

The above solution has in fact been implemented at a platinum tailings dam, but it will be some time before a judgement of the results can be made.

5.0 KIMBERLEY DIAMOND MINE TAILINGS DAM - A STUDY OF PROBLEMS ASSOCIATED WITH THE PRESENCE OF FLOCCULATED CLAY

5.1 Introduction

Ideally, when using hydraulic fill techniques, the clay fraction should remain in suspension and be carried to the pool, thus minimizing the clay content along the beach and the negative effects of a high clay content on the permeability and the shear strength of the wall material.

However particle size grading analyses conducted on material from the beaches of Premier and Kimberley Tailings dams have revealed that a relatively large amount of clay is being trapped along the length of the beach. (Blight (1979) and tests conducted by Blight on Premier Mine tailings.) The beach material appears to consist of "layers of an undifferentiated mixture of sand, silt and clay, separated by thin clay layers" (Figure 5.1).

Presented in Figure 5.2 are the dimensionless plots of $d_{50}/(d_{50})_{total}$ versus x_o, and the 'curves of distribution', illustrating the fractionation observed at Kimberley tailings dam.

The plots show that at Kimberley, there is very little particle size separation along the beach and the contents of the various fractions remain fairly constant along the beach. Blight (1979) attributed this behaviour to the fact that the tailings is strongly flocculated, i.e. the clay particles are attracted to, and become attached to one another.

It is interesting to note that although the total tailings at Kimberley and Premier mines are fairly similar, the degrees of particle separation achieved are very different. Although both tailings contain flocculated clay, it is felt that the difference

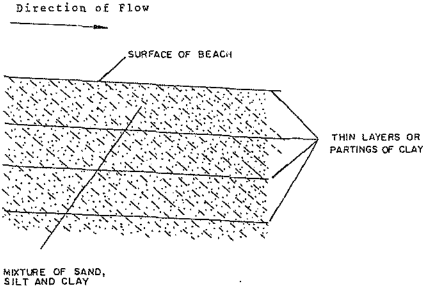
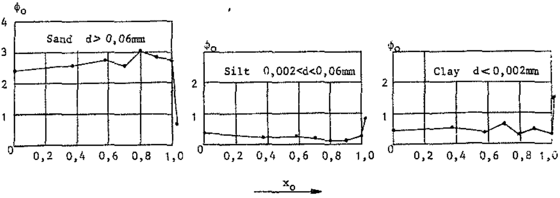
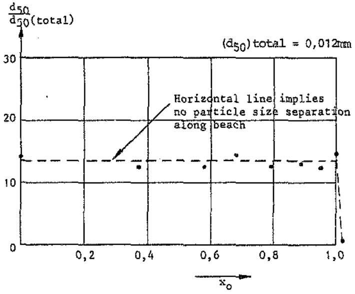


Figure 5.1 : Composition of Material on Beach of Kimberley Tailings Dam (after Blight (1979))



a. Curves of Distribution



b. Plot of d_{50}/d_{50}(total) versus x_o

Figure 5.2 : Particle Size Separation along the Beach of Kimberley Diamond Mine Tailings Dam.

in separation arises from the vast difference in the beach lengths, which result in a difference in behaviour of the flocculated clay, and hence a difference in the flow characteristics of the slurry stream.

The tailings dam at Premier Mine is a valley dam, with a beach length of 150 to 200m. This beach length can be attributed to the fact that the 'pool' is actually a very large water reservoir, and thus the water level probably does not change very much with time. (The observations on the beach profile actually indicated that the level of the pool had dropped slightly in the time between the end of the deposition cycle and the day on which the observations were taken.) For this situation, the beach length will probably increase with time, since, as the total drop increases (as the top of the beach builds up), so the length of the beach increases (see Chapter 2).

At Kimberley, a different situation occurs since the pool occupies almost the entire surface area of the dam, resulting in very short beach lengths of 5 to 25m. This large pool is simply a result of the fact that an excessive amount of water is being retained on the dam. Since the pool size remains constant, the beaches do not increase in length, and are at their shortest at the beginning of a deposition cycle (see Hydrocyclones).

Let us now compare the behaviour of the slurry flow at each dam:

Firstly, it is necessary to note that while a low shearing rate (i.e. low velocity) may accelerate the formation of flocs, a high shearing rate may be responsible for the breaking up of flocs (Graf 1971). Thus the high velocity of flow in the delivery line will probably not allow the formation of flocs, while once deposited on the beach, flocs may form at lower velocities.

At Premier Mine, the deposited slurry behaves initially like an unflocculated slurry, since high velocities exist at the top of the beach, allowing little floc formation, and hence the viscosity of the suspension remains low (the viscosity increases as the suspension becomes more flocculated - see Section 5.2). Thus the beach develops in the same way as discussed in Chapter 2.

However, as the velocity decreases with distance from the deposition point, the shearing rate also decreases, and thus more flocs begin to form. As noted in Chapter 3, these flocs, being greater in size than the individual clay particles, are more readily trapped by the larger particles settling out of the slurry. Due to their increased size, the flocs may also behave like silt sized particles, with the overall effect being an increase in the clay content along the beach.

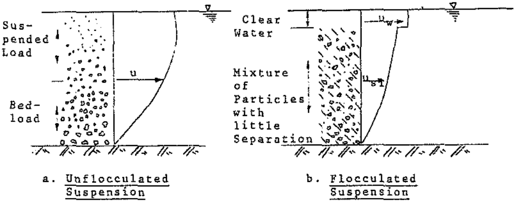
Since the beaches at Kimberley mine are so short, the backwater effect of the pool extends over the entire length of the beach, causing subcritical flow at the top of the beach. The low shearing rate thus accelerates the formation of flocs, and the slurry becomes very viscous even at the deposition point.

The slurry stream thus behaves like a highly viscous 'mud', being 'pushed' along the beach by the freshly deposited material, rather than 'flowing' along the beach.

One can thus imagine a difference in the velocity and particle distributions as shown in Figure 5.3.

For the unflocculated suspension, or the flocculated suspension at high velocities, the velocity distribution may be assumed to be continuous, the particles being sorted gravitationally into the 'bedload' and the 'suspended load'. (This is evidenced by the good degree of separation occuring at Premier tailings dam.)

However for the flocculated suspension, while the velocity is shown to be very low, a discontinuity in the velocity distribution is also shown, since it was observed that the flocculated solids, being viscous, undergo an immediate settlement as a 'body'. This immediate settlement results in a clear water layer, which flows over the slower moving viscous suspension.



a. Unflocculated Suspension

b. Flocculated Suspension

Figure 5.3: Velocity and Particle Distributions of Dispersed and Flocculated Suspensions

The flocculated suspension is also shown to have a poorly defined particle distribution since the formation of flocs and the resulting high viscosity of the suspension inhibits gravitational sorting.

The result of the high viscosity and the poorly defined particle distribution is that, although the total material is separated into a coarse fraction (beach material) and a fine fraction (deposited in the pool), there is little evidence of particle size separation along the beach, while the clay content is high along the length of the beach.

Discussed in this chapter are two possible methods of achieving the desired particle size separation, the two methods being:

1. the deflocculation of the clay content of the slurry by the addition of deflocculants, and
2. mechanical separation of the tailings into coarse and fine fractions, using hydrocyclones.

5.2 The Deflocculation of Clay in Diamond Tailings

5.2.1 Introduction

As mentioned in the introduction, a notable characteristic of a slurry containing flocculated clay, is the high viscosity of this suspension at low shearing rates.

Clays such as bentonite (sodium montmorillonite) are thus very useful as drilling muds due to their thixotropy, i.e. the clay (in the presence of water) behaves like a liquid at high shearing rates, and can thus be utilized as a lubricant. However, once the drilling is stopped, the clay becomes a viscous mass as it flocculates, and thus seals the borehole against losses and prevents the collapse of the sides of the hole.

Included in Appendix A_1 is the theory of flocculation and deflocculation of clay minerals, which can be summarized briefly as follows:

If the net effect of the attractive and repulsive forces between clay particles is attractive, the particles move towards each other and become attached i.e flocculated.

The deflocculation of clay is achieved by increasing the repulsive forces between the clay particles (usually by replacing the 'exchangeable cation') so that the net effect is a repulsive force, in which case the particles tend to move away from each other, i.e. become dispersed or deflocculated. Deflocculation of a suspension results in both a decrease in the viscosity of the suspension as well as a decrease in the rate of sedimentation of the clay particles from the suspension.

Since the poor particle separation achieved at Kimberley results from the high viscosity of the slurry, a logical way of improving the separation is to deflocculate the suspension whereupon the resulting slurry would have the following properties:

i. Due to the lower viscosity of the suspension, the flow properties of the slurry on the beach will be much improved. Firstly, the velocity of the stream at the top of the beach will be higher with the result that, in combination with the *gravitational sorting, most of the coarse* particles will be deposited at this point, instead of being transported further along the beach. This implies that the average slope of the beach would be steeper than before, which in turn implies higher velocities along the length of the beach. This implies both a better degree of separation along the beach, as well as an increase in the quantity of fines transported to the pool.

ii. Since the clay flocs will be dispersed, and the suspension will be less viscous, gravitational sorting will occur to a greater extent, with the dispersed clay particles remaining in suspension and being transported to the pool.

Overall, on deflocculating the clay content, one could expect both a better degree of separation of the material, as well as a reduced clay content along the beach.

5.2.2 Identification of Clay Mineral Types in Diamond Tailings

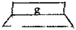
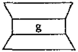
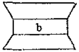
Since the deflocculation of clays requires the replacement of adsorbed flocculating cations by cations which tend to deflocculate the clay, it is therefore necessary to identify the clay types present in the tailings and the cations presently adsorbed to the clay.

5.2.2.1 Possible Clay Mineral Types Present in Diamond tailings

The material at both Kimberley and Premier Diamond Mines is mined from volcanic pipes filled mainly with the ultrabasic rock kimberlite. In addition to kimberlite, the pipes contain masses of non-volcanic material derived from the formations traversed by the pipe.

Extensive studies have been carried out on kimberlites to identify the minerals present. The many various minerals identified are fairly common in most kimberlites, the clay minerals of interest to this study being montmorillonite, saponite and vermiculite (Kresten 1973), all of which have undergone a certain amount of isomorphous substitution (Table 5.1). The predominance of these minerals depends on the extent of alteration and weathering of the original kimberlite

Table 5.1 Some Clay Minerals and their Properties

Mineral	Structure Symbol	Isomorphous Substitution	Interlayer Bond	Cation Exchange Capacity (meq/100g)	Basal Spacing
Kaolinite		little	O-OH Hydrogen strong	3-15	7,2 Å
Montmorillonite		Mg for Al 1 in 6	O-O Very weak expanding lattice	80-150	9,6 Å to complete separation
Saponite		Al for Si	O-O Very weak expanding lattice	70-90	9,6 Å to complete separation
Vermiculite		Al, Fe for Mg Al for Si	Weak	100-150	10,5-14 Å

(After Lambe and Whitman (1969))

g/b -Gibbsite or brucite sheet

 -Silicon sheet

5.2.2.2 X-Ray Diffraction Analyses

In order to identify the clay minerals present in the tailings, X-ray diffraction analyses were carried out on specimens from each tailings dam. To separate the clay fraction, -200μm samples were allowed to stand in 1 litre sedimentation cylinders (in distilled water) for 24 hours. The top portion of the suspension was then removed and part of each sample was soaked in a 1 Normal magnesium chloride solution for 24 hours (soaking in $MgCl_2$ tends to accentuate basal reflections of smectite clay minerals which were suspected to be present - Figure 5.4). The excess $MgCl_2$ was then washed off as efficiently as possible by repeated addition of distilled water followed by agitation and separation of the solids by means of a centrifuge.

The six samples were then analysed by the department of Geology at the University of the Witwatersrand. The X-ray traces, all very similar, conclusively indicated the presence of smectite clay minerals (first order basal reflections >15Å were observed in each case). Montmorillonite and saponite are members of the smectite group of clay minerals and it has generally been found that,in smectites, the adsorbed cation is Calcium (Ca^{2+}), a flocculating cation.(Prof. J.R. Mc Iver, personal communication, Mitchell 1976, and Grim 1968.) (Note that a brief review of the structure of smectite minerals has been included in Appendix A_2.)

Returning to the theory of deflocculation, the isomorphous substitution undergone by these minerals and the presence of a flocculating cation (Appendix A_1), point to the fact that these minerals will readily flocculate in the presence of water.

It was thus assumed that the flocculation problem in the diamond tailings was as a direct result of the presence of these clay minerals and that this assumption should be the basis for the application of the deflocculation theory.

Referring to Table 5.1, it can be seen that the clay minerals in

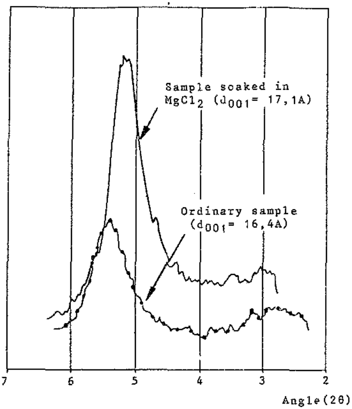


Figure 5.4 : Example of X-Ray Trace on Clay in Diamond Tailings (Kimberley Diamond Mine - First order basal reflections)

question exhibit similar characteristics, i.e. cation exchange capacity and isomorphous substitution.

As a simplification therefore, the theory is applied to a single clay mineral, montmorillonite, as if this were the only clay mineral present. The presence of other clay mineral types (known or unknown) is acknowledged, but it is assumed that they will be influenced by deflocculants in the same manner as the montmorillonite, should this influence be possible.

5.2.3 Laboratory Deflocculation of Tailings

The degree of deflocculation (or flocculation) of a suspension is not quantifiable, but can only be illustrated in relative terms.

In Section 5.2.1 it was noted that the major characteristic changes of the suspension on addition of a deflocculant are:

i. a decrease in viscosity and

ii. a decrease in the rate of sedimentation of clay particles from the suspension.

This implies that a comparative study may be made by measuring the variation of viscosity with increasing deflocculant concentration, and observing, by means of sedimentation cylinders, the effect of the optimum deflocculant concentration on the suspension. (Although the sedimentation cylinders do not model the actual situation accurately, it is nevertheless felt that this is an adequate means of conducting a comparative study.)

A number of commonly used sodium deflocculants were tested in this manner, and the results of the tests on the tailings from both Premier and Kimberley mines are presented below together with the laboratory procedure for testing.

5.2.3.1 Viscosity Tests

The viscosity of the suspension was measured using a portable viscometer which consists of two coaxial cylinders, the outer cylinder being driven at a constant speed by a two-phase synchronous motor. When immersed in a suspension the outer cylinder causes the liquid between the two cylinders to 'rotate', and the viscosity is measured as a function of the drag exerted by the liquid on the inner cylinder.

For each deflocculant tested, an initial reading at zero deflocculant concentration was taken, this reading being the basis for the calculation of percentage reduction in viscosity.

The variation in viscosity was noted for increasing concentrations of added deflocculant solution, the concentration being determined by noting the mass of added deflocculant and the total mass at each step.

(Note on presented curves:
Although initial viscosity readings were quite similar, no two initial readings were exactly the same, probably due to differences in the solids concentrations. Furthermore, one must be careful when interpreting the observations, since, while a low shearing rate may accelerate the formation of flocs, too high a shear rate may be responsible for the breaking up of flocs. Thus only the results obtained at the lower shearing rates have been presented. The presented plots are therefore intended to reflect trends and should not be interpreted as being exact.)

5.2.3.2 Determination of the Best Deflocculant Concentration for Practical Use

In order to determine the variation in the viscosity of a suspension for varying concentrations of added solution, and thus the best solution for practical use, let us firstly consider the addition of a single deflocculant, namely, soda ash.

Figure 5.5(a) shows the results obtained by the addition of varying concentrations of added solutions of Na_2CO_3 (Soda ash) in distilled water.

Taking as an example the 5% curve, this curve relates to the change in viscosity when a 5% solution (5g solid Na_2CO_3 in 100g solution (H_2O + Na_2CO_3)) is added in such quantities so as to give the overall concentration of solid Na_2CO_3 with respect to the total solution i.e. xg Na_2CO_3 solid per 100g total solution.(The total solution includes the tailings and the added deflocculant solution.)

As the exchangeable cation is most probably Ca^{2+}, we can refer to the clay as Ca clay.

With reference to Appendix A_3 which deals with the behaviour of clay in the presence of a salt solution, we can describe the reaction occurring as:

$$\text{Ca clay} + Na_2CO_3 \qquad \text{Na clay} + CaCO_3$$

(Note that in these equations no valency is ascribed to the clay, and where a cation M is adsorbed on the clay, the clay is denoted M clay no matter what the valency of the ion M. For this reason, these equations may not "balance" on the left- and right-hand sides (Ryan 1978).)

Calcium carbonate has a low solubility ($1{,}3.10^{-4}$ moles/litre) relative to soda ash (which is highly soluble) and we can conclude that the reaction will proceed to the right (evidenced by the achievement of deflocculation).

Thus at high enough concentrations of deflocculant, the sodium ions replace the calcium ions to produce a deflocculated sodium clay.

Also plotted in Fig. 5.5(a) is the contribution of added H_2O to the

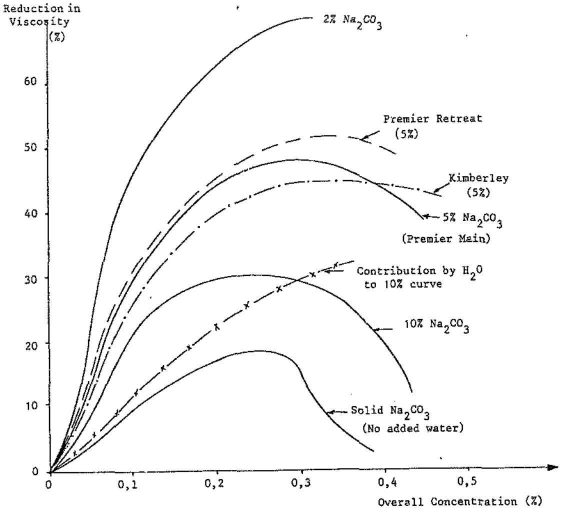


Figure 5.5(a) : Percentage Reduction in Viscosity versus Overall Deflocculant Concentration using Soda Ash

(Note: Tests conducted on Premier Main Tailings unless otherwise indicated.)

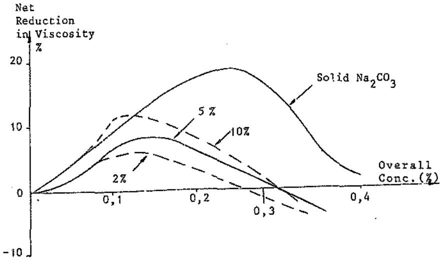


Figure 5.5(b) : Net Reduction in Viscosity versus Overall Concentration (Soda Ash)

reduction in viscosity for the 10% Na_2CO_3 curve. This curve is obtained by adding an equivalent amount of distilled water to the suspension as would be added in the 10% solution of soda ash and water.

Similar curves may be plotted for the other added solutions, and it is found that for a 2% solution the 'water contribution curve' lies very close to the deflocculant curve, i.e. the net effect of the deflocculant is very small when added in a low concentration solution.

We can illustrate this by plotting the net effect of the added deflocculant, i.e. the overall reduction in viscosity minus the reduction in viscosity attributable to the added water (Figure 5.5(b)). The decrease in reduction of viscosity at higher concentrations is due to an effect known as "overdoping" whereby the cation exchange capacity of the clay is exceeded, at which stage any further addition of sodium ions will crowd the double layer and reduce the negative potential of the clay (Ryan 1978).

From the resulting curves it can be concluded that the deflocculant has the greatest net effect on the reduction of viscosity *when added in solid form (i.e. no added water)*, although the addition of deflocculant in the form of a low concentration solution produces a far greater overall effect. This can be explained (refer to Fig.A4(b)) by the fact that for a deflocculated suspension, the resultant repulsive force between clay particles is greater in a more dilute suspension (greater separation distance between particles) than in a less dilute suspension in which the resultant force may even be one of attraction.

Comparing quantities of water and solid deflocculant required to achieve a specified overall concentration of say 0,2% we find that if added to 1Kg of tailings, we need approximately 2,08g Na_2CO_3 and 40g H_2O to achieve the specified concentration by adding a 5% solution. (See Appendix A_4 for calculation.) To achieve the same overall concentration by adding a 2% solution, we need approximately 2,22g Na_2CO_3 and 109g H_2O.

Thus a substantially larger quantity of water is added in the 2% solution, resulting in a more dilute suspension and thus a greater separation of particles. Also, the *viscosity of a suspension is* proportional to the solids concentration (Graf 1971) and thus, even for an unflocculated suspension, the viscosity would decrease for a decrease in the solids concentration.

It should also be noted that the above comparison shows that a greater mass of deflocculant is needed for the 2% solution. However the overall reduction in viscosity is far greater on addition of the 2% solution, *and a direct comparison of the two* solutions i.e. achievement of the same reduction in viscosity, yields a result where less deflocculant is required in the 2% solution. For example, to achieve a reduction in viscosity of 45%, we need 1,05g Na_2CO_3 and 52g water in the 2% solution, and 2,08g and 40g respectively in the 5% solution.

Thus a problem arises when choosing the optimum concentration since:

i. For a specified overall concentration, although less solid deflocculant is required when added in solution of higher concentrations, a less concentrated solution will produce better results due to the dilution effect of the added water. In fact when observed in sedimentation cylinders, only the suspensions treated with 2% and 5% solutions showed a good enough degree of separation, with the coarse grains apparently settling out completely, and the clay fraction remaining in suspension. (Observations were made on suspensions with overall deflocculant concentrations varying from 0,1% to 0 25%.)

ii. On preparing the deflocculant solutions, it was noticed that at high concentrations, the added deflocculant tended to form a 'gel' which could only be dissolved through continued stirring of the solution. To avoid this, it is felt that for practical use, it will be necessary to add the deflocculant in a low concentration solution where the formation of the 'gel' is unlikely to occur.

iii. Although an added 2% solution seems to produce the best results, we know that the deflocculant is only contributing to a small degree, and is thus being inefficiently utilized.

iv. Most of the tests were carried out on the Premier Main tailings. Although the Kimberley and Premier Retreat tailings show similar trends in reduction in viscosity (Fig.5.5(a) - 5% curves), the settling tests conducted on these materials did not compare favourably with those conducted on Premier Main tailings (probably attributable to differences in the treatment processes). In order to determine whether these tailings are being successfully deflocculated, one would have to conduct a more detailed analysis, such as particle grading analyses of the separated coarse and fine fractions.

v. A simple solution might be to increase the water content, since in doing so we seem to achieve the same results. However although a specified reduction in viscosity may be achieved by the addition of pure water, settling tests reveal that the clay is still flocculated to some extent and the coarse grains are still held in suspension. In addition to this, distilled water was used for the laboratory tests and mine water certainly does not produce the same results (Figures 5.6(a) and (b)). The 'return water' curves were obtained using Premier Mine return water which is continually cloudy with suspended clay particles.

Thus since the deflocculant is being inefficiently utilized in the 2% solution form, and since only the 2% and 5% solutions produced the desired effects, it was concluded that further tests should concentrate on the effects of the added 5% solutions, even though this is not the most efficient solution.

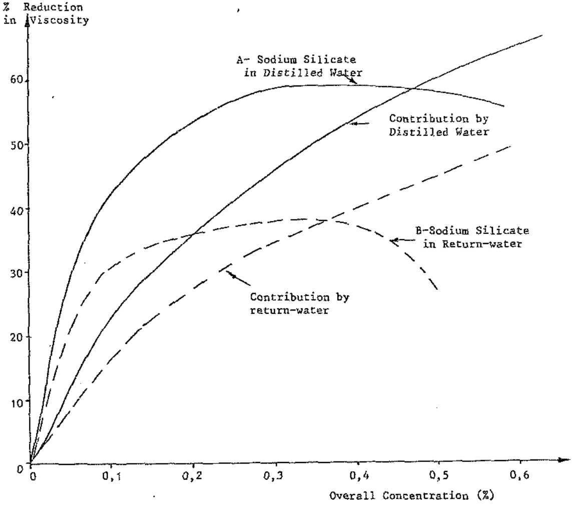


Figure 5.6 (a) : Percentage Reduction in Viscosity versus Overall Concentration. The Contribution by the added water. (5% Solutions)

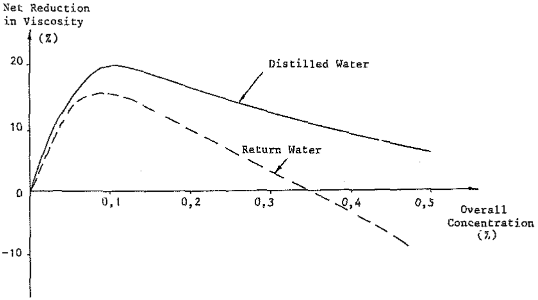


Figure 5.6 (b) : Net Reduction in Viscosity versus Overall Concentration.

5.2.3.3 Other Sodium Deflocculants

Similar tests were carried out on other sodium deflocculants in order to determine the most effective deflocculant, these deflocculants being:

Sodium Pyrophosphate - $Na_4P_2O_{13}$
Sodium Hexametaphosphate - $Na_6P_4O_{13}$
Sodium Silicate (Water Glass) - $Na_2O.n(SiO_2)$

Other sodium additives such as sodium chloride (salt) and sodium hydroxide (caustic soda) tend to flocculate the clay since the addition of either one increases the electrolyte concentration which has the effect of decreasing the double layer thickness (Mitchell 1974).

The results obtained by adding 5% solutions (deflocculant in distilled water) to the tailings are shown in Figure 5.7(a) together with the contribution by water to the reduction in viscosity. Figure 5.7(b) shows the net effect of the added deflocculant.

In order to choose an overall concentration for practical use, we must consider efficiency, effectiveness and cost. From Figures 5.7(a) and (b), we can see that very large reductions in viscosity may be achieved, but that at higher concentrations, the deflocculants are again being inefficiently utilized, since their effect drops off due to overdoping. The curves (soda ash excluded) are very similar, a maximum reduction in viscosity due to deflocculant alone, being achieved at approximately 0,1% overall concentration. At this concentration good deflocculation can be achieved (observations in sedimentation cylinders). However soda ash seems to be effective enough only in the 0,15 to 0,25% concentration range.

Since the cost of deflocculation is extremely high, we wish to

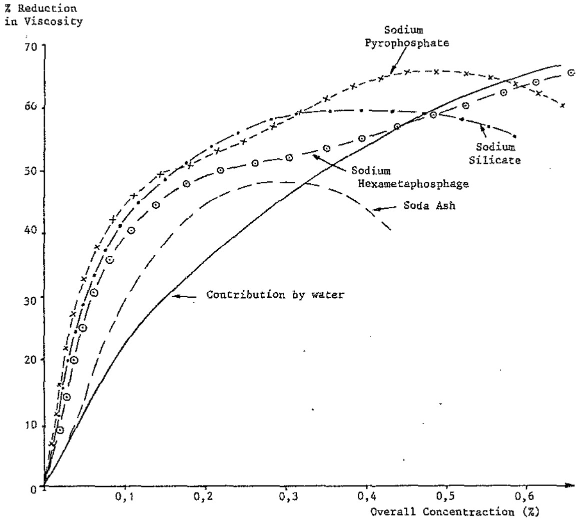


Figure 5.7 a : Percentage Reduction in Viscosity versus Overall Concentration for various *Sodium Deflocculants* (5% Solutions)

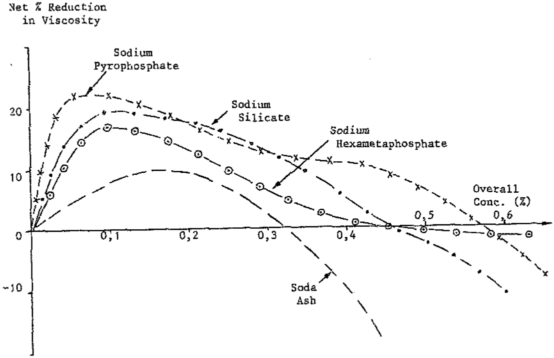


Figure 5.7 (b) : Net Reduction in Viscosity versus Overall Concentration for various Sodium Deflocculants

minimize this cost by using the lowest possible overall concentration. Thus for soda ash, we would choose an overall concentration of 0,15% while for the other deflocculants we would choose an overall concentration of 0,1%

5.2.3.4 Comparison of Costs

Current wholesale prices (June 1980) of the deflocculants used are as follows:

Sodium Hexametaphosphate	R1-26 per Kg
Sodium Pyrophosphate	R1-07 per Kg
Sodium Silicate	R0-35 per Kg
Soda Ash	R0-25 per Kg

In order to compare costs, a unit deposition rate of 100 000 tons of solids per month has been assumed. It has also been assumed that the solid material constitutes 45% by mass of the total pumped material. Thus the total pumped material has a mass of 222 000 tons per month.

The costs of deflocculants required to achieve the chosen overall concentrations are presented in Table 5.2. These costs have been calculated according to Equations A_1 and A_2 in Appendix A4.

Thus in terms of effectiveness and cost, Sodium Silicate would be chosen as the best deflocculant for practical use.

5.2.4 Addition of Flocculating Agents

At a later stage of this study, it was learnt that, since diamond tailings has such a high clay content, flocculating agents are added to the tailings to accelerate the sedimentation of fines in a thickener before it is pumped to the tailings dam. The objective of the addition of the flocculants is to achieve maximum clear water draw-off for re- use in the extraction plant.

Table 5.2: Approximate Costs of Deflocculant Required for Unit Deposition Rate of 100 000 tons of Solid Material

Deflocculant	Overall Concentration (%)	Cost per 100 000 tons Solid Material 5% Solution	 2% Solution
Sodium Pyrophosphate	0,1	R285 700-00	R294 700-00
Sodium Hexametaphosphate	0,1	R242 600-00	R250 300-00
Sodium Silicate	0,1	R 79 400-00	R 81 000-00
Soda Ash	0,15	R 84 200-00	R 88 300-00

Even with the addition of flocculants, a problem nevertheless exists in that the entire clay content does not settle out even in a very large pool such as that at Premier Diamond Mine. Thus the pool water is continually cloudy due to the presence of suspended fines.

In order to use both systems, one would have to deflocculate the slurry before pumping, and add flocculants at some stage after the slurry has been allowed to beach. At present, the flocculant additives are added in lower concentrations than those discussed for the deflocculants, and at lower costs (approximately R50 000-00 per 100 000 tons of solids). However, to nullify the effects of the added deflocculants, the flocculant dosage required for the two-way system might certainly increase, as might the cost.

The cyclic process involved can be envisaged to be a major factor in determining the feasibility of the use of deflocculants since the costs involved in the design, installation and operation of such a system would be far higher than the estimates in Section 5.2.3.4 .

5.2.5 Conclusions

It has been shown that the addition of sodium deflocculants to a suspension of tailings containing a large quantity of flocculated clay has potential as a means of improving the degree of particle separation of the slurry along the beach.

However [illegible]remely high costs which would be involved in the deve[illegible] operation of a cyclic system capable of both defloc[illegible] and flocculating the material where required, render the feasibility of this method as a solution to the problem, doubtful.

5.3 Mechanical Separation using Hydrocyclones.

Let us again consider the problems experienced at Kimberley, that is, in addition to poor particle separation and the occurrence of clay layers, the lengths of the beaches are extremely short.

The short beaches are problematic since, when deposition occurs on one side of the dam, the level of the pool is raised (by raising the level of the penstock outlet) thus maintaining the pool size. As the level of the pool rises (Figure 5.8), the short beaches on the other sides of the dam become submerged.

This situation is logically undesirable since the raising of the phreatic surface, in combination with the clay layering, results in a situation which may promote piping through the wall of the dam. Furthermore, due to the layering effects and the proximity of the edge of the pool to the wall, the underdrainage cannot function efficiently, resulting in high pore-pressures being set up in the wall material, implying a reduced factor of safety against a slope failure.

It is felt that this problem is however solely attributable to the fact that an excessive quantity of water is being retained on the dam, resulting in an incorrect proportioning of the pool area to the total surface area of the dam.

A logical way of improving the situation would be to keep the dam surface as dry as possible, thus increasing the beach length and improving the flow properties as discussed in Section 5.1 . However, this is not always possible since one requires an alternative storage location for the excess water, and in addition to this, a certain amount of water must be retained on the dam surface to allow the sedimentation of fines carried to the pool and so obtain a clear water draw-off.

By using deflocculants, or by increasing the beach length, although one might improve the particle separation, there is *little probability of limiting the formation of clay layers unless*

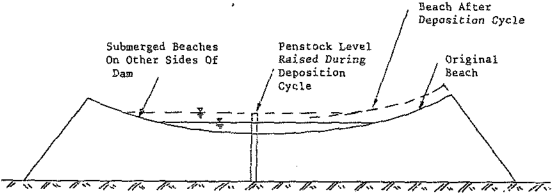


Figure 5.8 : Submergence of Beaches at Kimberley Tailings Dam

training walls are utilized as suggested in Chapter 4.

The use of hydrocyclones to mechanically separate the tailing was thus considered as an alternative solution to the problems discussed above. Presented below are some aspects of the working principles of the hydrocyclone, as well as suggested design considerations which would help to simplify such an operation.

5.3.1 The Working Principles of the Hydrocyclone
(After Bradley (1965) and Rietema and Verver (1961))

Figure 5.9 describes the working principles of the hydrocyclone.

The slurry (feed) is injected tangentially into the feed inlet, immediately commencing downward flow in the outer regions of the cyclone body, creating the outer 'spiral'.

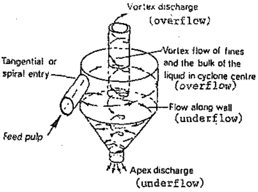
The outlets are normally placed on the axis of the cyclone (as shown) such that the rotating fluid is forced to spiral towards the centre to escape. The existence of the overflow outlet and the inability under normal feed pressure and flowrate conditions for all the fluid to leave at the underflow outlet, assist the inward migration of some of the fluid from the downward moving mass.

The amount of inward migration increases towards the underflow outlet, and the fluid in this migratory stream ultimately reverses its vertical velocity direction and flows upwards in the inner spiral, to the overflow outlet.

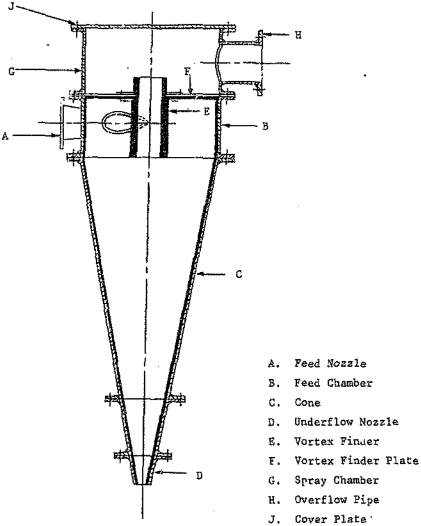
Due to the inward migration of the fluid (water), the rotational motion has thus built into it an inward radial motion. Particles of suspended solid are thus subjected to two opposing forces:

i. An outward radial force due to the centrifugal acceleration.

ii. An inward radial force due to the drag force of the inward moving fluid.



a. Main Flow Patterns Within a Hydrocyclone



b. Working Parts

Figure 6.9 : Working Principles of the Hydrocyclone

'Separation' of the feed solids into coarse and fine fractions is achieved by virtue of the variation of the size of the particles (separation in terms of S.G. may be preferred), since depending on the size of a particle, that particle will either be forced into the outer (coarse particles) or inner (fines).spiral, escaping from the cyclone through the underflow or overflow outlet respectively.

The cyclone 'split' size (referred to as the S_{50} size) is defined as the particle that has an equal probability of reporting either to the underflow or the overflow.

By varying the dimensions of the cyclone or its working parts, one can vary both the split size as well as the under- and overflow water contents. For example, a decrease in the underflow outlet diameter will produce a coarser underflow with a lower water content, since more of the material is forced to exit through the overflow outlet due to the 'throttling' of the underflow outlet.

Bradley (1965) summarizes most of the formulae developed to predict the material properties of the underflow and the overflow, as well as the efficiency of the cyclone. Although an in depth literature search was conducted in this direction, it was generally found that the many semi-empirical formulae vary to some extent, with no single method being available for general use.

Rietema and Verver (1961) comment on cyclone design:

> "The design of a cyclone is a highly critical affair that is generally reserved for specialists, particularily since the practical 'know-how' is usually kept secret by the manufacturer of the apparatus."

One will in fact experience this problem of 'secrecy' when approaching cyclone manufacturers, and thus it is best to accept that the cyclone design will, in most cases, have to be left to the manufacturer. (Note that for this reason, a cost estimate of such a system could not be made). However, for a given material, one can, by considering the mass-balance of the system, provide the manufacturer with the required properties of the separated materials, i.e. the desired split and the water contents.

5.3.2 Some Suggested Design Considerations

In suggesting the use of hydrocyclones as a possible solution to the problem at Kimberley, Blight (1980) notes that the hydrocyclone is used worldwide in tailings dam construction, and is reported to provide a consistent split of the product with a minimum of supervision. It is thus obvious that many benefits will be gained by the consultation of the available literature which studies the use of cyclones in tailings dam construction.

At least two systems of cyclones can be used:

i. 'On dam cycloning' in which the tailings delivery line is tapped at intervals, the branch pipes leading to hydrocyclones set up on the crest of the dam. The coarse underflow is deposited immediately under the cyclone and builds up a mound of coarse silt and sand, while the fines overflow is piped to the interior of the dam. The cyclones are periodically moved to allow the mounds of deposited material to overlap into a continuous embankment.

ii. 'Central cycloning' in which the tailings are separated into coarse and fine fractions by a bank of cyclones before being delivered to the dam.

In the case of Kimberley dam, the central bank system seems to be the most promising system, since the spigot system in present use can thus be retained to deposit the underflow. Although a second delivery line would be required for the overflow, this should not be very costly since the 'bank' of cyclones could be situated in the pump station close to the dam, and thus only a short delivery line will be required.

A further benefit of the 'bank' system is the fact that this system does not require any special considerations on the dam itself. The on-dam system however, requires special support of the cyclones and the delivery pipes on the dam as well as supervision in lifting and moving the cyclones. However the use of the bank system will depend to a large extent on the required split and whether a sufficient water content can be obtained in the underflow to obtain a pumpable slurry.

Even with the use of hydrocyclones, it is envisaged that the short-beach problem may still exist since it is probable that the same size of pool will still be required. Furthermore, in using cyclones, the amount of material available for beaching at the wall may be considerably reduced, and this consideration has in the past forestalled the use of such a system on diamond tailings which does not have a large content of coarse material.

The use of cyclones does not directly solve this problem, but rather provides a better construction material as well as better control over the material. The following system is thus proposed in order to provide a solution to the short-beach problem as well as providing solutions to the other problems encountered with these dams.

Figure 5.10 shows a sketch of the proposed system which utilizes the paddock system commonly used on gold tailings dams. The coarse tailings (underflow) is retained within the paddocks, being uniformly spread over the paddock by utilizing the present spigot system, while the fine tailings is 'open ended' into the body of the dam.

For this case, the acceptable split will be determined by considering the volume of material required in the paddocks (underflow), as well as the permeability of this material, i.e. the ratio of k_h/k_v must be sufficiently low.

The benefits achieved by using this system are :

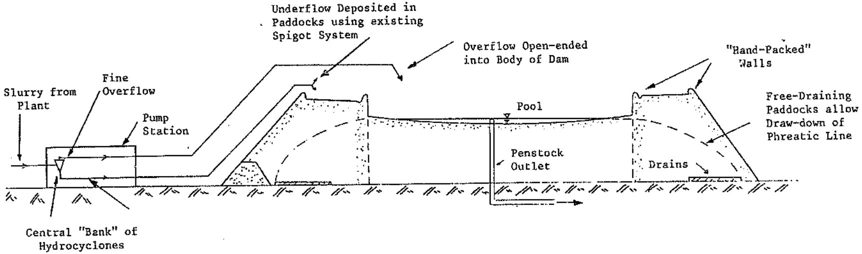


Figure 5.10: Suggested Tailings Dam System For Kimberley Tailings Dam

The benefits achieved by using this system are :

i. The layering problem will not be critical since any significant layering will only occur in the body of the dam, while the paddock material, being more isotropic, will allow efficient drainage into the existing underdrains.

ii. The size of the pool will not be critical since the paddock can act as a water retaining 'shell', although the water level in the pool should never be allowed to approach the top of the beach.

iii. The general difficulties in handling a flocculated slurry will no longer be experienced since the underflow produced will certainly be a more manageable material.

Thus although individual solutions may be suggested for the individual problems, it is felt that the use of cyclones will provide a simple and fairly inexpensive solution to most of the major problems encountered at Kimberley tailings dam.

Blight (1980) suggested the use of cyclones as a short-term alternative pending the outcome of the investigation of the addition of deflocculants. Since this investigation showed that the feasibility of the use of deflocculants is doubtful, and since there is a definite need for solutions to the problems discussed, it is proposed that the use of cyclones in conjunction with the above suggested system, be investigated as a long-term solution to the problems encountered with flocculated tailings.

6.0 CONCLUSIONS

As set out in the Chapter 1, the overall aim of this investigation was to study the behaviour of a free flowing slurry and the resulting properties of the dry, 'beached' material, with a view to solving various problems presently experienced in the construction of tailings dams.

Although unforeseen practical difficulties were encountered in attempting to quantify the hydraulic properties of the slurry flow, the visual and measured observations conducted during this study allowed the behaviour of a free flowing slurry to be investigated resulting in the understanding of the mechanisms of beach development and particle size separation along the beach.

The important conclusions resulting from this study are:

6.1 The Beach Profile

Characteristic of free flowing slurries with high sediment concentrations, is a continual reduction of the flow velocity attributable to the interdependent influences of the stream and the bed on one another. This continuous reduction in the velocity results in a beach having a parabolic profile described by the equation:

$$y = i_{av}.L.(1-x/L)^n \qquad \text{where } i_{av} = H/L$$

and n is a grade indicator.

The parameter n is largely dependent on the particle size distribution of the total tailings, while the magnitude of the parameter i_{av} (the average slope) is proportional to the content of coarser material in the total tailings, and is inversely proportional to the deposition flowrate.

This equation of the beach profile can easily be used in a computer programme and has already proved valuable in providing a more accurate method of calculating deposited volumes of tailings, as well as a means of modelling the progress of a tailings dam mathematically.

It is however felt that the beaching parameters observed for relatively short beaches are not entirely applicable to very long beaches. As evidenced by the beach profiles for the long beaches on gold tailings dams, it is very probable that for flow on beaches of sufficient length, the subcritical flow will tend to a uniform flow condition, resulting in different beaching parameters, i.e. a decrease in both n and i_{av}.

6.2 The Variation of Material Properties along the Beach

6.2.1 Fractionation along the Beach

Associated with the continuous reduction in the velocity of flow, is a continuous reduction in the size of particle (d_{50}) which the stream can transport.

The results of tests carried out on samples extracted along the beach show that the degree of separation, measured in terms of the decrease in d_{50} along the beach, varies as the average slope varies, i.e. the flatter the slope, the less the degree of separation along the beach. Furthemore, it is evident that the degree of separation is inversely proportional to the uniformity of the deposited tailings.

The tests also show that, in general, the contents of the various soil fractions vary along the beach as follows:

i. The sand content decreases with increasing distance from the deposition point.

ii. The silt content increases along the beach.

iii. The clay content remains fairly constant along the beach.

iv. A large proportion of the fines is carried to the pool.

This investigation showed that the present construction techniques are efficient in achieving a good degree of separation along the beach so that the free-draining coarser material is deposited at and near the deposition point for use in constructing the 'wall'.

6.2.2 The Variation in Shear Strength along the Beach

As a result of the variation in the particle size distribution along the beach, the permeability of the material also decreases along the beach, associated with the increase in the content of fines.

The decrease in the permeability results in a decrease in the rate of consolidation along the beach, and hence a decrease in the shear strength.

A major influence on the shear strength of the material at the top of the beach is the development of capillary tensions in the pore water (resulting from sundrying) which tend to overconsolidate this material. The dilatancy of the overconsolidated material increases the shear strength of this material relative to the normally consolidated material further along the beach, when sheared at the same consolidation pressure.

6.3 The Layering Problem Encountered on Tailings Dams

On all tailings dams, thin layers of fines were observed to overly large areas of the beach surface. These layers result from a number of causes, of which overflowing from rivulets of concentrated flow was observed to be the most problematic. This overflow contains suspended fines which are distributed over large, continuous areas surrounding the sliming region.

In order to minimize the formation of clay layers and the negative influences of these layers on the stability of the wall, it is recommended that the use of training walls be investigated as a means of containing the slurry flow on the beach, thus eliminating the overflow of fines onto areas surrounding the sliming region.

6.4 Kimberley Tailings Dam

The various problems experienced at Kimberley tailings dam are as follows:

i. A general difficulty in handling the material which is strongly flocculated, the resulting high viscosity preventing the separation of particles into coarse and fine fractions. The material at the top of the beach thus contains an undesireable quantity of clay (montmorillonite) .

ii. The presence of impermeable clay layers which create an anisotropic (layered) system which causes a raised phreatic surface. The raised phreatic surface and the clay layers may result in flow slides or piping through the wall.

iii. The development of very short beaches, attributable to the incorrect proportioning of the pool size to the total area of the dam.

In order to improve the flow properties of the slurry and thus the degree of particle separation, an investigation was carried out to determine the feasibility of the addition of deflocculants to disperse the clay fraction and thus reduce the viscosity of the suspension.

It was however concluded that, although this is a promising method of improving the properties of the slurry, the feasibility of this solution is doubtful due to the extremely high costs of the added deflocculants, as well as the cyclic process which would be required to ensure clear water draw-off from the pool.

Although the formation of clay layering may be reduced by using training walls to contain the slurry flow, it was nevertheless concluded that the use of hydrocyclones be investigated as a long term solution to all the problems listed above.

Since it is envisaged that the size of the pool will remain problematic, and since the amount of material available for beaching near the wall will be reduced through mechanical separation, it is recommended that a paddock type system, similar to the system used on gold tailings dams, be used at Kimberley. In retaining the coarse material in the paddocks, this system efficiently utilizes the separation of particles achieved by the cyclone to produce a structurally stable outer 'shell', which will safely contain the liquid tailings in the body of the dam, while being adequately drained by the existing underdrainage system.

6.5 Further Research - The Use of Modelling Techniques

In the study of the behaviour of a free flowing slurry, the theory of beach development was presented in a qualitative fashion, emphasizing the system variables which may produce changes in the beaching characteristics of a slurry. This qualitative presentation was in fact necessitated by the practical difficulties experienced in attempting to quantify the hydraulic properties of the slurry on the actual tailings dam.

The question that arises at this stage is, should a more detailed analysis be required, how much further and in what direction should continued research in this field proceed?

Firstly it must be recognised that, since hydraulic fill

Author Bentel Gary Michael
Name of thesis Some aspects of the behaviour of hydraulically deposited tailings. 1981