The application of multi-parametric block models to the mining process

by A. Bye*

Synopsis

The development of 3D multi-parametric models facilitate the provision of resource information well in advance of the mining face. Using the model, one can evaluate mining areas not only for grade and tonnage predictions but also for predictions of rock mass quality. Blast design and milling requirements can be derived from the rock mass quality predictions. This information can be used for overall mine planning and evaluation, costing, production optimization and slope design. This allows the full range of mining activities and costs to be interconnected, thereby lowering costs and improving efficiencies through the application of the multi-parametric model.

Feasibility studies for new projects require an expected budget expenditure estimate to within 5% of actual costs. This level of accuracy is expected by mining companies and investors but cannot be achieved without a sound knowledge of the rock mass variability. By developing a 3D multi-parametric model as part of the feasibility study and using the same geological model exploration boreholes, a significantly better understanding of the rock mass conditions can be obtained. This rock mass information can be used for equipment selection, economic pit layouts, processing plant design, underground mining layouts and support requirements, to name but a few design parameters that depend on rock mass conditions. The initiative at Anglo Platinums, Potgietersrust Platinum Ltd.'s (PPRust) operation, 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.

The ore reserve model has gained international acceptance as an invaluable tool for 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 for multi-parametric models to be recognized as vital tools in the mining process, as is the case with ore reserve models.

Introduction

A 3D multi-parameter model has application for any major mining venture that requires a detailed understanding of the variability in rock mass conditions. These models give engineers a tool whereby they can assess the spatial variability of the rock mass information and identify opportunities or data-deficient and high risk areas.

By having detailed geotechnical information available in a 3D model that can be readily accessed and interpreted, significant production optimization, 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 accommodate the poor quality area before it is excavated. It also follows that geotechnical zones can be readily identified and the slope optimized accordingly. Figure 1 details the development process for multi-parameter models.

At PPRust the multi-parametric model was used to improve blast fragmentation delivered to the plant as well as the load and haul department. 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. Substantial benefits have been realized in the drill and blast department by developing empirical correlations, which relate the mining rock mass rating (MRMR) values in the multi-parametric model to a blastability index, fragmentation, required powder factor and costs. As the multi-parametric 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.

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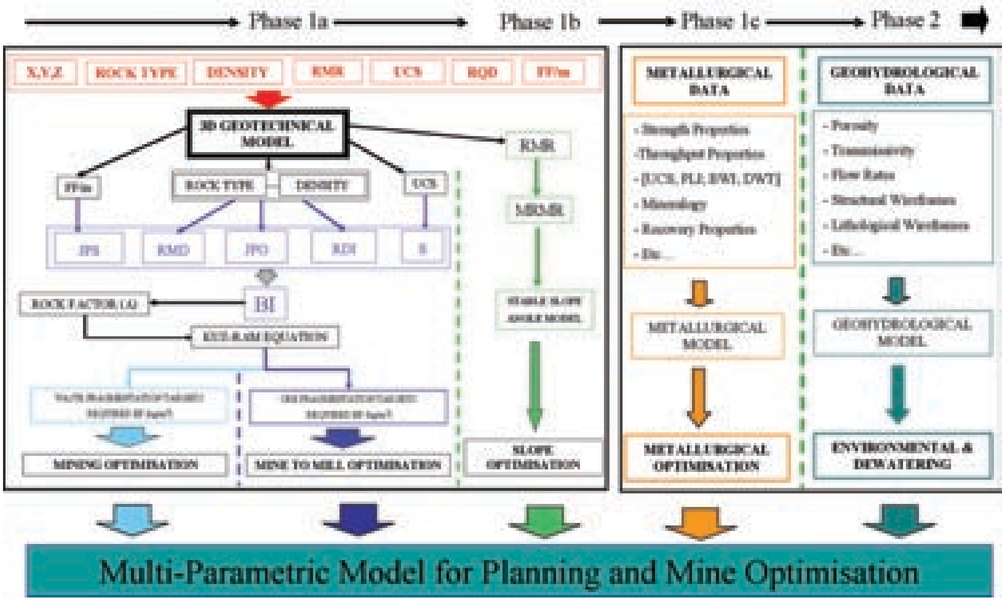

Figure 1—Multi-parametric modelling for planning and optimization

Figure 2—PPRust's Sandsloot open pit

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

Data collection

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 is required to collect geotechnical information both from exploration boreholes and in-pit mining faces. In addition, extensive field and laboratory testing should be undertaken in order to define the complete set of geotechnical properties for each rock type in the mining area.

In the case of PPRust's Sandsloot open pit (Figure 2) 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 parameters, namely mining rock mass rating system

(MRMR), uniaxial compressive strength (UCS), fracture frequency per metre (FF/m) and rock quality designation (RQD), were modelled using geostatistics to generate a 3D multi-parametric model. Data was interpolated between exploration boreholes and exposed mining faces which had been mapped. In order to undertake geostatistical modelling, the major structural features and rock types were constrained in the geotechnical model using wireframes. The result was a block model containing 15 m x 15 m x 15 m blocks of interpolated geotechnical information. The size of the model blocks are linked to the mining bench height of 15 m.

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 5-year period, geotechnical data was collected from 29.213 m of exploration borehole 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 geological 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, were collected. This included line survey and major structural information such as rock quality designation, joint orientation, joint roughness and joint continuity. Laboratory samples, Schmidt hammer and point load readings were used for calculation of uniaxial compressive strength.

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 were 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.

The borehole and face map database were combined and the data were 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 (normal distribution) of the data sets and the data being relatively evenly spaced, the inverse distance interpolation method (ID2) 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 x 15 m x 15 m blocks that contain interpolated geotechnical information such as MRMR, UCS, RQD values, as well as the rock type.

Functionality

In order to create a user-friendly environment from which any unskilled Datamine user can run the fragmentation model, a visual basic front-end was created. The user interface/functionality for the models is provided via a simple front-end query screen. The mining engineer can overlay the outline of the planned blast area and run a query on the model. The query function interrogates the model and provides a summary table of all the relevant mining information, i.e. rock type, geotechnical properties, blastability index (BI), design fragmentation target, blast tonnage, required energy factor and the expected drill and blast costs associated with that mining area. For longer-term planning and budgeting, the mining slots are queried in series to provide the required drill and blast information. Figure 3 illustrates a 3D view of the block model and the cell attributes.

Slope design model

The delineation of similar geotechnical domains or zones is an accepted practice in geotechnical engineering and slope design parameters are thereafter defined for each of these domains. The definition of these domains is generally broad based and restricted to dominant rock types or major structural features. A major shortcoming of these methods is that the data collected are only representative of a visual mining face or isolated borehole and do not take into account the 3D rock mass conditions. The rock mass information used for design is therefore limited and often results in overly conservative or high-risk slope profiles, as the 3D rock mass conditions are not accounted for.

The development of the slope design model provided the opportunity to move away from one design process for the entire pit, toward the customization of slope designs and configurations, which were then developed to cater for local variations in the rock mass condition. The model would therefore aid the engineer in defining an optimum slope configuration based on the 3D rock mass conditions represented in the model. The availability of the geotechnical information in 3D and the improved level of confidence of that data, will result in improved open pit slope designs (Figure 4).

An additional function was also built into the model aimed at calculating a stable inter ramp angle based on the MRMR values within the model. The equation for deriving a stable slope angle was taken from the design chart 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.

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 further application of the multi-parametric model is to use the scheduling software to generate economic mining shells based on the comprehensive geotechnical and mining

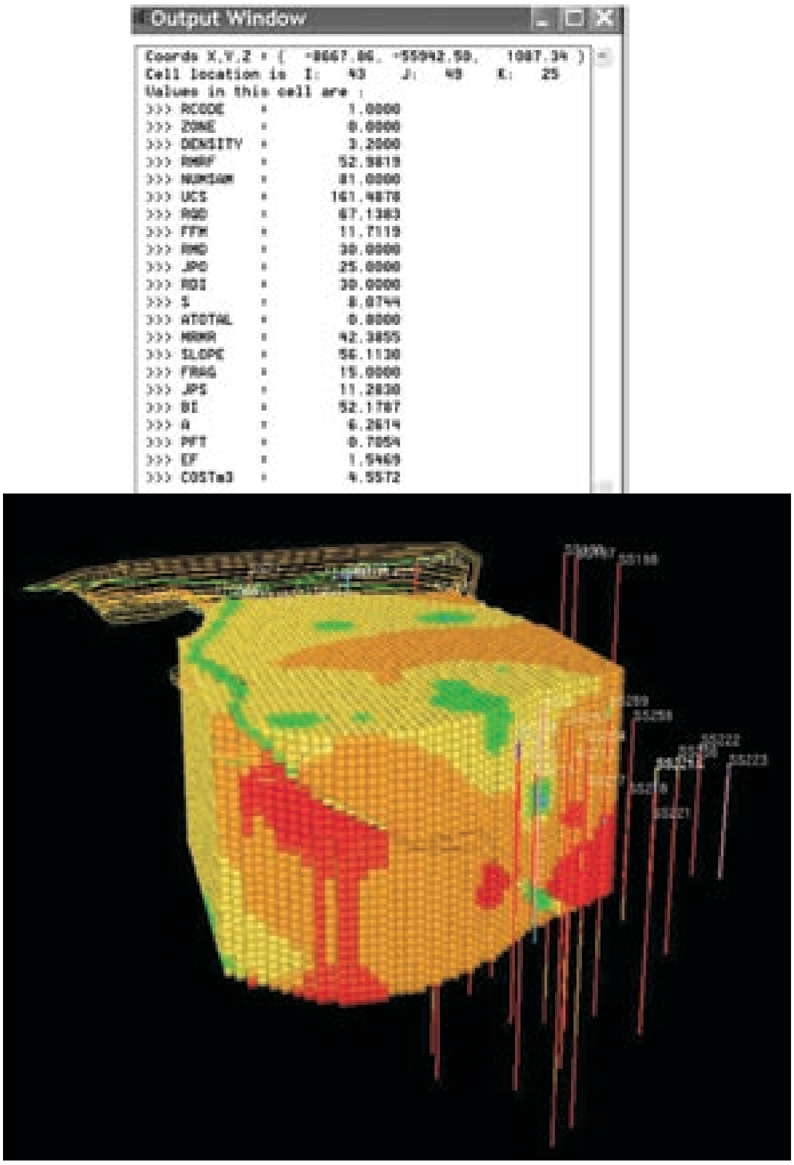

Figure 3—3D Datamine™ view of the multi-parametric model (view looking south) The information listed above in the output window is related to an individual model cell

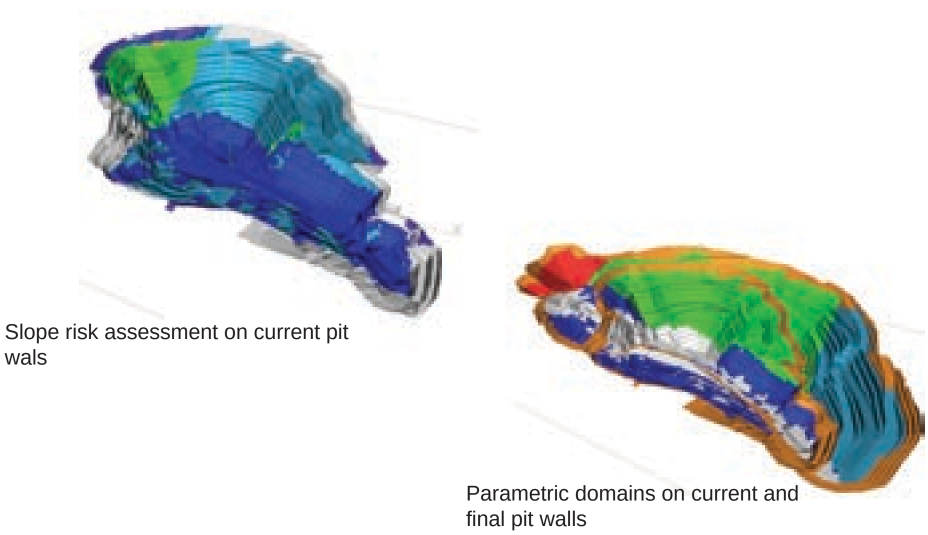

Figure 4—3D parametric domains and slope risk derived from the model (view looking north)

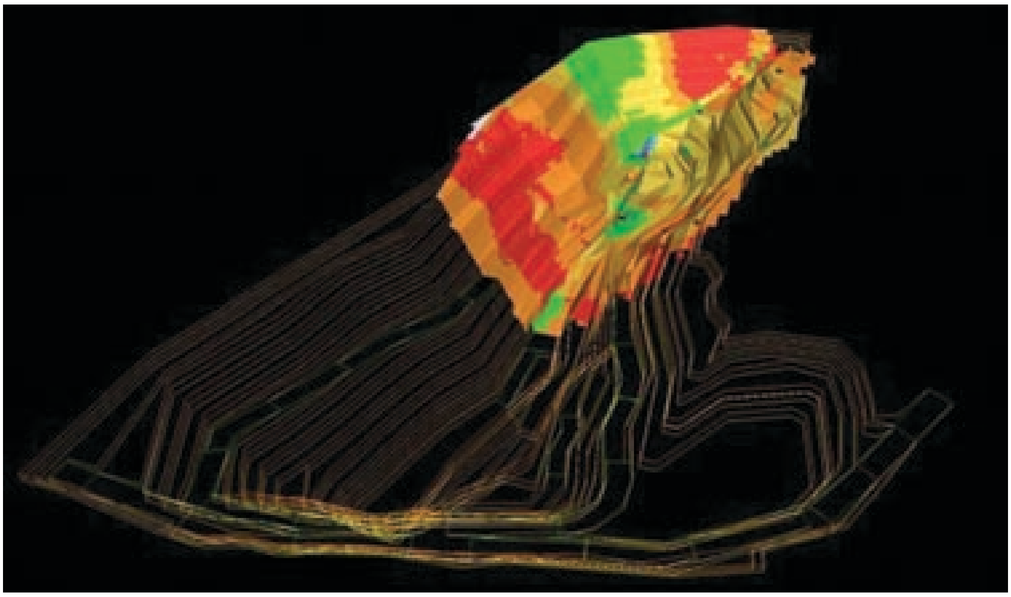

Figure 5—Wireframe sliced through the 3D slope stability model illustrating the appropriate stack design angle for the various areas of the pit (view looking north)

information contained in the multi-parametric model. As the multi-parametric model has a stable slope angle contained in each cell, it is feasible that the scheduling software could generate far more accurate economic shells based on this information, rather than a single slope angle for the entire pit highwall (Figure 5).

Figure 5 illustrates an oblique view of the final design pit with a colour-coded wireframe of the slope stability model, draped onto the design slopes. The model blocks are evident on the wireframe and are filtered based on the stack angle value. For example, in the north west corner of the design pit, light grey cells are evident, indicating poorer rock mass conditions and a stable stack angle of 55 degrees. The model intersection wireframes provide a powerful design tool, whereby any area or interim design slope within the open pit can be visualized and the design adjusted accordingly.

Fragmentation model

Drilling and blasting is the first step in the physical mining process and therefore plays a major role in the performance of downstream functions. The inherent rock mass properties are one of the biggest unknown factors in blast design and play a major role in blasting costs and the productivity of the downstream functions. The 3D multi-parametric model provides detailed rock mass information and can therefore be applied to the blast designs in order to improve the efficiency of blasting.

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 to 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 explosives 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 concentrating 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.

At PPRust the fragmentation model has optimized the blast design and planning process, by firstly reducing the level of uncertainty associated with rock mass information; secondly by defining precisely the customer requirements, and thirdly by combining the entire process into a 3D model that can be queried for any planned mining slot. The fragmentation model is a dynamic tool to ensure that the customer requirements are consistently achieved (Figure 6).

In order for a mining company to remain 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 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.

Fragmentation model 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

Figure 6—Photos illustrating poor (left) and good fragmentation (right). The impact of the poor fragmentation (choking the grizzly) is evident in the left photo

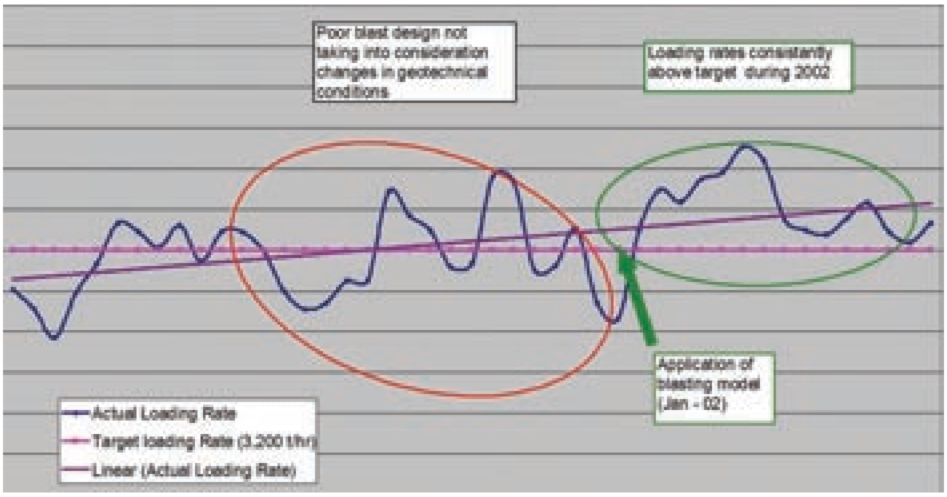

Figure 7—Loading rates showing the impact of the fragmentation model on blast design

on the rock slopes left behind. A reasonable compromise between the conflicting demands can be achieved only if the blasting engineer has a very sound understanding of the factors that control rock fragmentation, highwall damage and slope stability. This understanding is significantly enhanced through the use of a 3D multi-parametric 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 multi-parametric 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.

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 in order to give a summary of all the model information for that planned mining block. In addition, a dxf file can be exported from the model, which facilitates the pattern and blast design in other software packages.

The fragmentation model was applied to the Sandsloot pit from January 2002 (Figure 7). Each individual blast design was adjusted based on the model recommended powder factor. In this way a dynamic blast design was instituted, which was aimed at delivering a consistent blast fragment size to the loading operations and the processing plant.

Figure 7 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 consistently remains 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 the 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

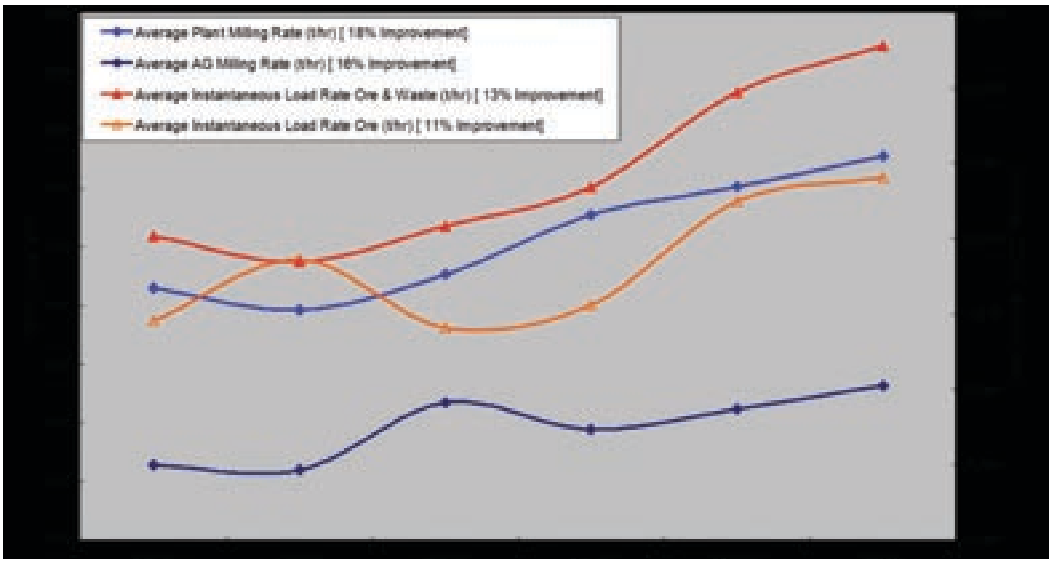

Figure 8—Graph illustrating the performance of the Drill and Blast Department's two customers during 2003. The loading rates include ore and waste and the milling rates include both the AG and ball mills

was undertaken for the period from January to June 2003 (Figure 8). There is a clear improvement across all the performance indicators, which include the following:

- ➤ Average plant milling rate (autogenous grind (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 AG milling rate for 2001 was 156 t/h, which 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 US$4.5 million.

The variability in material strengths experienced in the Platreef is due to the interaction of the Bushveld Complex magma with the sedimentary footwall rock types. This has resulted in a range of metamorphic alteration minerals, which control the material strengths of the rock types. The extensive occurrence and variability of these alteration minerals will continue to necessitate 3D modelling, prediction and dynamic blast design.

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.

Pit design

Mine design interrogates an ore reserve model to generate an economic mining shell using Datamine™ NPV Scheduler™ or Whittle 4D™, which are based on the Lerchs-Grosman algorithm. The scheduling software proposes pit outlines and preferred areas of mining, based on grade and mining cost-per-ton. At Sandsloot and most other mines, a single mining cost-per-ton is applied to the entire pit, except for consideration of the hauling costs related to pit depth. A practical pit is then designed around the economic mining shell, generated by the scheduling software, using an average stable slope angle. The schedule is based on the mining costs versus the grade and tonnage for each ore reserve block.

A further application of the multi-parametric model, would be to use the scheduling software to generate economic mining shells based on the comprehensive geotechnical and mining information contained in the multi-parametric model. As the multi-parametric model has a stable slope angle contained in each cell, it is feasible that the scheduling software could generate far more accurate economic shells based on this information, rather than a single slope angle for the entire pit highwall.

Feasibility projects

Feasibility studies for new projects require an expected budget expenditure estimate to within 5% of actual costs. This level of accuracy is expected by mining companies and investors but cannot be achieved without a sound knowledge of the rock mass variability. By developing a 3D multi-parametric model as part of the feasibility study and using the same geological model exploration boreholes, a significantly better understanding of the rock mass conditions can be obtained. This rock mass information can be used for equipment selection, economic pit layouts, processing plant design, underground mining layouts and support requirements, to name but a few design parameters, which depend on rock mass conditions. There is the potential for the application of multi-parametric models to be equally successful in underground operations, as well as considerable scope for the implementation of these methods as a tool for mine evaluation and feasibility assessments of new ore deposits.

Metallurgical model

At PPRust, work is continuing towards including mineralogical properties into the block model and thereby developing a metallurgical model. Mineralogy is closely linked to rock type and alteration and therefore has a spatial distribution. Plant recovery is directly affected by the mineralogy of the processing material and therefore an expected recovery could be included in the model cell. In addition, a correlation between rock hardness and expected milling rates can be obtained by incorporating metallurgical test data such as bond work index (BWI) and drop weight test (DWT) data. The metallurgical throughput data is related to rock type and mineralogy and therefore a milling rate model could also be developed.

Geohydrological model

Groundwater plays a significant role in the productivity of most mining operations. In terms of mine planning, its influence is normally incorporated as a 'factor' in the scheduling process. A 3D geohydrological model used during the scheduling process would add considerable value to the mining plan and ultimately productivity. It is envisioned that geological and structural wireframes are used to delineate separate geohydrological zones, which can then be populated with the appropriate hydrological properties. The influence of these zones on mine productivity can be assessed as the open pit or shaft is deepened or extended.

Conclusions

A 3D multi-parametric model has application to any major civil or mining venture that requires a detailed understanding of the variability in rock mass conditions. A multi-parametric 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 multi-parametric 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, pre-split and blast designs, as well as equipment and explosives requirements. The mining costs could be broken down 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 for comminution and drill and blast costs.

There is the potential for a similar geotechnical programme and the application of a multi-parametric model to be equally applicable to underground operations. In addition, 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 for a mining operation, to the extent that it is now a prerequisite. 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 multi-parametric models. In the race for reduced mining costs and increased productivity, the development of a multi-parametric model provides a cost-effective tool to improve productivity and reduce mining costs.

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