Batu Hijau Open Pit Slope Design Based on Geotechnical Models and Past Performance

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Abstract
Batu Hijau is a large copper-gold open pit owned and operated by PT Newmont Nusa Tenggara in Indonesia. The pit is currently around 700m deep from original topography with a highwall on the west side approximately 640m high. Final slopes are planned to approach 980m. It is situated in a structurally complex and highly variable rock mass and receives approximately 2800mm of rainfall per year. At Batu Hijau, the design philosophy is that of ‘slope management’ rather than ensuring slope stability, i.e. acceptance and management of slope instability at acceptable levels of risk (Leech, 2007). In order to optimize the geotechnical slope design, the geotechnical models need to be analyzed together with the assessment of historical performance of the pit walls to determine the geotechnical design domains and slope angles.

The Batu Hijau geotechnical group have developed reliable geotechnical 3D models for the different elements involved in the design i.e. lithology, alteration, major structures, joint sets, RMR, rock strength (PLI), as well as a block model of the significant historical failures. These models were developed using geology mapping, geotechnical core logs from exploration geology, rock fabric data from oriented core logging, bench face and photogrametry mapping, PLI tests for every core run, and the failure register. Data is stored in a SQL database.

With the basic geotechnical models, the geotechnical domains are defined based on rock mass strength and rock structure. Subsequently, kinematic and limit equilibrium stability analyses are conducted to determine the recommended pit slope angles for each domain.

Kinematic analysis for the design process is usually done for specific faults and/or joint sets or statistically analyzed to define the probability of failure. With these procedures alone, it is not possible to explicitly identify the structure or combination of structures that could cause a failure and where in the pit this failure could occur. At Batu Hijau, the historical failures model and back analyses were used to identify the critical structures. This is done by studying the geotechnical and failures model of previous phases of the pit with the objective of identifying the critical structural sets. This methodology has assisted in identifying and locating potential areas of concern and in defining alternative designs that could improve slope performance.

1 Introduction

The Batu Hijau open pit copper-gold mine is located at eastern Indonesia on Sumbawa Island, and is owned and operated by PT Newmont Nusa Tenggara (NNT). The Batu Hijau cumulative production until the end of 2010 is about 9.2Mt concentrate, with Cu 6,093Mlbs (av. 29.9%) and Au 5,990Koz (av. 19.4g/t). Overall slope heights are planned to approach 980m. The end of mine will be reached in 2024 with 6 years of stockpile re-handle after completion of the open pit.

Since the grades are relatively low, the economics of the mine is driven by maximizing the slope angle. Small changes in the slope will significantly impact on the economics of the deposit. This paper discusses the slope design based on geotechnical models and past performance of the pit slopes, emphasizing the importance of integrating the geotechnical information in a system that can be used to gain a better understanding of the geotechnical conditions of the mine.
2 Background

2.1 History of Batu Hijau

NNT was formed in 1985 and aimed to conduct systematic exploration for epithermal gold mineralization on the islands of Lombok and Sumbawa. A Contract of Work was granted by the Government of Indonesia in 1986. The Batu Hijau deposit was discovered in 1990 and exploration continued until 1996. In 1997 the Feasibility Study was approved by Government of Indonesia and then continued onto the construction stage. The first stripping commenced in 1998, and production started in 2000.

2.2 Climate

At Batu Hijau the climate is seasonal, subject to a ‘wet’ monsoon from October to April and a ‘dry’ monsoon from May to September. About 85% of the annual rainfall, about 2800 mm, occurs during the wet season. Typically, rainfall events are of relatively short duration, but of high intensity.

2.3 Geology

The Batu Hijau pit area is dominantly underlain by andesitic volcanic lithic breccia and minor fine-grained volcaniclastic rocks. These rocks occupy the lower to upper part of an Early to Middle Miocene volcano-sedimentary rock succession with a thickness of more than 1500m in the district (Garwin, 2002). The rock sequence shows gentle dips and thick to massive bedding. Limestone interbeds about 1 to 25m thick occur in volcanic sedimentary units at Bambu, about 2km southwest of the pit area.

Tonalite porphyry intrusions form a steeply dipping cluster of upward tapering, nearly conical stocks in the center of the deposit. The Old Tonalite is limited to narrow remnants along the margins of the Intermediate Tonalite stock that are observed only from drill cores. The Intermediate Tonalite comprises the largest part of the main tonalite complex. This body measures 450m by 250m in surface exposure on the pit floor, 255m above sea level. The Young Tonalite forms NE-trending vertical dykes, 10m to 20m wide that intrude the Intermediate Tonalite. Intrusive breccias are common along the margins of the Intermediate Tonalite and to a lesser extent, the Young and Old Tonalites.

The Volcanics / Diorite contact hosts the intrusive Tonals. Several phases of Tonalite have been identified. The older Tonalites are grouped with the Intermediate Tonalite since it is impossible to differentiate the tonalite phases without microscopic examination. The Young Tonalite is “dyke-like”, oriented approximately North-North-East (NNE) to South-South-West (SSW) and is sub-vertical.

The Intermediate Tonalite surrounds the Young Tonalite and geometrically it is somewhat similar to an inverted cone. Therefore, the section orientation for modeling the remaining lithologies is radial. The Intermediate Tonalite has been displaced by faulting.

2.4 Mining

Development of the Batu Hijau open pit is being achieved by a conventional truck and shovel operation. The primary loading fleet consists of 111 Caterpillar 793C trucks and seven electric rope shovels. From a geotechnical perspective, two hydraulic excavators are dedicated to wall trimming and scaling, with two air-track rigs for drilling pre-split, and a contracted drill completing in-pit horizontal drains to improve stability. Artificial ground support has not been applied in the mine to date.

Currently phases five and six are being developed.
2.5 Open Pit Design Process

The slope management design philosophy at Batu Hijau Pit was presented by Simon Leech in Slope Stability 2007 (Leech, 2007). This philosophy requires the acceptance and management of instabilities at acceptable risk levels, rather than designing based entirely on achieving stable slope pit walls.

The Batu Hijau Open Pit design process flowchart is shown in Figure 1 and is similar to other mine sites and is commonly used by mining industry. This process will give good results if supported by the increased durability and reliability of the geotechnical model (Leech, 2007).

At Batu Hijau in order to maintain and increase the reliability of the model, continuous geotechnical investigation programs are carried out. All the information is kept in a database and is used to model the different geotechnical aspects of the open pit as will be described below. It is implicit in the design a commitment to continuous improvement.

3 Geotechnical database

At Batu Hijau, the geotechnical information is stored in an SQL database and managed using Acquire™. The data is divided in three primary groups; drilling, mapping and monitoring. The Geotechnical database is independent but linked to the Geology database in order to obtain deposit characteristics required for the geotechnical pit modeling.

The geotechnical core logging, including oriented core, slope face mapping, joint sets and their characteristics and major geological structures, rock laboratory testing, slope stability monitoring, groundwater monitoring with VWP and recorded failures data, is all included in a database which has allowed for optimal utilisation of the geotechnical data. The data is used for structural model wireframing, geotechnical block modeling, pit slope design, monitoring reports, failure analysis, etc.

Figure 1. Slope design flow diagram.
4 Geotechnical models

The data available is used to generate models that help the understanding of the pit geotechnical characteristics. From these data several geotechnical models are generated like major geological faults, an RMR 3D block model, a 3D distribution of every discontinuity mapped in the pit, as from oriented core holes; a distribution of every failure recorded in the history of the mine, the monitoring prism displacement vectors, the hydrogeology monitoring holes with the location of every vibrating wire piezometer, the first intersection of water in the horizontal drains and the initial flow can be plotted in space (model still under development). The software used is MineSight®.

4.1 Major geological structures

Five general trends are recognized with relative ages from early to late as N-S, E-W, NE, Radial and NW patterns. The N-S and E-W discontinuous structural orientations are interpreted to be the earliest that are spatially and temporally associated with the Tonalite porphyries and copper mineralization. The early E-W structures are truncated by late movement of the NE trending family structures. Late reactivations of E-W faults are associated with “D-type” pyrite and base metal veins (Priowasono & Maryono, 2003).

In general, there are three main structures mapped in Batu Hijau, namely the Katala, Kelud and Tongoloka Puna faults. The Katala and Tongoloka Puna faults are subvertical and strike northwest forming boundaries to the more concentrated faulting of the Fault Corridor. In this area, faults are spaced at approximately 50m apart and have continuity across the pit wall. Although less frequent, there is also a minor orthogonal fault set.

For geotechnical purposes the 16 major geological faults that have been modeled are shown in Figure 2.

![Figure 2. Major faults.](image-url)
4.2 Rock Mass Rating Model

The Batu Hijau RMR Block Model was generated with Minesight® using geotechnical logs of 439 bore holes with depths ranging from 300 m to 1000m. The dimension of blocks are 25 x 25 x 15 meters (LxWxH) and the model was created by composting the RMR's for each borehole “run” into 15m high benches and then assigning a value for each block by interpolating from the boreholes by the inverse distance method. The number of samples used in the interpolation as well as the average distance to the samples is recorded in order to estimate the reliability of the data in each block.

The parameters used to calculate the RMR were: intact rock strength (estimated with ISRM hardness index and PLI), RQD, fracture spacing, roughness, weathering, infill type and thickness and assumed dry groundwater conditions.

The RMR model has been verified over the last three years and proven to be reliable and has helped to identify areas of potential failures when analyzed in conjunction with the other elements of the geotechnical models.

4.3 Discontinuity mapping

Structural mapping data since the initial stages of the project have been kept and can be queried or extracted from the database. These data, orientation and characteristics, can be imported into 3D mine software and can be
coded according to location, geotechnical domain, lithology, alteration, or any other condition that could help the interpretation of the data. To date the number of discontinuity data recorded exceeds 70000 discontinuities.

Geologists have mapped major structures and recorded the northing, easting and elevation of every point mapped. Geotechnical engineers have mapped the pit wall exposures using scan line techniques as well as photogrametry (Sirovision) and also utilizing oriented core holes. The data can be presented in 3D and filtered by dip, dip direction, type of structure, infill characteristics, roughness, lithology, alteration, geotechnical domain, elevation, etc.

The use of more than one mapping technique is encouraged since data obtained from scanline and boreholes is biased, but in combination, it provides data in two close to perpendicular directions, while photogrametry will help mapping shallow joint sets parallel to the wall.

In Figure 4, the discontinuity data available for the Batu Hijau pit is presented. Lines parallel to the wall are scanline surveys and those perpendicular are oriented core. Points are geological structural measurements. Photogrametry mapping can be seen as patches of points like in the left side of the picture (East side).

### 4.4 Geotechnical domains

Batu Hijau pit has been divided in 8 geotechnical domains considering the geology (rock type and alteration), major fault structures, rock fabric domains, and RMR classification. Four major structures are primary boundaries on the geotechnical domains these are: Bromo, Tongoloka Puna, Tambora and Tongoloka South.

They were selected based on observed pit wall performance at the footwall and hanging wall. Two domains were selected based on alteration, GT Dom 6 and GT Dom 7, since they correspond to the mineralized intrusions at the center of the deposit.

![Figure 4. Plan view of discontinuity mapping by points, scanlines, oriented core and photogrametry.](image)
The current domains are distinctively divided by the Tongoloka Puna fault a NW-SE trending structure that separated domains 4, 5 and 8 from the others. Domains 4 and 5 are bounded by the Tambora fault, while domains 5 and 8 are bounded by the Tongoloka South fault. Domains 1 and 2 are defined by RMR characteristics being Domain 1 the material with lowest strength present in the pit. GT Dom 2 and 3 are separated by the Katala Fault.

After identifying the major boundaries, the Rock Fabric Domains were superimposed. Based on the condition of rock fabric, the pattern boundaries look similar with the major structural barrier. One additional adjustment was made at the East wall to define the boundary between the North and the East Geotechnical Domain Blocks. This line is clear in the RMR model as it is a boundary of poor quality rockmass to the North and fair to strong rock to the East.

The eight geotechnical domains are presented in Figure 5.

4.5 Pit slope past performance

Since 2000, Batu Hijau has recorded slope failures that involved two or more benches. In the ‘failure register’, there is detailed information about the mode of failures, cause of failure, the location and dimensions of failure, factors that influenced the instability, orientation of faults and joints involved and other characteristics. Until April 2011, the failure register contains around 250 recorded failures. Some of them are extensions/propagation of previous failures.

Failures are recorded on file and then included in the database. The electronic file also includes photographs, interpretation and if structurally controlled, a stereoplot with the faults and joints measured. Almost all the failures have some sort of back analysis in order to determine the strength parameters of the joint/fault and or rockmass.

Recorded failures are difficult to review in separate files and usually the engineers rely on their memory. For this reason a 3D model of all the pit wall failures recorded was prepared.

Figure 5. Eight geotechnical domains, cut at 0m RL.
4.5.1 Failure block model

From the topographic survey of the failure area and the interpreted failure surface underneath, solids of failed rockmass were generated. These solids are located in space. Since MineSight® can not store information in solids, 3D blocks were coded with the main characteristics of the failure such as: date, slope aspect, orientation of the structures involved, precipitation in the previous 24 hours of the failure, cumulative precipitation of 7 days prior to the failure, interpreted failure mechanism, factor that trigger the failure, geotechnical domain, lithology alteration, etc.

The purpose is to visualize the information in its location which provides; the comparison year by year, following the mine development and the possibility to query the block and obtain the information related to the failure. The block model facilitates a visual analysis of the failure by relating it to slope direction and major faults and identifies if the same pattern is repeated in every mining phase. It also records a visual history of the mine performance, reducing the need to rely on memory. Specific failures can be then reviewed in more detail in the electronic files that contain the photograph, and detail analysis. The distribution of the failures around the pit is shown in Figure 6.

5 Slope stability design analysis

The design of the pit slopes at Batu Hijau, is mainly based on kinematic analysis since the rockmass strength can be considered moderate to strong, with the exception of the NE sector. Overall slope designs are checked for stability by kinematic analysis of major faults, limit equilibrium and most recently using finite element numerical models.

In the NE sector the stability is controlled by the rockmass as well as by a series of relatively shallow dipping (45°-55°) and widely spaced (around 70 to 100m) faults. These faults have caused failures in the past.

5.1 Kinematic analysis

When a new design or revision is required, the discontinuity database is filtered in order to obtain only the data that is closer to and behind the pit wall to be designed and eliminate previous information in the pit that has been excavated. These data are then grouped by geotechnical domains and subsequently a probabilistic analysis of undercutting for planar and wedge mechanisms are performed.

Figure 6 Failures 3D block model color coded by year of occurrence.
Discontinuity data for each domain, after filtering, commonly exceeds 1000 measurements. A design percentage of probability of undercutting is defined according to what is considered acceptable risk for each domain. Different criteria are used for BFA and IRA with a much lower value for IRA than for BFA.

With the probability of undercutting results, a review of them is done comparing the selected BFA and IRA to previous phases of mining slope angles and failure history for each domain. The slope angles recommendations are provided to the Mine Engineering group in order to run the pit optimization and design.

5.2 Overall stability

Once the Mining Engineering group has generated the optimized open pit, the design comes back to Geotech group for overall stability analysis and review.

The design is reviewed to verify that the IRA and BFA recommendations have been implemented, that the design has not created unwanted features such as convex shape walls that the orientations are favourable in order to prevent planar or wedge failures; and to check for the maximum bench stack.

If everything is according to recommendations then a limit equilibrium stability analysis is performed. The model includes the estimates of pore pressures in the ground based on interpretation of piezometric data, rockmass strength based on the RMR model, strength anisotropies based on unfavourable joint orientation, major faults, etc. In some instances a finite element analysis (Phase 2®) will also be carried out.

6 Design implementation and monitoring

During mining; quarterly, monthly and weekly mining planning meetings are carried out; in these meetings the mine plan is discussed. The geotechnical engineers review the plan prior to the meeting and present their comments on the areas to be mined. Their comments will highlight areas of concern identified in the geotechnical models, by interpreting previous failures, faults, rockmass, etc in the areas to be mined, and provide recommendations on the blasting technique to be applied to protect the limit wall. An example is shown in Figure 7.

The performance of the pit slopes is evaluated in various ways. The limit wall blast area is inspected immediately after the blast to determine if there is back break damage. Once the wall trim is completed the geotechnical engineer will assess the wall condition and verify that it meets the standards, toe and crest position, no loose rocks in the wall face, that the catch bench is clear of debris.

Movement detection monitoring is done with two Reutech MSR 300 slope monitoring and surveying radars. Slope deformations or unusual movement patterns (acceleration or step changes) provide an early indication of wall instability. The radar offers real-time monitoring and alarm setting capabilities and is a proactive warning device for slope instability.

In addition to the MSR radars, two Robotic Total Station (RTS) EDM monitoring systems are in operation, where the surveying of prisms located around the pit and on pit slopes is automated. The system consists of two Leica TPS1200, located at approximately opposite sides of the pit.

The survey results from Radars and RTS are graphed on a time-displacement basis. Predictions of the estimated time of failure are possible by extrapolation of the displacement rates.
7 Phase 5 West Wall case study

7.1 Phase 5 slope performance

During mining at the pit bottom of the Phase 5 West Wall, the Batu Hijau Pit experienced a significant failure. The failure was registered as Failure WS_P5_064 and it occurred on August 2010. The chronology of the failure can be summarized as follows:

A crack was observed on May 28th, 2010 at bench -60mRL. On July 29th, another crack was observed, at -45mRL. A first failure event occurred on July 30, 2010. The wall was monitored with one of the MSR radars. More cracks developed on August 23, 2010 and movements indicated acceleration.

Evacuate people and equipment at 03:00am (August 24, 2010) from Phase 5 and all mine activities were stopped until failure occurred at 06:40am. The failure was recorded on video.

The failure extended 100m wide x 105m high (from bench -45 to -150mRL) and it involved partial width loss of the ramp at -45mRL ramp. Remedial emergency work alternatives were evaluated and implemented.

Failure #64 is located in the Phase 5 West wall on Geotechnical Domain 7 which corresponds to Young Tonalite. The failed slope has a slope aspect of 55°/050°. The failure video showed that a shallow dipping structure (around 43° to 45°) was the cause of the failure, it daylighted at -90mRL and cracks were observed after excavating -120mRL.
7.2 Phase 3 and Phase 4 performance

Reviewing the slope performance in this area for Phase 3 showed that similar failures occurred on the West wall. Detailed review of the failure reports of previous phases indicated that Failure #64 in the current Phase 5 is similar to the two failures in Phase 3. However, no failure occurred when mining Phase 4 (Figure 8). The models of rockmass strength and rock fabric in the west area of Phase 3, 4, and 5 showed that these are similar.

The difference between Phase 4 and Phases 3 and 5 is in the slope aspect. While in Phase 4 the West wall has a slope aspect of 090°, in Phases 3 and 5 it was 050°.

7.3 Phase 6 design review

Based on the slope performance in each mine phase, a study of future mining in this area in particularly Phase 6 was conducted to determine the potential for a similar problem. The discontinuity data was reviewed and a joint set with average orientation 45°/050° (dip/dipdir) was identified which was not predominant among the data recorded. This joint orientation matches the back analysis of F#64 and was highlighted as a major control of the instability.

Oriented core log data was filtered in a search for similar discontinuity orientation and several were found but with spacing greater than 15m (Figure 9). Since the spacing is relatively big the numbers of structures mapped are much less than the most frequent structures that can be easily identified in the field.

Alternatives for improving the stability of Phase 6 design include: reduce the IRA, re-orient of the slope wall and/or include artificial support in the design. The alternatives were analysed and selected to change the orientation of the west wall into a more favourable orientation (towards 090°). This alternative in Phase 4 had a stable wall.

8 Conclusions

The paper presents Batu Hijau experience with the geotechnical database and how this data is used to generate a series of 3D geotechnical models.

These models disentangle the complex geotechnical conditions of the pit and when used in combination in a single system helps identify the potential issues and the location of these areas. The failures block model keeps the history of the mine in the same system so there is no need to rely on memory.
The models also provide the geotechnical characteristics used for the design and the stability analysis. During implementation, the geotechnical engineers can show and explain to the mine operators where the potential problems could be and provide recommendations in order to reduce the risk of slope failures.

If a failure occurs, the models can help identify the main causes of the failure, provide geotechnical characteristics for the back analysis and future phases of the pit can be redesigned to reduce the probability of failure.

Our experience at Batu Hijau indicates that pit slope design has to be done by analysing the data and considering the pit slope performance history. During kinematic analysis clusters of joints are analysed in a stereo plot but only one or two structures are needed to cause a problem. These structures can be single out if in a previous phase of mining a failure was recorded.

When detailed analysis of past history is taken into consideration the location and characteristics of these failures will give an indication of what would happened in the next phase of mining.

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10 References

