

RESIDUE DISPOSAL AT SADIOLA HILL GOLD MINE: STABILITY EVALUATION BY FIELD TESTING

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ABSTRACT

Mining companies have adopted many different approaches to metallurgical process residue disposal as this aspect can significantly influence the viability of a project. Sadiola Mine is located in Mali, West Africa, in a remote area with poor infrastructure, and exploits a gold ore body hosted in a lateritic saprolite. Milling of the saprolite ore produces very fine residue with a substantial clay content, resulting in a deposit with a high void ratio and compressibility. One of the concerns at design stage was the deposition procedure for the residue and its influence on the stability of the embankment. Because of the high void ratio of the early deposition it was uncertain if the day-wall paddock construction method typically used in South African gold mines would be successful. Finite strain consolidation theory, based on laboratory determined consolidation and permeability parameters, indicated a slow rate of consolidation for uniform deposits potentially resulting in substantial excess pore pressures and marginal stability for embankments constructed by upstream methods. It was therefore decided to adopt a design and construction approach that permitted a two year delay of the decision regarding the raising method, until the effective field characteristics of the residue could be determined. Subsequent field testing, during operation, showed that fine layering had developed in the lower layers, lengthening the field time rates of consolidation and strength increase. The in-situ properties of the residue were examined by in-situ testing and the subsequent evaluation of the stability showed that the deposit would be stable for upstream raises constructed using the cycloned coarse fraction from the residue. The use of the observational method and field-testing allowed the adoption of techniques which would conventionally not have been accepted for a fine residue. The owners were thus able to reduce costs and mitigate their risks using the test data.

1 INTRODUCTION

Declining gold prices during the early 1980's resulted in gold mining companies having to adopt cost-effective approaches to all aspects of the mining process, including that of residue disposal. For this reason, the developers of the Sadiola Hill Gold Mine explored the available options for the residue disposal including some with greater technical complexity that offered substantial savings.

The purpose of this paper is to document the operational history pertinent to the design and the evaluation of stability of the Sadiola residue deposit. It describes the data available at concept and design stage and their influence on the design. The subsequent developments, concerns and evaluations, to verify that the embankments are stable, are described and discussed. The paper describes the background to the project, residue disposal concepts, operational experiences, and the field testing to evaluate strength and ensure stability.

2 PROJECT BACKGROUND

2.1 Regional description

Sadiola Mine is located in the west of the Republic of Mali, West Africa close to the border with Senegal, and was the first large-scale mine in the area. There was therefore no prior experience regarding the characteristics and performance of the fine clayey residues from these saprolite ores.



Figure 1: Locality plan of Republic of Mali (courtesy of www.map.com).

The mine is located about 80 km south of Kayes, the regional capital, which is sited on the Senegal River and about 800 km from Dakar on the railway line to Bamako (Figure 1). Road conditions in the region are poor with the nearest tarred road being about 300 km distant.

As Sadiola is only about 200 km south of the Sahara desert the climate is controlled by desert conditions. Temperatures in summer reach 50 °C and drop to a minimum of 4 °C in winter; with an average range of 20 °C to 40 °C. Winter and spring are characterised by winds and dust storms (The Harmattan) that often obscure the sun. Rain falls in the summer months (June to August) in short, sharp showers. The mean annual precipitation is 814 mm and the mean annual evaporation is 2 877 mm.

2.2 Project description

The Sadiola deposit occurs within an inlier of Greenstone Facies metamorphosed Birimian rocks known as the Kenieba Window. The ore deposit consists of two parts, an upper oxidised cap and an underlying sulphidic zone. The upper portion of the ore is a saprolite derived from the weathering of metasediments with a lateritic surface layer extending to a depth of 6m. Prior to the establishment of the mine, there were some hand-excavated shafts in the area but these were not extensive, as the gold was not readily extracted by panning. Construction of an open pit mine with a conventional mill, cyanide leaching and CIL extraction plant began in 1994 with full production achieved by June 1997,

with 380,000 oz of gold produced in the first year. The plant is currently processing ore at a rate of 5.3 Mtpa, in comparison to its design capacity of 4.0 Mtpa.

2.3 Conceptual design considerations

As part of the feasibility study 200 t of ore were shipped to South Africa and tested at the Anglo American Research Laboratories. Small samples of residue were tested for residue characterisation. These indicated that the residue would be substantially different to the crushed, silty sand that is conventionally produced by deep South African underground mines, and that different techniques would therefore be required to produce an economic and stable deposit for residue disposal. The residue is a well-graded fine clayey silt that was expected to behave more like that at the Boddington Gold Mine, Western Australia. An initial earthfill starter wall was designed that provided safe stable storage for the first two years of residue production and allowance was made for post-commissioning, large-scale field tests of alternative deposition and embankment construction procedures during these first two years of operation. Six different construction techniques were considered: day-wall paddock building as is commonly practised in South Africa, upstream raise construction based on coarse beach residue deposition from spigots, upstream and downstream earthfill embankment construction, upstream construction using cycloned sand from inception, and conversion from paddock-building to cycloning after three years of production.

The lowest technical risk to the project would have resulted from impounding all future residue behind a downstream constructed earthfill embankment. This would also have been the most expensive by almost twice that of the cheapest option, and it was desirable to determine if one of the cheaper wall-building options could be implemented.

2.4 Design of residue embankment

The samples that were delivered for metallurgical testing were mostly used to confirm the gold extraction process and those made available for residue characterization testing were possibly not representative of the final mine and metallurgical plant product. These samples were however all that was available for residue characterization to predict behaviour on deposition. A laboratory bench scale cyclone test was carried out to obtain classified samples for testing. The properties relevant for the stability analysis were:

Grading

Sample	% Passing (mm)			
	0,015	0,075	0,045	0,002
Feed	100	82	70	37
Underflow	100	86	50	22
Overflow	100	98	92	60

Permeability and Consolidation Parameters

Sample	Permeability (m/sec)	Coefficient of consolidation (m ² /year)
Feed	1,4 x 10 ⁻⁹	17
Underflow	3,3 x 10 ⁻⁹	50
Overflow	1,5 x 10 ⁻⁹	12

Triaxial Shear Strength Tests (UU = unconsolidated, undrained; CU= consolidated, undrained with pwp measurements)

Sample	UU Test		CU Test	
	Friction Angle	Cohesion (kPa)	Friction Angle	Cohesion (kPa)
Feed	29	202	23	10
Underflow	26	174	33	20
Overflow	31	112	24	20

It was apparent that:

- The residue was fine and there was only a low percentage of ‘coarse’ that could be separated by cycloning.
- The residue would not consolidate rapidly.
- The ‘as tested state’ of the UU test samples, and the extent to which test results would represent field strength, were questionable.
- Estimates of pore pressure dissipation would be required if CU parameters were to be used and the very low permeability of all samples suggested very low rates of consolidation and pore pressure dissipation.
- If the coarser fraction could be separated out from the fines then stronger material would be available to construct residue embankments or embankment raises.

Based on ‘as tested’ UU strength parameters, the stability analysis showed that stable embankments could be constructed. Uncertainty remained regarding:

- The practicality of operations that would ensure a deposition process that produced a segregated beach with a coarse residue outer wall.
- The rate of pore pressure dissipation and strength gain of the feed and overflow over which any coarse embankment advanced (if any) during upstream construction.

2.5 Observational approach and design details

The adopted design basis was therefore that of the ‘observational approach’ sometimes adopted in conventional geotechnics. At Sadiola the decision was made to build an initial earthfill starter wall to provide a head-start of around two years, during which time various trials would be conducted to determine the residue material characteristics, and to establish the optimal method for embankment raising.

Another key project decision made at the implementation stage, was that an independent technical audit would be carried out after two years when a definitive deposition procedure was in place.

The design, construction and subsequent investigation approach adopted, and the lessons learned from this approach, have been described by Mulpeter et al (2003).



Figure 2: Photograph of Sadiola residue deposit from the air (September 2001)

2.7 Field testing to determine the optimum wall raising technique

The start-up deposition procedure comprised deposition of the residue slurry from forty-two spigots on the earthfill starter embankment constructed across the valley. This produced a beach adjacent to the starter wall and pond remote from the embankment. Provision was also made for deposition within a test-paddock. Methods that were tested in the field after commissioning included wall building by paddock formation, spigot deposition, double-spigotting and cycloning. Paddock formation and double-spigotting proved only partly successful (Mulpetter et al. (2003)).

The residue produced by the metallurgical plant indeed proved to be fundamentally different and was found to contain significant quantities of clay (30% typically). The residue was found to behave as a viscous, partly non-segregating slurry, that has the propensity to trap water within the voids (Mulpetter et al. (2003)). Very little segregation of coarse from fine particles was observed in either of these deposits. A conclusion from this testing was that any procedure that relied on separation of the coarse and fine fraction by gravity along a 'beach' would be extremely unreliable. In addition all the procedures would require constant supervision with a large, dedicated, well trained labour force.

2.7 Cycloning

A set of tests of cyclone operation and product evaluation was also performed. At the end of the test programme, it was concluded that of the lower cost options, the cycloned wall option was preferable as this would more reliably ensure a coarse outer body of sufficient width, without weak clayey residue layering. It was also concluded that cycloning would only produce the required quantities of coarse product, with the required geotechnical parameters, if there was an adequate blend of laterite, or coarse ore with the saprolite ore feed to the plant. The plant feed was modified at the time of field-testing to ensure that 15% of the ore feed was lateritic gravel to facilitate coarse underflow production. The gravel is reduced in the milling process to sand or coarse silt size that is readily classified to the underflow by the on-wall cyclones. This is the prime reason why the cycloning has been successful

with this problematic material. The underflow product typically contains around 6% clay fraction with a specified upper limit of 10%. Although this is a relatively high clay content, the geotechnical properties of this material are such that a relatively free-draining wall is produced.

Based on the results of the laboratory and field testing the embankment section shown in Figure 3 was designed, and implementation of cycloned residue upstream raising commenced in 1998. The construction method involves the upstream raising of the embankment using a large number of small cyclones at relatively close spacing. The cyclone coarse residue raised embankment in September 2001 is shown in Figure 4. The low volume of underflow (~15% by weight) produces a relatively narrow coarse beach residue as is evident in Figure 5. The initial cycloned raise is constructed on the initial deposit of spigotted feed (see Figure 3) and the subsequent raisings progressively advance over the overflow within the interior of the impoundment.

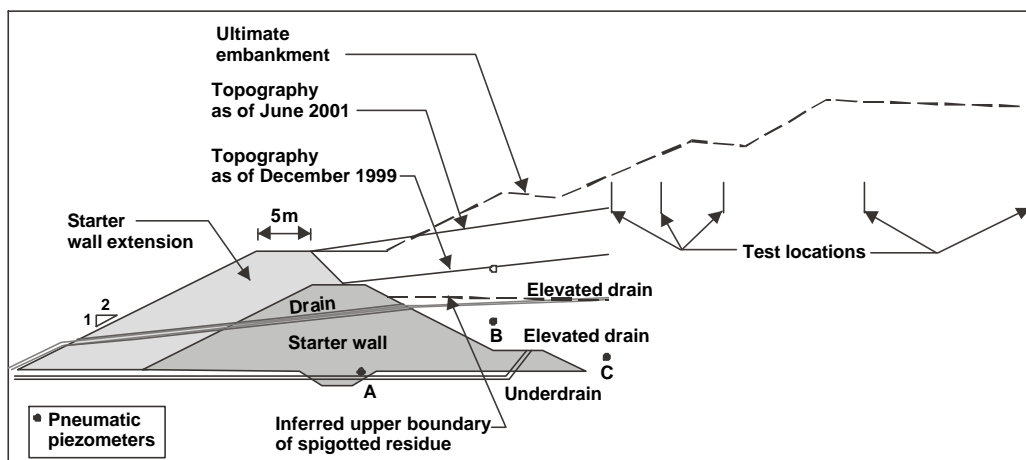


Figure 3: Typical cross-section



Figure 4: Sadiola deposit showing cycloned upstream raising (Sept. 2001)



Figure 5: Sadiola deposit showing narrow sand beach – note overflow discharge location to ‘pond’ at end of short beach



Figure 6: Pushing frame used for shear vane testing – also for piezocone probing

3 FIELD TESTING

3.1 Initial Field Testing

Robertson Geoconsultants Inc. were appointed in 1998 to conduct an independent technical audit of the facility and ensure that after two years of operation, the residue deposit was designed and operated according to “international” standards of good practice. Further, to review the design for future raisings of the embankment with respect to its stability for the remaining mine life and post closure.

Concerns identified during the audit included the potential for low shear strength fine ‘clayey’ layers in the zone of initial deposition behind the starter wall, placed before the cycloning operation was started, as well as the potentially low shear strength of the cyclone overflow over which the embankment would advance. At that stage the following programs were introduced to monitor field performance:

i) Monitoring of Grading

The grading of the feed, underflow and overflow were regularly checked to monitor any variations in parameters. This action identified that the residue feed was coarser than predicted at design stage, that there would be more underflow available and that the overflow was coarser than anticipated.

ii) In-situ Field Investigations and Tests

A field programme of in-situ sampling, piezometer installation, piezocone probing and shear vane testing were executed. An initial program of field testing was performed in 1999 comprising:

- Piezocone testing at 20 positions on five sections such as that illustrated in Figure 3.
- Shear vane testing at 1 m intervals at 16 positions on the same five sections.
- Auger sampling at 1 m intervals to a depth of 6m to determine in-situ void ratios and index properties
- Sampling of feed, underflow and overflow for settlement and consolidation, shear strength, permeability, grading and index testing.

The apparatus for shear vane testing is shown in Figure 6. The same pushing frame was also used for piezocone testing.

This investigation showed that the earlier residue was inter-layered and that there were zones of unconsolidated weak clayey residue present. Finite strain consolidation modelling of the compressible, low permeability clayey layers using FSCONSOL computer code indicated that excess pore pressures were likely to exist. The available piezometer locations were inadequate to check for such excess pore pressures. The in-situ shear vane testing provided an estimate of the undrained shear strengths then existing in the deposit and was used for stability analyses. While the weak layers were not of immediate concern for embankment stability, due to the low height of the initial raises, consolidation with pore pressure dissipation was required to achieve the shear strengths that would be required to support the increase in embankment height during future raises. The available information was insufficient to determine excess pore pressures, predict future dissipation rates and therefore determine future shear strength conditions and stability.

3.2 Subsequent Field Testing

The 1999 field test program was substantially repeated in 2001 to determine the changes in pore pressure dissipation, consolidation and strength increases that occurred with increases in the embankment height, upstream advance of the raises and time. In addition 20 high sensitivity vibrating wire piezometers were installed on the five sections to monitor pore water pressures and evaluate drainage characteristics within the residue body, and vibro-core sampling was performed for 15 to 18 m depth at 6 locations to obtain continuous samples, field moisture contents and hence the void ratio profiles of the deposited residue. The increase in embankment raising achieved by 2001 enabled the testing locations to be advanced further into the impoundment from the starter wall crest. Thus the probing was able to investigate the conditions within the overflow deposition zone from pre 2000 deposits. Each section investigated had four probe positions at successively greater distances from the starter wall crest. Some additional sampling, for residue characterization and void ratio determination was performed in the very high fines area adjacent to the decant tower.

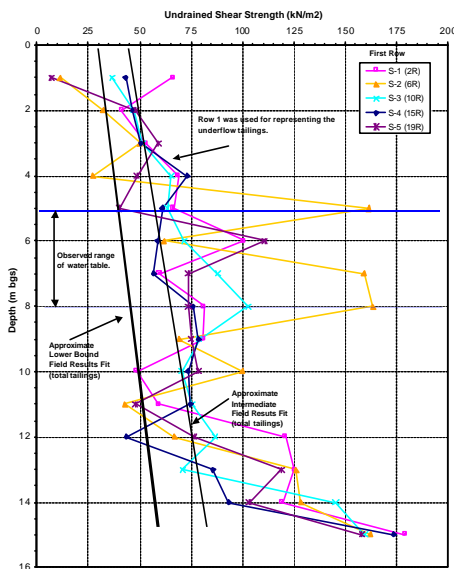


Figure 7: Field Test Data and Shear Strength Profile - First Row

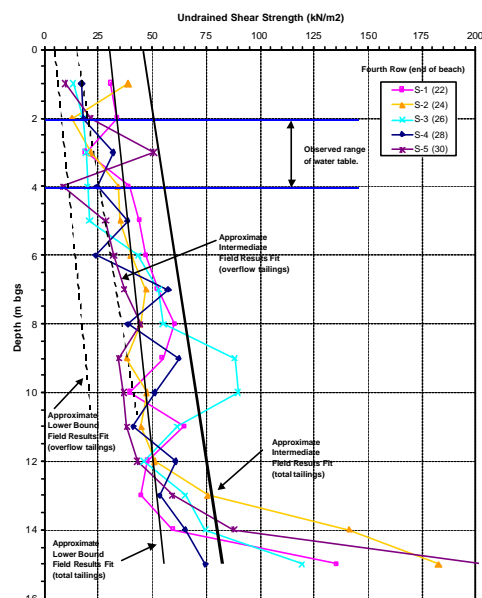


Figure 8: Field Test Data and Shear Strength Profile - Fourth Row

During the 2001 field testing campaign consideration was given to the research finding of Morris and Williams (2000) that excess pore pressures are generated in the soil following insertion of the vane. These excesses (up to 75% of the initial effective stress, Morris & Williams (2000)) persist for some time following vane insertion and their effects on the measurement of shear strength may have been misinterpreted for many years. According to these authors, the broadly accepted model developed by Blight of field vane testing and the accepted criteria for undrained shear strengths are based on this misinterpretation. Consequently, vane shear strength estimates obtained using standard test protocols may be in error and the resulting undrained shear strength measurements may be conservatively low.

An attempt was made to determine the sensitivity of the Sadiola residue to vane insertion rate, and the appropriate delay between vane insertion and performance of the test to allow excess pore water pressure dissipation. A programme of variable insertion rates and variable delay times was performed. It was found that the shear strength was not sensitive to insertion rates investigated but dependent on

the delay period. The shear strengths after 10 minutes delay were significantly greater than after the 2 minutes delay typically required by standard test protocols. The 10 minutes required for pore pressure dissipation agreed well with the 5 to 12 minutes that was necessary to reach ambient pore pressure conditions determined during piezocone testing.

The shear vane strength profiles determined for the row of shear vane tests performed closest to, and furthest from the starter wall crest are shown in figures 7 and 8. A large reduction of shear strength is apparent, indicating that drainage, consolidation and shear strength conditions are less favourable with increasing distance from the starter wall crest. Continued upstream raising will advance the embankment over increasing weak material. The low strength total residue from initial deposition is observed between 10 and 12 m depth in row 1 (Figure 7). Below this there is an increase in shear strength due to drainage to the pervious foundation soils and starter wall drain. High strength coarse layers are observed in this row. The results for Row 4 indicate that more uniformly low shear strengths exist at this distance from the starter wall. The two dark lines on each of the figures indicate the approximate lower bound and typical strengths interpolated from all the probe results.

In addition to the above observations the following conclusions were reached:

- Drainage of the upstream cycloned sand embankment zone by the installed drainage is effective in lowering the water table to the base of this zone.
- The excess pore pressures that may be produced by upstream embankment construction are effectively dissipated by the internal drainage conditions in the zone affecting the current embankment stability.
- There has been an increase in the strength of the residue generally consistent with the increase in effective stresses resulting from embankment raising.
- There are zones or layers with measured shear strengths that are less than predicted by effective stress theory, and the stability of the embankment may be determined by the extent to which they occur and to which a failure surface can form along these layers.

4 STABILITY REVIEW

The stability of the Sadiola embankment raising was checked, taking into account the field investigation results, laboratory shear test results and finite strain consolidation modelling calibrated against the observed field conditions.

The laboratory testing of the cyclone overflow was performed on samples subjected to unidimensional consolidation to field stresses. Four consolidated undrained triaxial shear tests were performed at two different initial isotropic consolidation stresses in both compression and extension. The residue was found to be not strain softening and susceptible to liquefaction flow failure that could occur under monotonic (static) loading conditions. It was therefore concluded that the residue was not susceptible to either static liquefaction following failure initiation or dynamic liquefaction under low dynamic loads from blasting in the open pit mine.

An estimate of the undrained shear strength was derived from the CU results by expressing the undrained shear strength, S_u , as a function of the initial consolidation pressure, p . Based on the laboratory test results, a reasonable undrained strength ratio for use in the field where conditions will range between compression and extension would be $S_u = 0.3p$ (kPa).

Vane shear strengths measured in the outermost location of each of the five sections investigated (dotted line marked 'Approximate Intermediate Field Results Fit') were deemed representative of the overflow strengths. Comparison of these two estimates of shear strength is remarkably good. A similar examination of vane shear strengths and pore pressures in the feed residue suggests that the consolidated undrained shear strengths of the residue can be reasonably represented by the same expression as for the overflow. The in-situ vane shear tests showed that the coarser underflow is stronger than the finer overflow and the strength was evaluated to be represented by the expression $S_u = 30 + 0.3p$ (kPa).

The stability of the embankment was checked using these strength estimates and measured and assessed water table conditions using both the limit equilibrium analysis (SLOPE/W (2002)) and total stress, strain compatibility FLAC analysis (Itasca (1998)). The results of these separate analyses yielded the estimates of the factor of safety listed in the following table.

Crest Elevation (mamsl) Starter wall crest at 151 m	FLAC Factor of Safety	SLOPE/W Factor of Safety
160	2.78	2.06
169	1.68	1.77
175	1.45	1.48

The results are similar and indicate that factors of safety are adequate for embankment raising to a height of at least 38 m. It has been recommended that a field investigation program similar to that performed in 1999 and 2001 be performed in 2005 to re-evaluate the residue characteristics, layering, drainage, pore pressure and strength gains that are occurring and confirm the on-going stability for projected future raises of embankment elevation.

5 CONCLUSIONS

The Sadiola residue facility was designed and commissioned on the basis of deferring capital expenditure as far as possible, and adopting an 'observational approach'. This approach is reliant upon on-going and comprehensive investigation and monitoring to ensure that the residue facility performs as intended and that changes are made as and when necessary, as part of a continual improvement process. The deferred capital costs justify the increased costs of the required investigations, monitoring and facilities management.

The Sadiola residue is almost unique and the approach adopted did not always meet with approval from both owners and stakeholders. Although the residue is unusual it was not necessary to adopt expensive and conservative solutions. The outcome of the investigations have shown that a methodical evaluation of actual performance produces data which allows ongoing reviews and the introduction of mitigating measures to operations.

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