The strategic and tactical value of a 3D geotechnical model for mining optimization, Anglo Platinum, Sandsloot open pit

by A. Bye*

Synopsis

Sandsloot open pit is situated on the northern limb of the Bushveld Complex, 250 km north east of Johannesburg, South Africa. Sandsloot is currently the largest open pit platinum mine in the world and is one of six potential open pits in the area.

The geotechnical strength properties of the Platreef have posed significant mining and processing challenges to the PPRust operation since inception in 1992. In order to optimize the whole business as opposed to isolated cost centres a mine to mill initiative was embarked upon in 1997.

Initial work focused on ore characterization and an entire suite of data was collected for each rock type. This included mineralogy, geochemistry, geotechnical, blastability indices, as well as metallurgical strength data. The second phase involved the clear definition of customer requirements, namely the optimum performance criteria for the plant and mining departments. This involved extensive field trials and data capture to measure the interaction and influence of the mine to mill value chain.

Once the design targets were defined, a 3D geotechnical model was constructed to ensure that the targets were consistently achieved. The model is very similar to an ore reserve model; however, it is populated with geotechnical, metallurgical and blast index data. Through software queries the appropriate blast powder factor for each mining block can be obtained, thereby ensuring the correct fragmentation is blasted for the plant and mining operation.

The initiative has delivered significant results showing improvements across the mine to mill value chain. These include increased loading rates, reduced electricity and crushing consumables, as well as higher plant throughput. Additionally, the initiative has benefited both brownfield and greenfield projects on the PPRust operation

Introduction

Geology and the detailed understanding of its properties are fundamental to the optimal design and successful operation of any mine. To that end, extensive fieldwork was conducted at Sandsloot open pit (PPRust—Anglo Platinum) to collect geotechnical information both from exploration boreholes and in-pit mining faces. Over a fie-year period, geotechnical data were collected from 29, 213 m of exploration core and 6 873 m of exposed mining faces. Extensive field and laboratory testing was undertaken in order to define the complete set of geotechnical properties for each rock type in the Sandsloot mining area.

The geotechnical information collected was stored in the Datamine mining software package. The architecture of the database was developed along the principles used for generating an ore reserve model. The geotechnical data, namely mining rock mass rating system (MRMR), uniaxial compressive strength (UCS), fracture frequency per metre (FF/m) and rock quality designation (RQD), was modelled using geostatistics to generate a 3D geotechnical model. Data was interpolated between exploration boreholes and exposed mining faces. The modelling was constrained, using wireframes, by rock type and major structural features. The result is a block model containing 15 m^3 blocks of interpolated geotechnical information. The size of the model blocks are linked to the mining bench height of 15 m.

By having detailed geotechnical information available in a 3D model, which can be readily accessed and interpreted, significant production optimizations, feasibility studies and planning initiatives can be implemented. From a slope design perspective, the model is used to target data deficient zones and highlight potentially weak rock mass areas. As this can be viewed in 3D, the open pit slopes can then be designed to

* *Anglo Platinum.*

accommodate the poor quality area before it is excavated. It also follows that geotechnical zones can be readily identified and the slope optimized accordingly.

Rather than viewing the drill and blast department as an isolated cost centre and focusing on minimizing drill and blast costs, the study focused on the fragmentation requirements of the comminution and load and haul business areas. It is well understood that chemical energy is the cheapest form of comminution and that major downstream benefits can be derived by increasing drill and blast expenditure. 238 blasts were assessed to determine the optimum fragmentation requirements for ore and waste. Based on the study, a mean fragmentation target of 150 mm was set for delivery to the crushing circuit and a mean fragmentation of 230 mm was set for waste loading from the pit. Substantial benefits have been realised in the drill and blast department by developing empirical correlations, which relate the MRMR values in the geotechnical model to a blastability index, fragmentation, required powder factor and costs. As the geotechnical model can predict changes in geotechnical conditions, the blasting parameters can be adjusted in advance to ensure the load and haul and comminution plant's fragmentation requirements are met.

PPL operates autogenous mills, which are sensitive to the fragmentation profile delivered. The harder zones occurring in the ore zone therefore have a major impact on the plant's performance. Accordingly, these zones are identified and additional blast energy is introduced in order to achieve the target fragmentation for the plant. The 3D geotechnical model allows these optimizations to be undertaken proactively by the drill and blast department.

Geotechnical overview

The Platreef is a pyroxenite orebody hosted within the northern limb of the basic igneous rocks of the Bushveld Complex (Figure 1). It has an economic strike length of 40 km and contains platinum group elements, gold, copper and nickel. The Platreef is capped by the Main Zone hangingwall sequence consisting of gabbronorites. This in turn is overlain by Upper Zone sequences of ferrogabbros. The mineralization is hosted predominantly within pyroxenite and parapyroxenite. The parapyroxenites are conformable with the footwall of the Platreef and are essentially a contaminated metamorphosed pyroxenite formed between the cold country rock and the Platreef intrusive phase. The footwall to the Platreef in the Sandsloot open pit consists of metadolomite, known generically as 'calc-silicate'. Interaction of basic magma with the footwall sediments of the Transvaal Supergroup and varying degrees of assimilation has resulted in a unique suite of hybrid rock types, which provide a host of engineering geological challenges.

The open pit is disturbed by two normal faults and a major oblique sinistral fault. There are three major joint sets that influence the Sandsloot area. These large foliation planes dip steeply, and are laterally and vertically continuous over hundreds of metres. They not only pose slope stability problems but also affect drill and blast performance.

Table I documents the results from the extensive geotechnical programme that was undertaken for the various rock types occurring at Sandsloot. It is evident from the results that the ore zone contains a range of rock harnesses and elastic properties, which have a major impact on drill and blast as well as comminution performance.

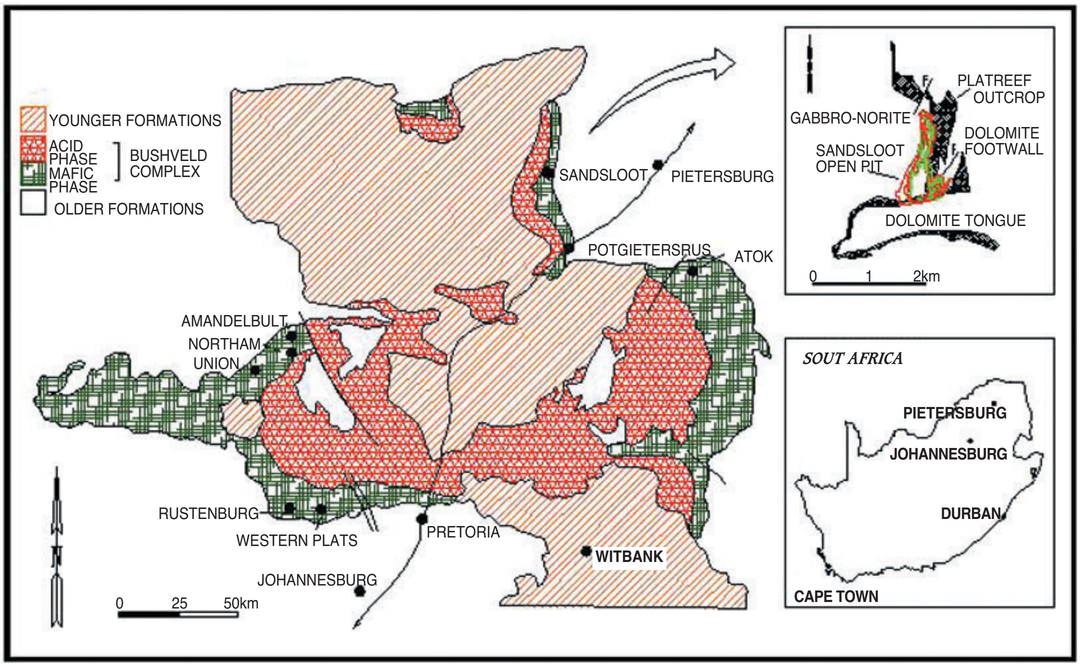

Figure 1—Location of Sandsloot open pit and general geology of the Bushveld Complex

Mining process

The Platreef orebody at Sandsloot is tabular in geometry, dips at 45° and is approximately 50 m in width. These properties allow the orebody to be excavated by open pit mining methods, which is considerably cheaper than conventional underground mining. The stripping ratio is the ratio between the waste and ore mined or the amount of waste that has to be removed in order to access the ore. Due to the 45° dip of the orebody, the stripping ratio is relatively high at 8:1, when compared with open pits such as Phalabora which have a much lower stripping ratio of 1.5:1.

Sandsloot open pit is the largest open pit platinum mine in the world. In a single month the mine crushes over 425 000 tons of ore and excavates 50 million tons of ore and waste annually. The open pit is in the process of a third cut, which has a depth of 200 m below surface. Subsequent cut-backs will extend this to a maximum of 320 m. The benches are 15 m in height and mining blocks are 100 m x 50 m. The pit is scheduled to expand in a series of phased cut-backs until mining ceases during 2010, when it is predicted that the economic cut-off between open pit and underground will be reached.

The productivity of mining equipment depends largely on the blast fragmentation size. An economic balance has to be found between the very high loading rates produced from a highly fragmented rock mass, and the drill and blast costs associated with producing such a fragmented rock mass. Add into this the crushing and milling benefits associated with very fine blasting of the ore and it can be seen that achieving a minimum mining cost is not as simple as optimizing isolated cost centres such as the quantity of explosive used. The process is, however, simplified by having detailed geotechnical, geomechanical and mineralogical information from the rock mass. From this information, mining blocks can be assigned optimum drill and blast configurations that not only improve comminution and loading rates but also the ore concentration process. It follows that an integrated approach to mining, which involves all cost centres, is needed to successfully reduce overall mining costs and improve productivity.

In order for a mining company to stay competitive in the modern economy, it is essential that it operates at the lowest possible cost. Mining companies are therefore constantly striving to reduce the operating costs of the mining equipment by improving the equipment's performance. By providing comprehensive geotechnical information, in the form of a 3D model, equipment requirements can be accurately defined and therefore performance and mining efficiencies can be optimized.

Data collection

The development of a detailed geotechnical database at Sandsloot was based upon extensive field mapping using line surveys, as well as geotechnical face-mapping and logging of exploration boreholes. Over a five-year period, geotechnical data were collected from 29 213 m of exploration core and 6 873 m of exposed mining faces.

Geotechnical mapping involved the visual separation of a mining face into similar geotechnical zones based on rock type and structure. Each zone was then mapped individually and all the data required to rate the zone, using Laubscher's (1990) mining rock mass rating system (MRMR), was collected. This included line survey and major structural information such as rock quality designation (RQD), joint orientation, roughness and continuity. Laboratory samples, schmidt hammer and point load readings were used for calculation of uniaxial compressive strength (UCS).

The diamond drill exploration boreholes are logged for the same information as described above. There is therefore a common set of data between the open pit faces and the exploration boreholes from which interpolation and predictions can be made. The data collected was evaluated and the derived geotechnical information then stored in a Datamine database. Datamine is one of the numerous mining software packages available that are designed to model ore reserves and plan mining operations.

Table I

Geotechnical properties of the Sandsloot rock types

Rock type	Hangingwall Norite	Ore zone Pyroxenite	Ore zone Para-pyroxenite	Ore zone Serpentinized parapyroxenite	Footwall Calc-Silicate
UCS (MPa)	190	160	200	250	130
Tensile strength (MPa)	9.5	8.0	10.0	13.5	7.0
Young's modulus (GPa)	82	72	134	108	50
Poisson ratio (m)	0.232	0.173	0.218	0.264	0.288
Density (kN/m^3)	2.9	3.2	3.3	3.1	2.9
RQD%	80	65	75	70	55
FF/m	9	13	10	11	16
MRMR	55	48	51	56	47
MRMR class	(III A)	(III B)	(III A)	(III A)	(III B)
Drillability class	Low	Medium-high	Very-low	Low	Medium-high
Abrasive class	Medium-high	Low	High	Medium-high	Low

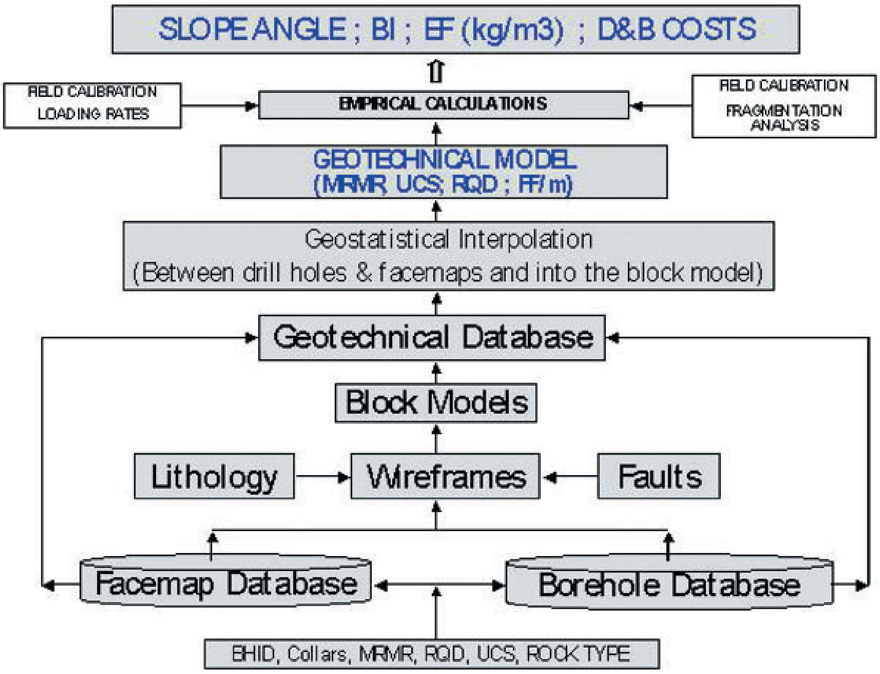

Figure 2—Flow diagram illustrating the model development process

The borehole and face-map database were combined and the data was then geostatistically interpolated between the borehole and face-map information. The face-maps were essentially treated as horizontal boreholes. The data were analysed using histograms and semi-variograms to determine the most suitable interpolation method to use for each modelled parameter, namely MRMR, UCS and RQD. Due to the bell curve nature of the data sets and the data being relatively evenly spaced, the inverse distance interpolation method was used as a first pass. As the database expands, future processing may require more advanced methods such as kriging. The models for each rock type and model parameter were combined into a single model containing all the information. The result is a 3D model with 15 m^3 blocks that contain interpolated geotechnical information such as MRMR, UCS, RQD values as well as the rock type.

Empirical calculations and application of the model

Rather than viewing the drill and blast department as an isolated cost centre and focusing on minimizing drill and blast costs, the study focused on the fragmentation requirements of the processing plant and load and haul business areas. It is well understood that chemical energy is the cheapest form of comminution and that major down-stream benefits can be derived by increasing drill and blast expenditure.

Over the last three years blast patterns have been adjusted in order to find an economic balance between drill and blast costs and overall mine productivity. Using the Modular Mining Truck Dispatch System, 238 blasts were assessed to determine the optimum loading rates for the equipment at Sandsloot. The method used was instantaneous loading rates, which measures the effective time that the shovel bucket was in the muckpile and is related to tons per hour. In other words, it is the ease with which a blasted muckpile can be loaded. The target loading rate for the equipment was set at 3200 t/h. The study revealed that from 169 waste blasts a powder factor of 1.17 kg/m^3 yielded an average load rate of 3 182t/h and 69 ore blasts yielded and average loading rate of 3 316 t/h from an average powder factor of 1.56 kg/m^3.

The loading rates were then related to fragmentation and a selection of the blasted muckpiles were assessed using the SPLIT desktop digital fragmentation analysis software. From the fragmentation analysis it was determined that the blast patterns yielded a mean fragmentation of 150 mm in ore and 230 mm in waste. The powder factors and achieved fragmentation in the ore blasts may seem excessive but this is due to the requirements of the autogenous milling system at PPL. Bye (2000) discussed in detail the substantial financial benefits that have been derived at PPL by harnessing chemical energy in the pit to increase the throughput in the plant.

Based on this detailed study, a mean fragmentation target of 150 mm was set for delivery to the crushing circuit and a mean fragmentation of 230 mm was set for waste loading from the pit. In order to incorporate this information into the geotechnical model, Cunningham's (1986) fragmentation equations were utilized. Cunnigham's equation (Equation [1]) gives a prediction of the mean fragmentation based on the explosive energy and rock properties. However,

at Sandsloot there was a detailed geotechnical model and known fragmentation targets. It therefore made sense to rework the Cunnigham equation in order to produce a required energy factor equation (Equation [2]) based on the inherent rock properties and fragmentation targets.

In order to obtain a required energy factor per geotechnical model block, Lilly's (1986) blastability index (BI) was derived from the geotechnical information contained in the model. The BI (Equation 3) was then used to calculate the rock factor for input into the required energy factor equation (Equation 2). The required energy factor equation (Equation 2) is derived from the target fragmentation, rock factor, explosive relative weight strength, rock volume and mass of explosives.

$$\overline{X} = A \times \left(\frac{V}{Q}\right)^{0.8} \times Q^{0.167} \times \left(\frac{RWS}{115}\right)^{-0.633} \quad [1]$$

X = Predicted mean fragmentation diameter (cm)

$$EF = 1/\left[\overline{X}/\left(\left(A \times Q^{0.167}\right) \times \left(\left(RWS/115\right)^{-0.633}\right)\right)\right]^{1.25} \quad [2]$$

EF = Required energy factor (kg/m³)
$\overline{X}$ = Required mean fragment diameter (cm).
A = 0.12 x BI (rock factor)
Q = Mass of explosive per blasthole (kg)
V = rock volume or yield (m³)
RWS = Relative weight strength of explosive (ANFO = 100)

$$BI = 0.5(RMD + JPS + JPO + RDI + S) \quad [3]$$

BI = Blastability index
RMD = Rock mass description
JPS = Joint plane spacing
JPO = Joint plane orientation
RDI = Rock density influence (25 x density-50)
S = Rock strength (0.05 x uniaxial compressive strength).

It became apparent that the model could be used to predict costs and, based on the standard drill and blast costs used, a Sandsloot a correlation was developed between the required energy factor (Ef, kg/m³) and cost per cubic metre (Equation 4). These costs included drilling, explosives, labour and maintenance. Figure 3 illustrates a planned blast outline overlain on the geotechnical model. A set of category filters can be seen, which relate the model block colours to the blastability index, required energy factor and costs. Figure 4 illustrates graphically the effect of the blastability index on the required energy factor and the associated drill and blasts costs.

$$\text{Cost per } m^3 = Ef \times 2.946 \quad [4]$$

$$Ef = \text{Required energy factor } (\text{kg/m}^3)$$

An additional function was built into the model to calculate a stable inter-ramp angle based on the MRMR values within the model. The equation (Equation 5) for deriving a stable slope angle was taken from the design chart

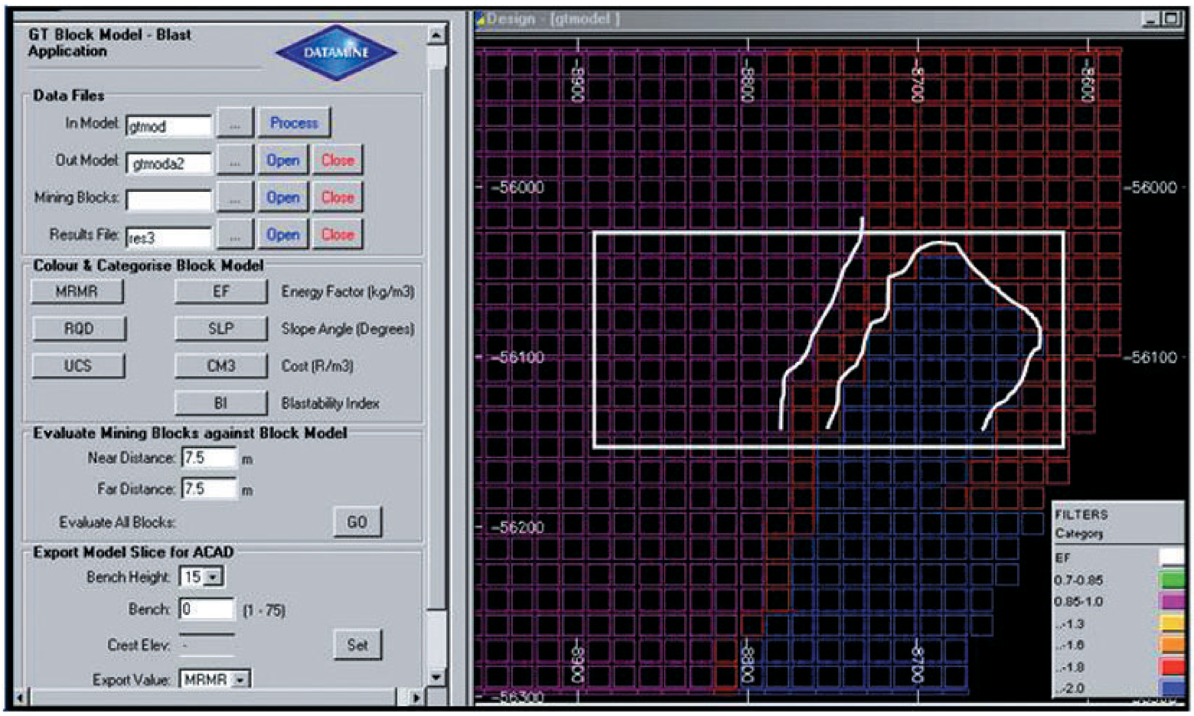

Figure 3—Plan view of blast outline with colour coded information on blastability index (BI), required energy factor (EF) and cost/m³ derived from the model

developed by Haines and Terbrugge (1991). A factor of safety of 1.2 was used to calculate a 100 m high, stable inter-ramp angle from the MRMR values contained in the block model.

$$\text{Slope angle} = 0.4456 \times MRMR + 37.226 \quad [5]$$
$$\text{MRMR} = \text{mining rock mass rating value}$$

Stewart and Kennedy (1971) showed that it was not only the steepness of the ultimate slopes in an open pit mine that had an influence on the overall profitability of an operation. They contended, on the basis of cash flow calculations, that there is frequently considerable economic advantage to be gained from using steep slopes during the initial stripping programme. This is particularly the case at Sandsloot where the stripping ratio plays a large role in profitability. The model can be used to optimize the pit slopes rather than applying a single design to the entire pit. A one degree slope optimization will generate an additional $46 million in revenue during the life of Sandsloot pit.

A Visual Basic front end in Datamine is used to query the model for energy factors, costs, etc. The planned drill pattern area can then be evaluated against the model to give a summary of all the model information for that planned mining block. Additionally a dxf file can be exported from the model so that pattern and blast design can be undertaken in other software packages.

Mine to mill results

Open pit mining involves a process of controlled destruction of the rock mass so that the waste may be stripped and the ore extracted. The blasting engineer is faced with the conflicting requirements of providing large quantities of well-fragmented rock for the processing plant, reducing drill and blast costs and minimizing the amount of damage inflicted on the rock slopes left behind. A reasonable compromise between the conflicting demands can only be achieved if the blasting engineer has a very sound understanding of the factors that control rock fragmentation, highwall damage and slope stability. This understanding was significantly enhanced through the use of a 3D geotechnical model.

Manual information systems used for design require significant dedication and time commitments and can be onerous to continually update. They often rely on the commitment of a single individual and are therefore not sustainable. The 3D geotechnical model is a user-friendly and sustainable tool, which can be readily updated and therefore does not suffer from the limitations of a manual system.

Figure 5 illustrates the average loading rates from 1999 to 2003. There is a clear distinction in performance before and after the fragmentation model was applied. The variability in loading rates is clearly evident prior to 2002 and this is due to the blast designs not taking into account the variations in rock mass conditions. After 2002 the loading rate is above the design target every month.

The application of the fragmentation model to blast design resulted in an 8.5% and 8.8% improvement in loading and milling rates, respectively, from 2001 to 2003. It must be stressed that these are actual production figures measured over a two-and-a-half year period and therefore represent a significant record of performance. A more detailed analysis of all the customer performance measures was undertaken for the period from January to June 2003 (Figures 6 and 7). There is a clear improvement across all the performance indicators, which include the following:

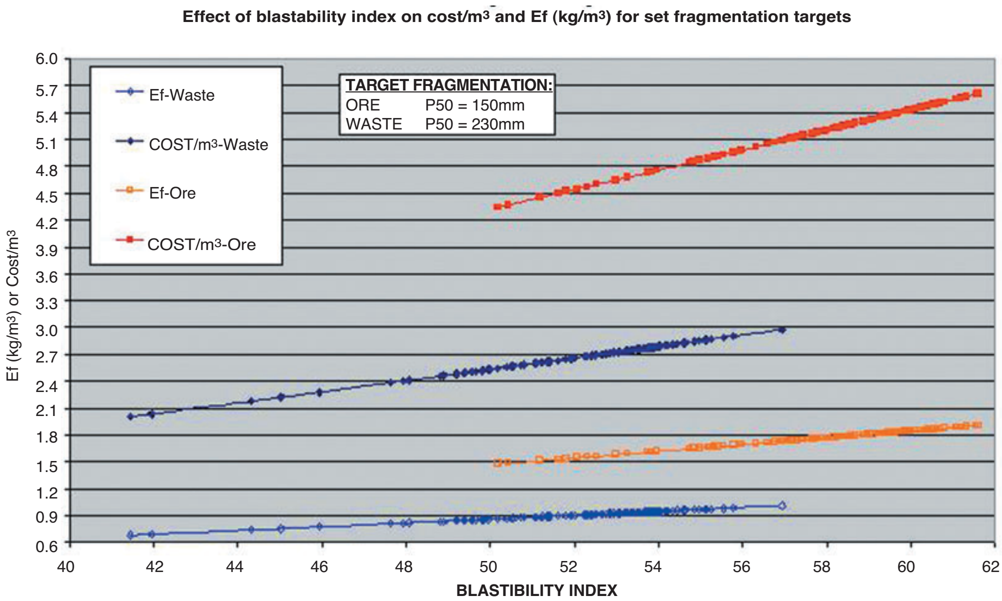

Figure 4—Effect of blastability index on costs and required energy factor for set fragmentation targets

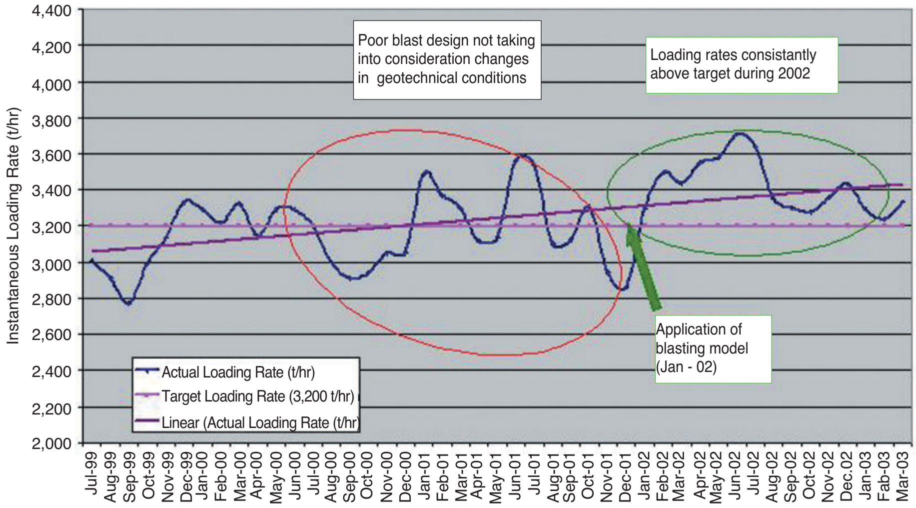

Figure 5—Loading rates showing the impact of the fragmentation model for blast design

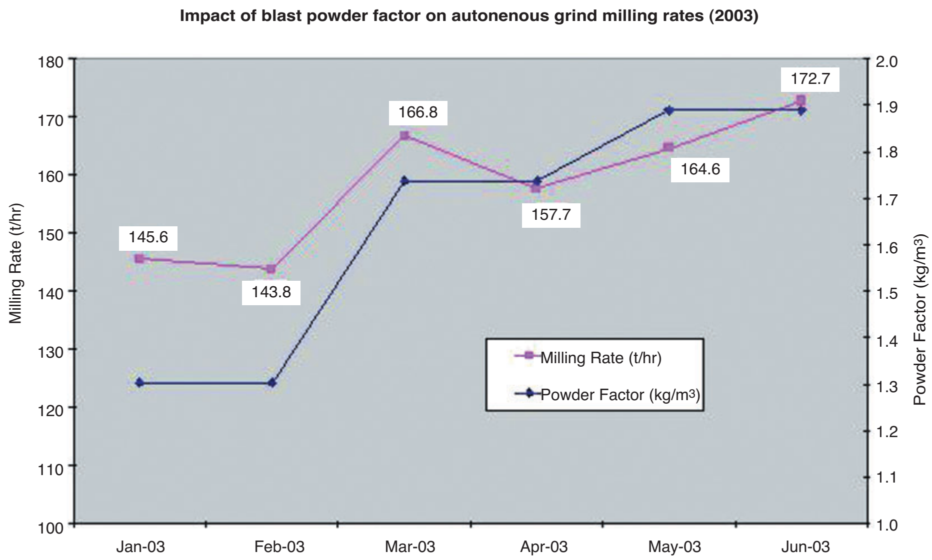

Figure 6—Loading and milling performance from 2001 to 2003

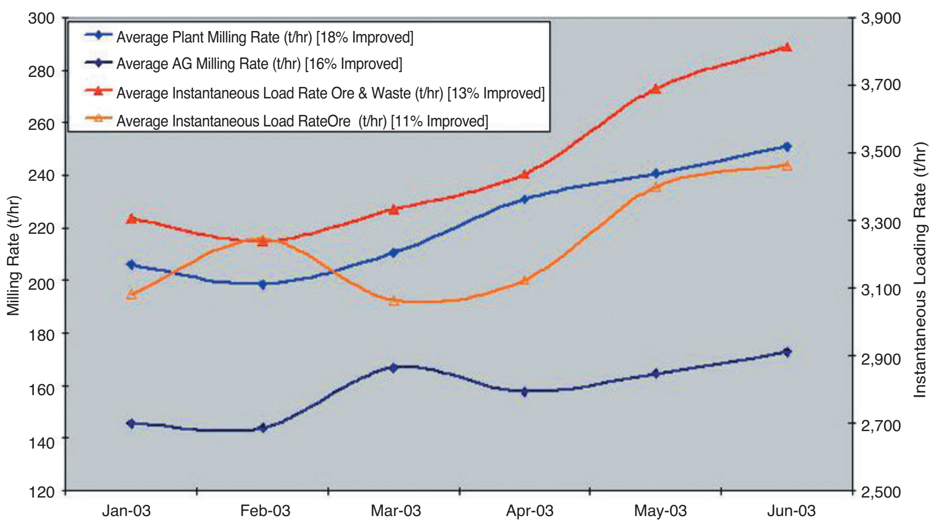

Figure 7—Graph illustrating the performance of the drill and blast department's two customers during 2003. The loading rates include ore and waste and the milling rates include both the AG and ball mills

- ➤ Average plant milling rate (AG and Ball mills)—18% improvement
- ➤ Average AG milling rate—16% improvement
- ➤ Average instantaneous loading rate (ore and waste) 13% improvement
- ➤ Average instantaneous loading rate (ore)—11% improvement.

These performance improvements represent a substantial value add to the overall business and the associated financial benefits are significant in terms of millions of rand per month. The improvement in the autogenous grind milling performance for the 18-month model application period from January 2002 to June 2003 was recorded. The average milling rate for 2001 was 156 t/h, while this improved by 5.5 t/h to an average of 161.5 t/h in 2003. The additional revenue generated by this increased efficiency for the eighteen-month period was $ 4.5 million.

This research illustrates the improvement in business efficiencies that has been realized at Sandsloot, not from restructuring but by assessing the company's total business process and defining a customer focus for the drill and blast department. This customer focus was facilitated by the use of a fragmentation model.

Conclusions

A 3D geotechnical model has application to any major civil or mining venture that requires a detailed understanding of the variability in rock mass conditions. A geotechnical model does not propose to generate solutions by creating information from a limited data set. It does, however, give the engineer a tool whereby he can assess the spatial variability of the rock mass information and thereby identify data-deficient or high-risk areas. There are numerous case histories detailing the failure or significant over-expenditure of civil, tunnelling and mining projects caused by a lack of knowledge of the variability of the *in situ* rock mass.

The 3D geotechnical model provides information well ahead of the mining face, which can then be used for rock quality prediction, production optimization, slope evaluation and design, as well as planning and costing. Using a similar query function as the ore reserve model, mining slots can be evaluated and not only grade and tonnage figures derived but predictions of penetration rates, powder factors, presplit and blast designs, as well as equipment and explosives requirements. The mining costs could be broken into drilling, blasting, crushing and milling costs, based on expected powder factors, penetration, crushing and milling rates, thereby further optimizing pit planning and expenditure. More detailed costing and budgeting can be undertaken especially in respect to comminution and drill and blast costs.

There is the potential for a similar geotechnical programme and the application of a geotechnical model to be equally applicable to underground operations. Additionally, there is considerable scope for the implementation of these methods as a tool for mine evaluation and feasibility assessments of new ore deposits. The ore reserve model has gained widespread acceptance as an invaluable tool to a mining operation. Certainly most financial organizations will not invest in a mining project that does not have an ore reserve model. There is the potential that the same acceptance as a vital tool to the mining process will follow the development of geotechnical models. In the race for reduced mining costs and increased productivity, the development of a geotechnical model provides a cost-effective tool to improve productivity and reduce mining costs. The Sandsloot case study illustrates this with $4.5 million in additional revenue generated over an eighteen-month period through the mine to mill campaign.

References

BYE, A.R. The application of geotechnical information to drill and blast operations at Sandsloot open pit. Bulk Mining Explosives, Annual Conference, Pretoria. 2000.

CUNNINGHAM, V.B. The Kuz-Ram model for prediction of fragmentation from blasting. *Proc. 1st intern. Symposium on rock fragmentation by blasting*, Lulea, Sweden. 1986. pp. 439–52.

HAINES, A. and TERBRUGGE P.J. Preliminary estimation of rock slope stability using rock mass classification systems. *Proc. 7th Int.Cong. Int. Soc. Rock Mech*. Aachen. Balkema, Rotterdam, vol. 2, 1991. pp. 887–892.

LAUBSCHER, D.H. A geomechanics classification system for the rating of rock mass in mine design. *J. S. Afri. Inst. Min. Metall.*, vol. 90, 1990. pp. 257–273.

LILLY, P.A. An empirical method of assessing rock mass blastability. The Aus.IMM-IE Aust. Newman Combine Group, Large Open-pit Mining Conference. October, 1986, 1986. pp. 89–92.

ÖZCĘLIK, Y. Effect of discontinuities on fragment size distribution in open-pit blasting—a case study. *Trans. Intsn. Min. Metall.* (Sect. A: Min. Industry), 107. 1998. pp. A146–A151.

STEWART, R.M. and KENNEDY, B.A. The role of slope stability in the economics, design and operation of open pit mines. *Proc. 1st Symposium on Stability in Open pit Mining*, Vancouver 1970. A.I.M.E. New York, 1971. pp. 5–21. ◆