CHAPTER 5

CONCLUSIONS

The consequences of a tailings dam failure are devastating and evidence of these abounds in the literature. Apart from the more than 1000 fatalities in the last century, countless millions of rand in property damage and production losses, not to mention devastation of the environment, have resulted from tailings incidents. South Africa, today, is even more at risk as financial pressures are mounting on mining operators as a result of lower gold prices and dwindling gold reserves. Another major concern is the development of settlements adjacent to, and in some cases even on tailings structures.

The safe design, construction, operation and reclamation of impoundment structures require an understanding of the nature and behaviour of tailings as a construction material. Of particular interest is the composition of this man-made material and the influence it has on the in-situ state of tailings. A research program was, therefore, initiated at the University of Pretoria to investigate the composition and state of South African gold tailings from the Witwatersrand gold reefs. Samples for this study were collected from the tailings delivery slurry and from the pond areas of two tailings impoundments at Vaal River Operations in the far West Rand. Piezocone soundings were also made through a cross section of one of the dams and at the sampling locations on both dams.

This chapter brings together the main conclusions of the study. The work has provided a better understanding of the condition and behaviour of gold tailings in a typical impoundment, viz.:

(a) The composition of the tailings delivery slurry as well as typical fine and coarse deposits in an impoundment.

(b) The normalised compression behaviour of tailings.

(c) Strength characteristics with reference to pre- and post failure stress paths in undrained loading.

(d) Interpretation of in-situ piezocone data in tailings.

5.1 TAILINGS DISPOSAL IN SOUTH AFRICA

5.1.1 Impoundment design, construction and operation

- Tailings dams are generally not designed with the same conservatism as conventional water-retention dams, for economical reasons.
- South African gold tailings impoundments are almost exclusively designed and operated as perimeter ring dikes with the tailings embankment raised, upstream, throughout the lifetime of the impoundment using the daywall-nightpan paddock system. Deposition is sub-aerial by open-ended pipe discharge, or in some cases by spigotting or cycloning. The daywall is raised to provide adequate freeboard, but also allowing maximum time, three weeks on average, for evaporation and desiccation to improve the mechanical properties, especially density, of the material. The rate-of-rise of the embankment commonly ranges between 1 and 3 m per year. Impoundment complexes can be operated as one or more isolated compartments, each with its own delivery and decant facilities. Decant systems are almost always of the penstock type with internal drainage structures absent in all but the most recent developments. In addition to internal and surface drainage measures, ground level catchment paddocks are provided around the perimeter of the dam to intercept contaminated runoff from the side slopes.
- When impoundments are raised by cyclone construction, the properties of the embankment building material can be optimised by controlling the cyclone underflow. This underflow should preferably contain only the coarse and bulky sand particles. Impoundments that are raised by open ended pipe discharge rely on particle sorting processes to grade the deposited material from coarse to fine, from the embankment to the decant penstock. However, with the paddock system of construction, significant amounts of fines are deposited in the daywall, especially at low points between discharge stations. This study has shown that a piezocone profile at the daywall compares better to a profile at the beach-pond interface than ones at the upper or middle beach areas of the dam. These impoundments, although more cost effective, rely heavily on the effects of desiccation to improve the stability of the embankment, as well as on proper phreatic surface control and continuous monitoring.
- Control of the phreatic surface from a design and operational point of view is the single most important factor in maintaining the stability and serviceability of a tailings impoundment. The controlled rate-of-rise and sequence of deposition should be tailored in relation to the post depositional properties of the tailings and any internal drainage structures to ensure both adequate storage capacity and a safe structure. The drainage properties of tailings are highly dependent on the in-situ composition and

state of the material. Entrapment of significant amounts of fines in the embankment wall will severely affect the drainage conditions in this critical area of an impoundment.

- The soil forming process on a tailings impoundment includes transportation of sediments, sedimentation, primary consolidation and, as shown in this study, significant secondary consolidation or creep. Depositional practices, variations in the mill product, and soil forming processes result in a highly layered profile with fine and coarse deposits alternating over small depths. Gold tailings do not segregate readily on deposition and heavy reliance is placed on desiccation to improve the properties of material deposited on or close to the perimeter embankment.
- On a typical gold tailings impoundment, raised by the daywall-nightpan paddock system, the composition of material at any location is highly dependent on the depositional sequence. As discharge stations are cycled around the perimeter of the dam, alternating layers of fine and coarse tailings are deposited at a specific location. For example, during this investigation it was found that layers of coarse tailings had been deposited within the decant pond. This happens when coarse particles are carried directly into the pond by concentrated flow. Scour channels of concentrated flow are common on the beaches of active impoundments. During the next cycle of deposition, when the concentrated flow channel is located somewhere else, a fine layer is deposited over the coarse layer, etc.

5.2 COMPOSITION OF GOLD TAILINGS

5.2.1 Delivery Slurry

- Gold tailings have been classified as a low to high plasticity, fine, hard and angular rock flour, slurried with process water in a flocculated slightly alkaline state together with soluble salts.
- Pulp densities normally range between 25 and 50% (dry density of 300 to 750 kg/m^3) when delivered to the impoundment site.
- The rheology of a gold tailings slurry lies somewhere between a Bingham plastic and a Newtonian fluid.

5.2.2 In-situ Composition

Electron microscope, energy dispersive x-ray spectrometry and powder x-ray diffraction technologies were fully exploited, together with standard soil mechanics laboratory tests, to determine the composition of the tailings.

- *Mineralogy:* It is common practice in South Africa to separate tailings particles into two classes, i.e. tailings sands (particles fractioned by sieve tests, > 63 μm), and tailings slimes (particles fractioned by sedimentation, < 63 μm). This study has shown that tailings consist almost exclusively of tectosilicates and sheet-like phyllosilicates, with quartz being by far the most abundant mineral. The coarser tailings sands are predominantly pure silica quartz, with up to 10% illite clay minerals. Tailings slimes on the other hand, although still dominated by quartz, contain significant amounts of phyllosilicates (20% muscovite, 15% illite and 20% pyrophyllite, kaolin and clinochlore) as well as traces of pyrite and other sulphides. Gold tailings, therefore, contain significant amounts of clay fines, and these can be expected to have a major effect on the mechanical behaviour of the material.
- *Specific gravity:* G_s normally ranges between 2.5 and 3.0 Mg/m^3. In this study the tailings had a specific gravity of 2.74 Mg/m^3, including the delivery slurry and all other samples collected, irrespective of sampling location. It is suggested that segregation processes on a gold tailings impoundment are driven by gravity rather than size. The sizing of the particles, according to density, is such that deposited layers are all at a constant specific gravity, irrespective of grade.
- *Grading:* Fully dispersed gradings were uniformly distributed in the fine sand and silt-size ranges with approximately 2% coarser than 200 μm, 10% finer than 2 μm and at least 50% slimes. Variations in the gradings between fine and coarse tailings were largely around the median particle size, D_{50}, which ranged between 6 and 60 μm. These gradings are representative of the near full range of published gradings from gold tailings literature. Non-dispersed the fines were flocculated and/or attached to the coarser sands so that no particles smaller than 10 μm could be detected in the hydrometer sedimentation test without adding a dispersant.
- *Particle shape:* The coarser tailings sands consisted of highly angular to sub-rounded bulky but flattened particles. The finer slimes consisted mostly of thin and plate-like particles characteristic of clay minerals, containing some bulky silt sized particles with properties similar to the sands. The general flattened shape of the particles caused sieve and hydrometer tests to consistently under-estimate the actual size distribution. Operators of cyclone systems will benefit greatly from a knowledge of the size split between predominantly coarse bulky grains and flaky fines in the delivery slurry, roughly 10 μm in this case.
- *Surface texture:* Surface textures ranged from completely smooth to rough on a micro-scale.
- *Chemical Interactions:* The principal chemical reaction that takes place in gold tailings is the oxidation of the sulphide minerals in the presence of oxygen and water or through anaerobic biological processes. Pyrite oxidation results in the formation of iron

oxides and sulphuric acid. Resulting changes in pH may trigger precipitation of bonding agents including silica, metal oxides and carbonates. However, no evidence of this could be identified. Other than that, the only other interaction of significance is crust formation on drying and evaporating surfaces. These crusts are superficial, however, and do not have an effect on the strength properties of the deposit, although they can reduce evaporation from exposed surfaces.

5.3 STATE OF GOLD TAILINGS

Having defined the fundamental characteristics of the gold tailings mix, it is possible to consider the in-situ state and mechanical behaviour of this material. A coarse deposited layer with more bulky and angular tailings sands, could behave like a clean, but fine sand. The finer layers consisting mainly of thin plate-like slimes, should behave more like a clay.

Sampling of tailings has always been a major problem due to the silty nature, low in-situ density and highly layered structure of tailings deposits. High quality undisturbed samples were recovered for this study either by cutting block samples, or by using a well-designed tube sampler. However, this was only possible provided direct access could be gained to the material. To prepare reconstituted laboratory samples, a method of settling high water content slurries proved to be effective in providing samples that are representative of the in-situ state.

The tailings considered in this study had an abundance of fines so that, irrespective of grade, the state and behaviour was controlled by the fines.

- *Stress and Stress History:* The stress regime in a tailings impoundment is largely the result of self-weight loading of the impounded martial. Under sub-aqueous deposition in the pond the stress history follows a normally one-dimensionally consolidated state with low effective stress levels as a result of the low densities. Under sub-aerial deposition on the daywall and beach areas, evaporation and desiccation can build in some overconsolidation with resulting increases in density and effective stress levels. However, desiccation suctions are short-lived due to re-wetting by precipitation and seepage from successive deposition cycles.
- *Density:* The in-situ dry density of coarse layers of tailings range typically between 1250 and 1650 kg/m^3 with an average of 1450 kg/m^3. In-situ density of the finer slimes is closer to 1000 kg/m^3. Thus, following similar soil forming histories, layers of fine tailings exist at density states of almost half those of coarse layers. These contrasting states are a function only of differences in composition resulting from slurry properties and soil forming conditions, which vary constantly at a specific location.

- *Compressibility:* Similar to density, compressibility of tailings is highly dependent on composition, especially on the relative percentages of bulky sands and flaky slimes. However, the virgin compression curves of both fine and coarse tailings could be normalised successfully using the void index. It is, therefore, possible to derive density profiles and bulk stiffness properties of a tailings sediment as a function of the confinement stress levels and some fundamental constant based on material composition only.

  For the range of stresses to be expected in an impoundment the density state and bulk stiffness of the material considered in this study could well be predicted using the normalised void index and correlations with the Atterberg limits as follows:

  $$I_v = \frac{e - e_{100}}{e_{100} - e_{1000}} = 2 - \frac{\ln p'}{2.303} \quad \text{Eq. 5-1}$$

  $$e_{100} = 0.647\left(\frac{PI}{2.24}\right) \quad \text{Eq. 5-2}$$

  $$e_{1000} = 0.53\ln\left(\frac{LL}{10}\right) \quad \text{Eq. 5-3}$$

  If the in-situ range and extent of the layering can be established, estimates of density and stiffness can be made based on parameters derived from simple laboratory tests on reconstituted samples of a similar composition. Information of this kind is extremely useful in estimating rate-of-rise, storage capacity and other operational parameters for a tailings impoundment.

- *Consolidation:* Consolidation characteristics are also significantly affected by composition, with tailings slimes reported to be 6 orders of magnitude slower to consolidate than tailings sands. The fast draining properties of tailings demand special care when performing permeability tests in the laboratory.

  Laboratory triaxial and in-situ piezocone consolidation data indicated that the shape of the tailings consolidation curve deviates significantly from that of the theoretical one-dimensional equation after Terzaghi-Rendulic. Acceptable estimates of the coefficient of consolidation can, however, be obtained by fitting the time for 50% consolidation, t_{50}, to the one-dimensional theoretical T_{50} for the appropriate boundary conditions.

  An important observation was the large percentage of creep or secondary consolidation that took place during consolidation stages. Creep is often ignored or assumed negligible in tailings literature.

- *Shear Strength:* The shear strength properties of the tailings were: zero effective cohesion, with an effective angle of internal friction of $\phi' \approx 34°$. It was found, as reported in tailings literature, that the strength properties are independent of composition. The internal friction angle can be assumed independent of grading, density, overconsolidation and effective stress level up to the onset of particle crushing.

Fine and coarse tailings, sampled from the same location, not only had the same strength properties, but also followed exactly the same undrained stress path up to the failure state. However, this can only be true provided that a specific relationship exists between the compositions of the different grades and their respective density states. Such states, representative of the in-situ condition, could be set-up repeatedly in the laboratory by settling remoulded high water content slurries. It is concluded that following similar sub-aqueous sedimentation-consolidation histories, tailings of different compositions (fine and coarse) will exist at varying density states, but so that their specific gravity and undrained shear strengths are the same. The validity of this hypothesis has not yet been confirmed on sub-aerial beaches and daywall areas, but the effects of desiccation only, should not alter the relative states between fine and coarse deposits. Particle sorting and horizontal rolling during sub-aerial deposition could, however, result in alternative structures compared with those following sub-aqueous deposition.

Further observations on the shear behaviour of the tailings suggested that material of the finest composition will reach a stable ultimate critical state, while material of a coarser composition is particularly prone to post failure phase transfer dilation and strain hardening. In addition, the coarser material with greater permeability may shear partially drained at the same strain rates that cause the finer material to behave fully undrained. The drained shear strength should be significantly higher than the equivalent undrained strength at the same initial density.

When analysing the stability of a tailings embankment, the composition and state of the material should be considered. Layers of fine tailings are likely to be saturated and if sheared undrained should be assigned the undrained critical state shear strength. On the other hand layers of coarse tailings, even if saturated, are likely to shear partially to fully drained, with an increased effective shear strength. Nevertheless, if the coarser material is sheared undrained, it will generate additional strength, over and above the critical state strength, as a result of post failure stress dilatency. This assumes a normally consolidated initial state. If the material has been subjected to desiccation, the effects of overconsolidation on the stress paths should be considered.

- *Structure:* Phyllosilicate-minerals with their large surface areas in tailings slimes are subject to and may be dominated by surface forces compared with the body force of gravity. Low surface area bulky tailings sands, on the other hand, are primarily subject to gravity forces. Based upon the evidence on electron micrographs and triaxial test data on undisturbed samples, the structure of pond-area tailings is determined by the randomly orientated and flocculated slime flakes rather than the coarser bulky sands. This is in agreement with the constant and independent shear strength properties of all samples studied.

Natural fine silts have a tendency to form open meta-stable packing arrangements following sub-aqueous sedimentation. No such open structures could be identified in either the fine or coarse tailings, which rather behaved like loose but stable particle arrangements that strain hardened to failure. Collapsible structure has only been evident in laboratory specimens artificially prepared by wet-tamping techniques, as reported in the literature.

The possibility of inter-particle bonding as a result of precipitating agents is dependent on pH fluctuations, following the oxidation of sulphide minerals in tailings. Oxidation, in the absence of anaerobic oxidising bacteria, can only take place to a limited depth on exposed surfaces, such as daywall and beach surfaces. Structural bonding could not be detected in any of the undisturbed samples considered in this study.

5.4 USE OF THE PIEZOCONE IN TAILINGS

The piezocone today is one of the most popular instruments used to probe and characterise tailings impoundments. Difficulties with sampling virtually eliminate the feasibility of controlled laboratory tests on undisturbed samples. Of all other in-situ devices, the piezocone is the one device which provides a continuous record of sub-surface conditions with depth at reasonable cost.

- *Stratigraphy:* The piezocone has been used by many engineers worldwide to successfully delineate the sub-surface stratigraphy of tailings impoundments. The small, localised nature and quick response-time of the pore pressure sensor, makes it ideal for locating layer interfaces in the highly layered tailings profile.

  A modified version of the Jones and Rust identification chart was used in this study to classify the tailings profile, which compared well to an exposed profile next to the CPTU sounding. Some aspects that need consideration in the classification process are:
  - The classification chart must comply with the location of the filter element on the piezocone probe.
  - Most classification systems were designed for saturated conditions.
  - Due to the small depth of individual layers the measured values of the pore pressure and especially cone resistance may not be fully developed.
- *Seepage Regime:* The piezocone is considered by many as the most reliable tool to determine the in-situ seepage regime in a tailings dam. It gives excellent data on the location of the phreatic surface and distribution of ambient pore pressures. In addition, it can be used to estimate the in-situ anisotropy in permeability. However, calculation of the coefficient of consolidation from pore pressure dissipation data is only practical in

the finest layers, as dissipation in the coarser layers is almost instantaneous. The highly layered nature of the tailings profile, often with alternating fine and coarse layers over small depths, makes interpretation of the drainage boundary conditions around the cone extremely difficult.

Due to the difference in the shape between theoretical one-dimensional consolidation curves and piezocone consolidation curves, it is recommended that the coefficient of consolidation be calculated using the time for 50% dissipation or t_{50} rather than t_{90}.

- *Strength and Stiffness:* Confidence in the strength and stiffness interpretation of cone penetration data in tailings has been lacking in the past. Reasons for this include a need to understand the drainage conditions around the advancing cone and the large imposed strain field. With a better understanding of the composition and state of tailings, it is now possible to at least justify the typical upper and lower bound cone measurements in tailings. Upper and lower bound penetration resistances are not the result of large differences in strength and stiffness, as was initially thought. These result rather from differences in drainage conditions and post failure stress-dilatency between layers of different composition.

  The following conclusions were drawn from the combined results of theoretical cavity expansion, effective stress and state parameter interpretations:

  - Usually for gold tailings, the friction angle of layers of different composition remains constant. However, this fact should be verified by consolidated undrained triaxial tests on reconstituted laboratory samples.
  - Unless it can be proved otherwise, cohesion should be taken as zero. Although desiccation suctions will induce some apparent cohesion on the daywall and upper beaches, these are soon relieved on re-wetting.
  - Coarse and fine layers of tailings vary significantly in density and stiffness, but the absolute values are so low in tailings (I_r typically being 15 to 40) that it hardly affects penetration resistances.
  - Cone resistance profiles typically follow lower and upper bound trends in tailings. For strength and stiffness interpretation, the lower bound measurements should be considered. The cavity expansion and state parameter approaches are both adequate in this regard. The upper bound measurements result from a number of factors including partial drainage and post failure stress-dilatency in the coarser layers. An effective stress approach should provide a reasonable upper bound estimate.

Considering the above, a much more rational approach to the interpretation of in-situ strength properties, based on piezocone data, has been made possible. The lower trend of penetration resistances can be used to calculate the effective strength properties of the tailings, fine and coarse, using either the cavity expansion or state parameter approaches.

The upper trend of resistances serves as an indication of the effects of post failure dilation and partial drainage in the coarser layers.