Geotechnical Characterization and modelling of the Mandena heavy mineral sand deposit

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ABSTRACT: Biological cementation of the Mandena heavy mineral deposit in Madagascar was causing difficulty in dredge mining and hence in planning and control of production rates. An investigation was initiated to better evaluate the geotechnical properties of the orebody sands. The investigation was aimed at defining the distribution and geotechnical properties of the cemented strata, in order to generate a site specific geotechnical model for the Mandena deposit. The geotechnical characterisation was developed using an integrated approach of several ground investigation techniques such as piezocone (also known as CPTu) testing, geotechnical drilling, SPT testing as well as laboratory testing. The final outcomes of the investigation included a 3D geotechnical model showing the distribution and extent of the cemented areas as well as the typical geotechnical parameter ranges associated with each of the defined geotechnical units. The interpretations developed were incorporated into the mine and production planning to ultimately optimise operational planning and control.

1 INTRODUCTION

QIT Madagascar Minerals (QMM) is a heavy mineral sand mining operation at Mandena, near Fort Dauphin in Madagascar. During the final planning and commissioning stages of the project, the need to fully characterise the unusual geotechnical conditions was identified and a geotechnical investigation was initiated.

2 NATURE OF THE PROBLEM

During the commissioning phase it was found that the mining production was being impacted by biologically cemented/indurated sands layers encountered within the sands. Upon closer inspection of the indurated horizons encountered within the dredging face it was discovered that these layers possess a high loading of both bacteria and fungi. It appears that the bacteria produces an extracellular (outside the cell) polysaccharide i.e. sugar and carbon salts which form a jelling biofilm to trap nutrients. There are a number of different bacteria. The fungi on the other hand produce a network of fibrous strands that bind the sand grains together. Thus the "apparent cohesive" strength or binding of the indurated sand is probably contributed by both bacteria and fungi (Lynn, 2008).

The main challenge of this project was posed by the many unknowns surrounding the nature and extent of this biological cementation that was presenting a geotechnical problem for the mining process. Typically the following questions arose:

- Is this a biological, geological or geotechnical problem, or all of the above?
- How does one go about modelling when not necessarily governed by apparent geological processes or markers?
- What tools and techniques would be best utilised to cope with the variable conditions being investigated? How effective will they be?
- How does one ensure the tools and techniques used can provide useful data that can be verified?
- How does one combine all the available data collected to generate a practical geotechnical model that will assist in a mining production environment?
- How does one approach the modelling of geotechnics and relate this to the geological resource model and mine plan?

3 DATA GATHERING AND EVALUATION

3.1 *General*

The scoping of the investigation was completed during various brainstorming sessions considering existing data, the most crucial engineering parameters required for mine and dredge design and also which geotechnical investigation techniques available could potentially obtain the needed data effectively. The scoping study also included trials using different rotary and vibrocore drilling techniques to confirm which would be most appropriate to use.

This process culminated in an investigation methodology involving two phases. Phase 1 focused on high density geotechnical rotary core drilling, logging, sampling and Standard Penetration Testing (SPT) as well as piezocone with pore pressure measurement (otherwise known as CPTu) testing within a limited area. Soil laboratory testing and rock testing was also completed on samples retrieved from the boreholes. It should be noted that following the trials, it was decided not to use a vibrocore drill as it was found that the vibration of the drill broke the intergranular bonds in the indurated layers, resulting in the indurated materials being recovered as soils.

Phase 2 focused on a lower density of testing on the remainder of the ore body. During Phase 2 all available historic information was used, including existing exploration borehole log data, where appropriate, to generate a 3D geotechnical model and typical geotechnical parameter ranges for the most important geotechnical properties.

In-situ measurements using a piezocone (CPTu) rig provided direct measurement of cone resistance (q_c), sleeve friction (fs) and pore water pressure (u), which can be used to derive various geotechnical parameters. Due to the expected variable conditions refusal of the CPTu equipment was expected on the hardest indurated layers. A standard drilling rig or hydro vibracore rig (sonic method) was therefore provided to advance through the hardest layers when encountered.

Selected CPTu locations were paired with high quality rotary core drilling, using a triple tube barrel and a mud flush intended to obtain cores of indurated sands and more cohesive/dense soil layers. Limited SPT testing was also completed in the holes and used to provide a comparison with the CPTu data. Detailed geotechnical logging of the core was completed. Sampling from the core for laboratory testing was conducted to confirm parameters derived from the CPTu interpretations and logging and to determine parameters that could not be derived from the CPTu testing and logging.

The combined Phase 1 and Phase 2 geotechnical database consisted of 147 CPTu locations, 48 Borehole and SPT test locations. More than 200 disturbed samples and approximately 80 core samples were tested in the laboratory.

3.2 *Field logging of Rotary Drilling Samples*

Poor recoveries obtained during drilling provided little material within the un-indurated zones and this posed various challenges during field logging.

To ensure consistent capturing of information that could later be calibrated and refined when combined with the other data gathered (such as the CPTu and laboratory information) a site specific approach to logging was adopted to ensure a consistent account of the indurated materials were captured. Generally zones registering SPT N_{field} values of over 50 blow counts (noted as “Refusal”) were deemed to be of very dense consistency or possibly of extremely soft to soft rock strength with a Uniaxial Compressive Strength (UCS) of 0.5-3 MPa. The presence of rock like indurated materials was logged only if core samples were available to confirm its presence, irrespective of the SPT N_{field} values recorded. Where it could be confirmed from core or SPT samples extracted, the thickness, spacing and depth of indurated beds were recorded.

Based on this approach, zones with similar geotechnical conditions were identified and provided with an overall description. This process was the first step in the generation of a site specific geotechnical framework/unit model.

3.3 *Correlation of in-situ testing methods*

A numerical correlation between the CPTu derived SPT N_{60} values, q_c and the SPT N_{field} values obtained in the paired locations was conducted.

To obtain a point value to correlate with the SPT N_{field} values recorded a linear average output value from the CPTu at the start and end of the SPT testing depths was assumed.

A graphical presentation of a typical CPT derived SPT N_{60} trend and SPT N_{field} values plotted with depth for test and drilling location No. 42 are shown in Figure 1 below.

Acceptable correlations were found to exist for 58% of the test positions providing correlation coefficients from 0.5 to 0.94. Visual assessment of the trends indicated that in several of the poorer correlating cases, trends were off set, but that overall visually the trends are similar.

Correction factors were applied to the SPT N_{field} values, but none of the standard correction factors (Clayton, 1995) (such as rod energy, overburden and anvil size) could provide a consistent improvement in the correlations obtained using the raw data.

3.4 *CPTu interpretations and borehole logs vs laboratory results*

Good correlation was found to exist between the rotary drill sample logging, laboratory results and the soil behaviour classes as defined by soil behaviour charts developed by Robertson *et al*. (1988) for the CPTu.

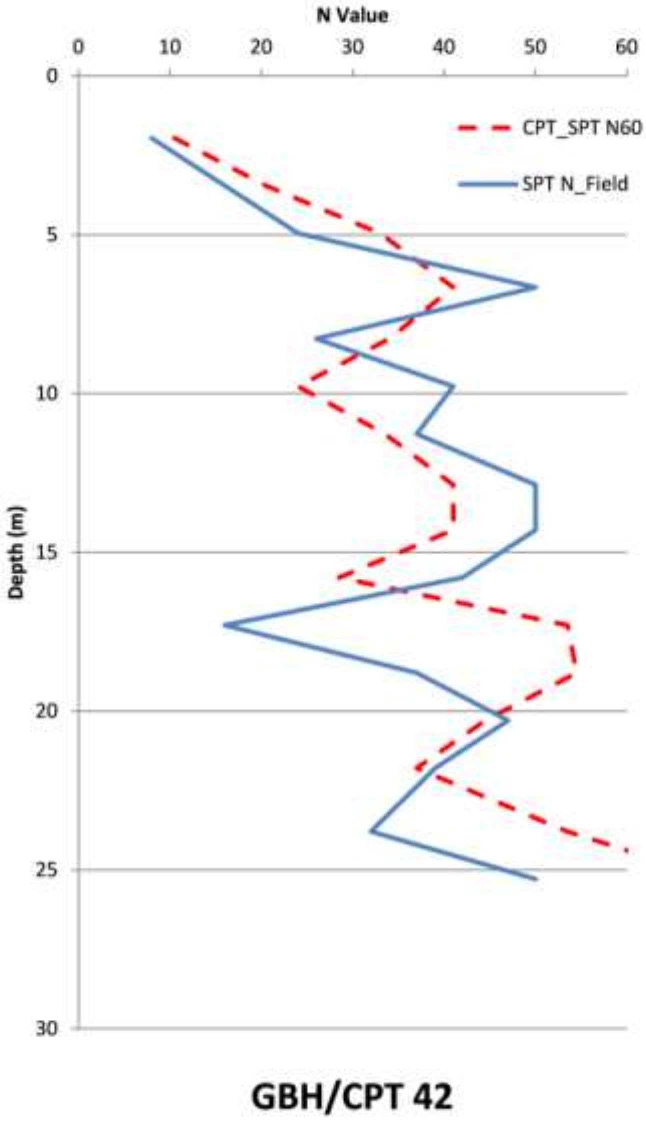


Figure 1. Graphical comparison of CPTu derived SPT N_{60} with SPT N_{field} values-Test location No. 42.

The CPTu identified sands and silty sands dominating the profile with some materials, typically those found at the base of the probe holes, classifying as silts or sandy clay type materials.

The laboratory UCS test results agreed well with the rock strengths identified during borehole logging with most falling within the strength range (UCS of 0.5 to 3.0MPa) predicted during logging (Extremely to Very Soft rock).

The permeabilities measured in the laboratory for the core samples were in line with permeability predictions based on the CPTu derived soil behaviour types (sands and silty sand).

However, some exceptions occurred when correlating CPTu information with samples extracted from the paired rotary drill holes indicating that significant variation in induration strength can exist over small distances.

3.5 *Generation of a geotechnical framework/unit model*

The processes described in Section 3.1 to 3.4 led to the definition of a geotechnical unit framework within which further data evaluation could take place. The framework focused mainly on defining zones that would have specific engineering implications for the mining operation.

General internationally accepted guidelines as provided in literature and summarized in the TRH10 (1987) document (Technical Recommendation for Highways-South Africa) relate CPT q_c to SPT N_{field} values and corresponding density descriptions as shown in Table 1 below.

Spikes in q_c values could be correlated with very dense to indurated layers located within generally medium dense to very dense silty sand layers. This finding agreed with what was observed during logging of the boreholes drilled. It also became clear that the CPTu was also more effective in picking up the presence of very thin indurated layers that would not be identified during drilling and SPT testing. The conceptual geotechnical unit framework determined considering all the gathered data available is shown in the Table 2 below.

Table 1. Internationally accepted consistency descriptors as a function of SPT N and CPT q_c value ranges obtained (adopted from TRH10)

Density Description	SPT N	CPT q_c (MPa)
Very Loose	4	2
Loose	4-10	2-5
Medium Dense	10-30	5-15
Dense	30-50	15-20
Very Dense	>50	>20

Table 2. Geotechnical unit model derived from Phase 1 fieldwork data and observations

Zone	Name	Geotechnical Description	Distribution
1	Aeolian Sands	Free flowing to non-free flowing loose to medium dense sands.	Usually the surface deposit. Occasionally absent.
2	Strandline Sands	Non free flowing clean to organic, occasionally ferruginised, medium dense to very dense sands.	Usually underlying Aeolian Sands. Occasionally exposed at surface. Seldom absent, but possible.
3	Strandline Sands with Indurations	Non free flowing medium dense to very dense sands of interbedded with extremely soft (UCS 0.5-1MPa) to very soft (UCS 1-3MPa) Indurat-	Lenses generally within Zone 2. Occasionally at top or base. Apparently random distribution. Sometimes absent.

Zone	Name	Geotechnical Description	Distribution
		ed sands /Sandstone.	
*4	Deposit Base Strandline Sands, Silts and Clays	Interbedded sands, silts and clays of variable consistency.	At base of and occasionally interleaved with Zone2/3. Sometimes absent.
*5	Residual Sandy Clay	Firm clay, silt or clayey sand.	At base of Zone 2/3 or 4.

*Zone 5 represents the clay basement and is not part of the resource, whereas Zone 4 is a transitional zone between the resource and basement.

Simple principles were developed to ensure a consistent evaluation, and optimisation of the geotechnical zone boundaries. These included:

- Adopting CPTu data as the more accurate and continuous record of in-situ conditions due to generally low sample recoveries in the boreholes.
- When delineating and optimising geotechnical zone boundaries density would have priority over descriptive properties (such as colour).
- Zone 3 conditions were inferred where significant spikes in the CPTu q_c could be observed of 30-40MPa, where vibracore drilling was required or where recovery of core samples confirmed the presence of indurated layers.
- If a section was logged in boreholes as a Zone 2 and the CPTu data indicated hard layers these Zones would be upgraded or adjusted to Zone 3 in accordance with CPTu data.

4 3D MODELLING APPROACH

During Phase 2, Phase 1 interpretations were verified. Phase 2 also included scrutinizing the geological exploration data gathered to aid in 3D modelling. This in itself provided a challenge as geological logging had been completed from a "geological and resource modelling perspective" whereas the "geotechnical zones" were based mostly on engineering properties of the materials as logged and measured using specific techniques.

The geotechnical zone modelling and numerical modelling were approached separately. The measured data was considered hard data, whereas the zone boundary interpretations made were based on a combination of the descriptive and in-situ measured data. Geotechnical zones were therefore modelled as separate "lithologies".

4.1 *Geotechnical Zone lithology modelling*

The geotechnical zone volumes were interpolated using spheroidal variogram settings using constant Kriging and a range of approximately 300m. The ellipsoid ratios were optimised to reflect the general dimensions of the volumes being modelled (i.e. disk shaped with small Z relative to ellipse radius).

Zones 1, 2 and 3 were modelled separately; however Zones 4 and 5 were combined and modelled as one composite region delineating the clayey deposit base consisting of either marine clays and/or residual clayey sands. Areas not defined by the interpolants developed from existing geotechnical data were inferred as comprising of Geotechnical Zone 2 type sands.

The interpolations where modelled assuming the following age succession:

- Zone 3 is considered the youngest, generally cutting indiscriminately through all deposited sands, as cementation took place after deposition of the strandline deposits.
- Zone 1 to Zone 5 (excluding Zone 3) was assumed to be increasing in age, however Zone 2 could be interleaved with Zone 4 type materials (clays and silty sand lenses) due to the nature of deposition of the strandline sands.

Correlation between the geological database generated during exploration drilling and the Geotechnical database were considered. After some review it was confirmed that the merging of the two datasets will not be ideal and would possibly skew the presentation of the geotechnical information gathered. The two data sets were therefore kept separate from each other within the modelling software. However, the geological data had to be utilised to some extent during modelling to supplement the limited geotechnical data points available. To correlate indurated conditions captured within the geological database an approach introduced by project geologist Hees (2010) was used to include an "induration" interval to identify zones where described/indicated and inferred indurated conditions can be expected. This interval could be used to group key lithologies within the Leapfrog modelling software to reflect the distribution of the indurated conditions as per the geological database, which could then be compared with the geotechnical zone boundaries. In areas where little data was available the Zone 3 model was extrapolated by utilising the reviewed and grouped geological data as well as imported sections. However, areas existed where indurated conditions were identified that were not captured in the geological database. Geotechnical data therefore took precedence in most cases when interpreting the Zone 3 materials boundaries.

4.2 *Numerical data analyses in 3D*

A design chart was developed by the dredge designers matching SPT N number to output in tonnes per hour (tph) for the existing dredge used when production issues ensued. For this reason the first attempts in modelling of geotechnical properties was focused on the SPT N numerical data as known relationships existed. Numerical modelling of the SPT N_{60} and SPT N_{field} values were undertaken and run using similar settings to the lithological model.

A separate 3D interpretation was made using only the numerical data gathered to interpolate areas associated with specific numerical parameter thresholds within specific orebody areas. Numerical data within each modelled zone could also be extracted and analysed statistically. The numerical model can currently provide 3D contour maps of a specific geotechnical parameter modelled at any level or on any section through the orebody volume. The numerical interpretations do not agree in all areas with the zone interpretations as selected locations were modelled using only descriptive logging information with no numerical geotechnical background data (e.g. hydrogeological borehole positions or exploration data). Gaps in the numerical data coverage still exist however the process demonstrated that numerical modelling of a geotechnical parameter can be very useful in this case.

5 MODELLING RESULTS

Of most significance to the mining operation is the spatial distribution of Zone 3, which is the most indurated zone. Modelling of Zone 3 showed it to consist of relatively continuous, but gently undulating indurated beds and/or lenses across the majority of Mandena area. It can be absent/under-developed in certain locations. The macro appearance of the indurated zones is that of large to small scale lensing rather than the existence of distinct indurated horizons but these macro lenses can be made up of various indurated horizons of variable thickness.

Zone 3 conditions are expected to be concentrated around elevations ranging from +4m msl to -1m msl.

Table 4 provides the numerical information extracted for each geotechnical zone modelled providing parameter ranges and typical values of the SPT N_{field} and SPT N_{60} values measured within these areas.

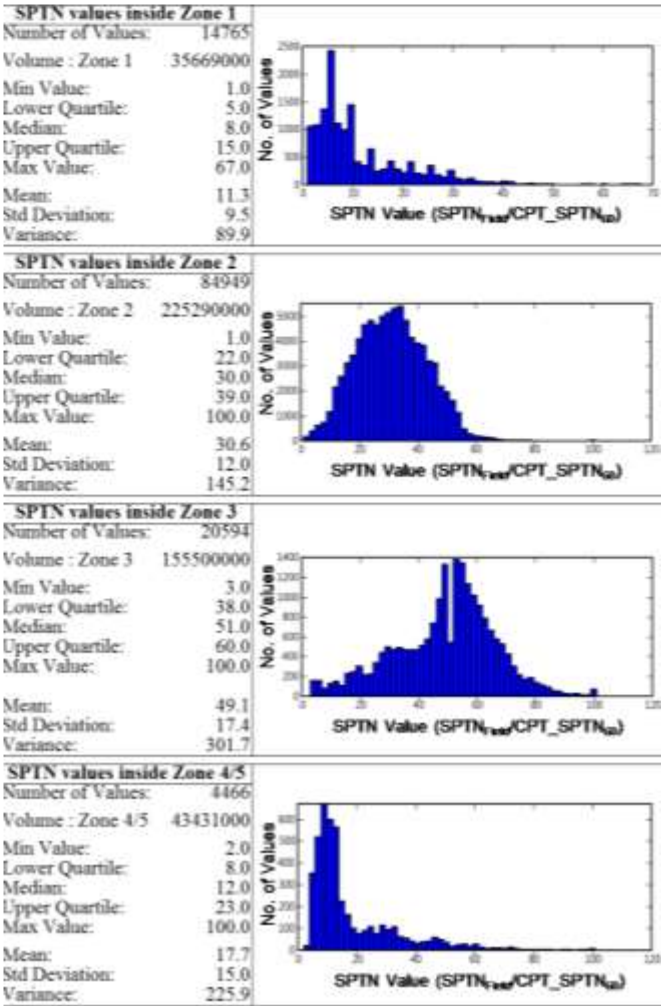
Numerical data available for the indurated conditions (Zone 3) is likely to be less representative due to early refusal of the CPTu, and the relatively small number of boreholes drilled also limiting conventional SPT measurement.

Laboratory testing results have confirmed the expected UCS values associated with the most indurated Zone 3 materials. At present the maximum strength/hardness of the indurated materials recovered and tested can be assumed to be around 2 MPa, as measured during the Phase 1 testing campaign.

Although the properties of Zones 2 and 3 are highly variable, the median SPT N value exceeds 30 for Zone 2 for the majority of the orebody.

The Zone 3 median SPT N value is estimated at 53 (possibly higher, if adjustments are made for rock like materials on which the CPTu and SPT refused-Table 4 refers). Current measured SPT N values for Zone 3 ranged from as low as 3 to 100.

Table 4. Numerical SPT N_{field} and SPT N_{60} data extracted within each geotechnical zone.



It is therefore clear from the data evaluation shown in Table 4 that the numerical data and the zone model has been successful in delineating distinct geotechnical zones that can be applied to the mine planning and design process.

6 APPLICATION TO MINING OPERATION

Based on existing design charts the dredge should be able to achieve on average around 1900tph Zone 2 materials and no more than 1300tph in the Zone 3 materials. By applying typical expected weighted SPT N values to certain mining blocks (e.g. by determining the weighted average volume each geotechnical zone represents in a specific mining block), one can more accurately predict advance rates and set realistic production targets and/or plan which areas should rather be earmarked for mechanical pre-conditioning to obtain the desired throughputs. This information can be/was also used to specify a larger dredge that would be able to deal with most of the geotechnical conditions predicted by the model.

Geotechnical parameters associated with the various zones modelled and the nature of the zones as reviewed in 3D have the following implications for the mining operations:

– The Zone 1 deposits will be easily excavated or dredged.
– Zone 4 and 5 materials may cause process inefficiencies due to their more cohesive nature causing blockages of, and build up on, processing equipment and hindering of heavy mineral separation due to increased slimes contents.
– All areas will be excavatable using mechanical excavators and bulldozers, although Zones 1 and 2 would be easier to excavate than Zone 3.
– Dredging of Zone 1 and Zone 2 is considered possible, however dredging of Zone 3 can result in significant drops in productivity when encountering the stronger indurations.
– In terms of the stability of excavated slopes in the dry mining pits it is expected that Zone 3 materials can stand vertically over long periods, although not necessarily with a sufficiently high factor of safety. Zone 2 materials may stand vertically for several metres over short periods but will collapse to lower angles over time. The Aeolian sands are generally free flowing and excavated slopes will collapse to an angle of 30° to 35°.
– Due to the variable nature of the deposit (introduced by the combination of the geotechnical zone thicknesses, the presence and scale of the Zone 3 indurations and localised hydrogeological factors) have to be considered. As a result no one specific slope stability solution or FoS can be assigned and slope stability management must be approached as a daily planning and production requirement requiring on-going assessment by a competent person.

7 CONCLUSIONS

The Mandena case study demonstrates the importance and necessity of geotechnical investigations in the early phases of a project to ensure understanding of the geotechnical parameters of an orebody and the potential limitations this could pose to the chosen mining process. Unfortunately the importance of these investigations in the early phases of mining projects (specifically referring to heavy mineral sand mining projects) are commonly forgotten or focus is only placed on civil or resource estimation applications rather than on the understanding of how geotechnical conditions could potentially impact on the mining process.

The case study further demonstrates the importance of using an integrated approach including various geotechnical and geological techniques to successfully characterize unusual and variable geotechnical conditions.

By using an integrated approach and combining data from geological and geotechnical sources it was possible to generate a geotechnical zone model in 3D into which any of the in-situ measured and/or derived parameters obtained from CPTu testing can be imported, modelled and/or data extracted and analysed statistically for application to the mining requirements.

This integrated method of investigating, defining and presenting large scale, and unusual geotechnical problems allowed the Mandena operation to enhance its production planning capabilities.

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