Open Pit Slope Depressurization using Horizontal Drains – a Case Study

Simon Leech [a)], Matthew McGann [b)]

[a)] *PT Newmont Nusa Tenggara, Geotechnical and Hydrogeological Dept., Jl. Sriwijaya # 258 Mataram 83126, Indonesia email: Simon.Leech@Newmont.com tel +62 8175749564*
[b)] *PT Newmont Nusa Tenggara, Mine Water Management Dept., Jl. Sriwijaya # 258 Mataram 83126, Indonesia email: Matthew.McGann@Newmont.com tel: +62 81917141081*

Abstract
The establishment of appropriate open pit slope design criteria evolves throughout the life of a mine, and is based primarily on an ever increasing understanding of the rockmass conditions, including groundwater and associated groundwater pressures that may be acting within the slopes. It has been highlighted over the past decade, that geotechnical engineering has not advanced significantly with respect to the integrated tools that are available to assist in the optimization of large open pit slopes, but it has long been realised that the reduction of groundwater related pore pressures, is an important component in the determination of whether a design can or has been successfully achieved. Therefore, it is essential to implement an extensive multidisciplinary technical program, incorporating mine, geotechnical and hydrogeological engineering expertise sourced both internal and external to the mining operation.
An integrated mine dewatering and slope depressurization program is necessary to increase the likelihood that mine plans can be achieved, and at an acceptable level of risk. How much slope depressurization is appropriate in a large open pit environment is difficult to quantify, and often a philosophy of "more must be better" has to be adopted due to the lack of integrated modelling tools that are available to assist in the optimization of the slope design. The slope designers often work in isolation of, or in parallel with hydrogeologists, whereas, ideally technically sound hydrogeological models need to be made available to slope designers well in advance. Scheduling pressures often require that results are needed within unrealistic time frames often leading to a "silver bullet" approach, primarily revolving around the desire to numerically model problems, prior to there being a fundamental understanding of the potential issues. Programs that lead to the establishment of reliable hydrogeological models in a relatively complex hard rock mining environment often take years to develop and must be sustained and improved upon so that relatively reliable predictions can be made, as to what the future hydrogeological conditions may be.
This paper presents a discussion of the on-going horizontal drain construction program at Batu Hijau, including how this is integrated with the operation of the mine, aspects of drilling related productivity, summary economics and a review of the results achieved. Also discussed is the value of appropriately installed groundwater monitoring infrastructure, which has allowed the results of the program to be quantified and has provided site specific data to allow for on-going optimisation. The program to date has had its challenges, but has been largely successful, with results confirming the benefit of installing horizontal drains in the right place and at the right time.

Key words: horizontal drain, slope stability, open pit, Vibrating Wire Piezometer, Indonesia.

Introduction
The Batu Hijau open pit mine (Figure 1) is owned and operated by PT Newmont Nusa Tenggara (NNT), and is located in the eastern Indonesian archipelago, on the island of Sumbawa (Figure 2). Total material to be mined is currently planned at about 3.8 billion tonnes; with an average strip ratio of 1.7:1, at 0.49 % Cu, 0.34 g/t Au and 1.06 g/t Ag. Overall slope heights are planned to be in excess of 900 meters. Given the size of the mineral deposit, the mine life is relatively short, at 27 years, which includes about six years of stockpile rehandle after completion of open pit development.
As with many relatively low grade, high tonnage mineral deposits, the economics of the Batu Hijau mine are primarily driven by maximising slope angles, material movement and mill throughput, and by minimising unit costs. Relatively small changes in any of these parameters can have significant impacts on the economics of the deposit.

Figure 1 *Satellite image of the Batu Hijau mine as at June 2007*

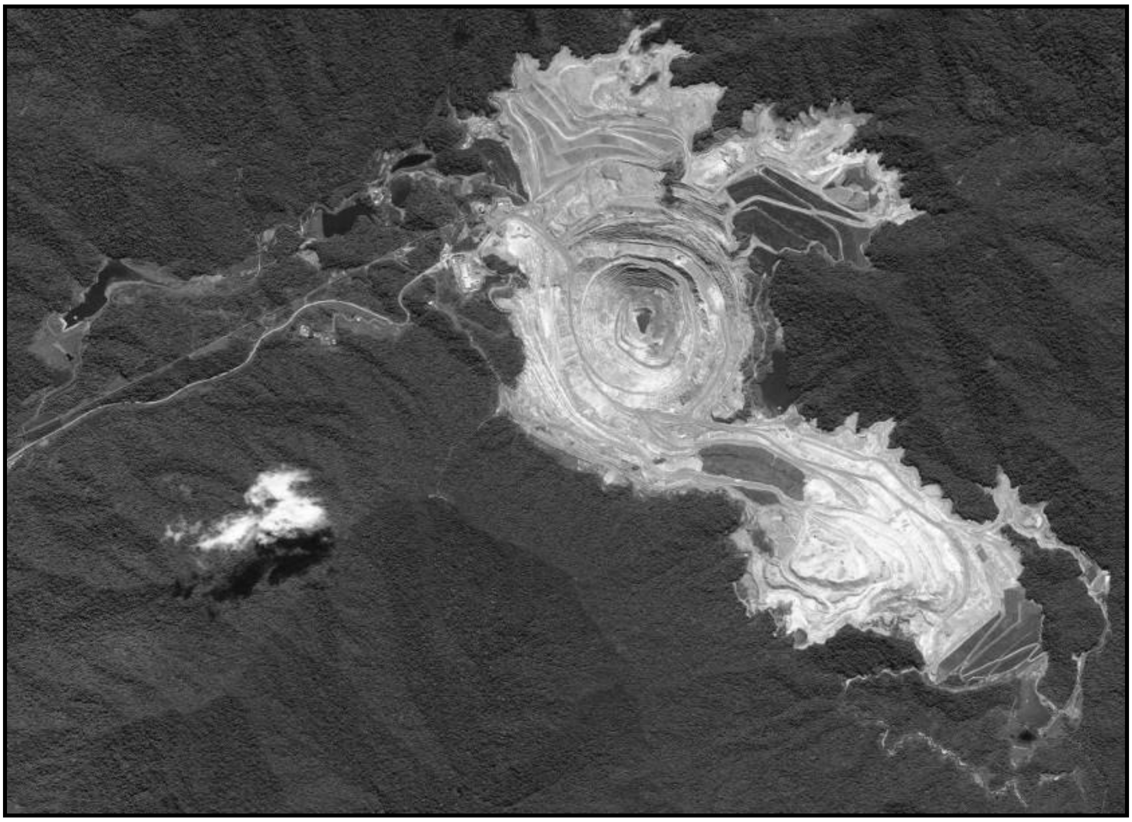
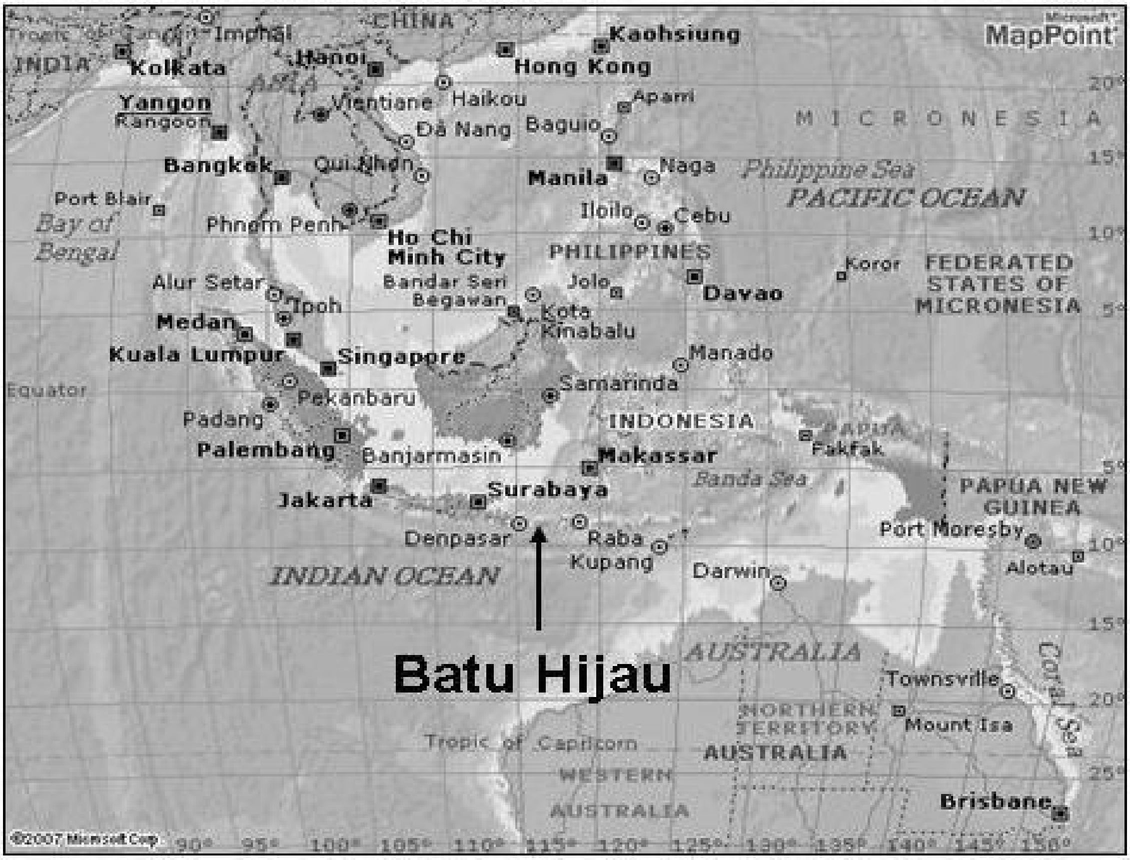


Figure 2 *Location of the Batu Hijau mine within the eastern Indonesian archipelago*



Background

NNT was formed in 1985 for the purpose of carrying out systematic exploration for epithermal gold mineralisation on the islands of Lombok and Sumbawa. A Contract of Work was granted by the Government of Indonesia in 1986. Surface exploration led to the discovery of porphyry copper-gold mineralisation at Batu Hijau in 1990, with further work up to 1996 leading to the delineation of a deposit.

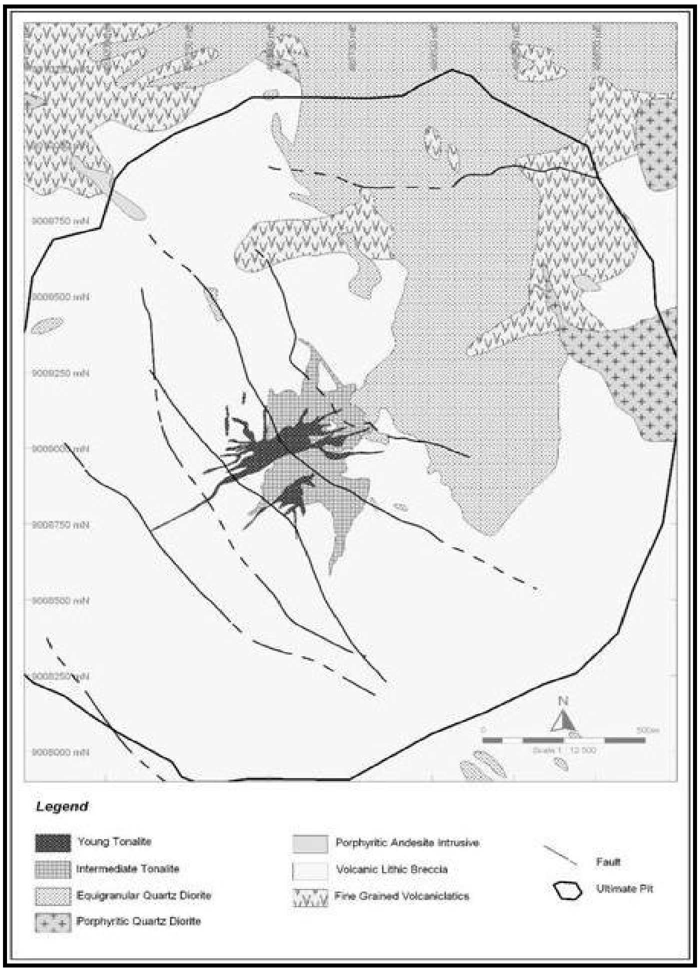
The Government of Indonesia approved the Batu Hijau Project feasibility study in May 1997, at which time construction permits were granted. Pre-stripping of the open pit began in October 1997, with the mill process commissioned late in 1999.

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 2,500 millimetre annual rainfall occurs during the wet season. Typically rainfall events are of relatively short duration, but of high intensity.

The country rock in the area of Batu Hijau consists of andesite volcanics, volcaniclastic sediments and porphyritic andesite (Figure 3). In the north-eastern area of the mine this sequence was intruded by a quartz diorite. Multiple tonalite porphyries were intruded along the contact between the volcanics and diorite, with the majority of mineralisation associated with earlier tonalite intrusions and higher intensity of quartz veining. As part of the mineralization process the basic lithology has been overprinted by extensive hydrothermal alteration.

On a district scale there are two major fault zones, the northeast trending Bambu-Santong and northwest trending Tongoloka-Batu Hijau Fault Corridor. The two intersect three kilometres northwest of the centre of the deposit. Major faults that transect the open pit are those associated with the Tongoloka-Batu Hijau Fault Corridor, with discrete faults spaced at about 50 meters. There is also a less persistent orthogonal fault set.

***Figure 3** Simplified geology of the Batu Hijau deposit*



Hydrogeogeology
At Batu Hijau the pre-mining groundwater level in and surrounding the mineral deposit was typically a subdued reflection of the topography. The steep gradients suggested that formation permeability was low and typically in the $1x10^{-6}$ to $1x10^{-8}$ meters per second range, but with some preferential flow paths providing for relatively rapid drain-down following recharge events. Although a number of fault zones were identified prior to the initiation of dewatering operations within the open pit, their influence on groundwater flows were not well understood.
The on-going hydrogeological characterisation program at Batu Hijau has lead to a continued refinement of the conceptual groundwater flow model, which in general terms is as follows:

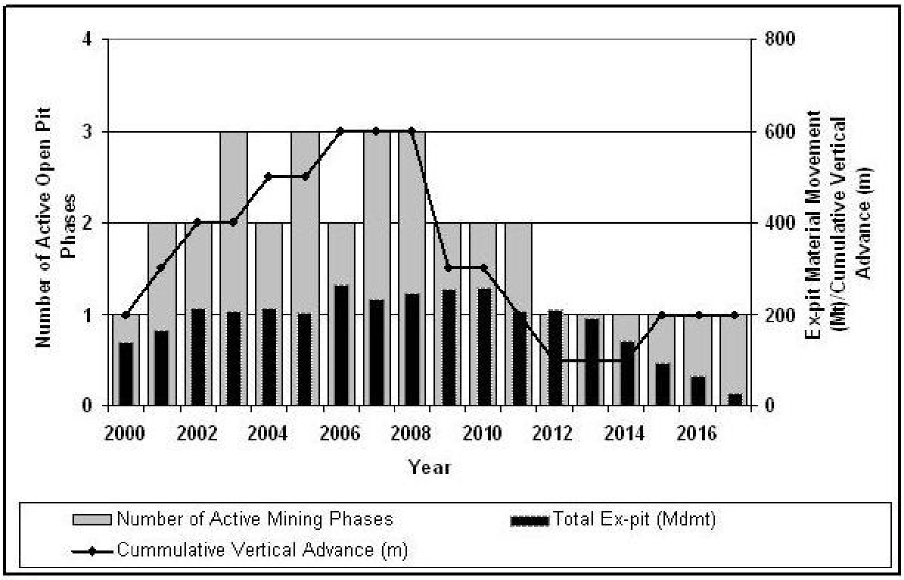
- Recharge in the deposit area is derived primarily from rainfall with minimal regional groundwater through-flows.
- Deposit permeability is greatest within the orebody and reduces radially from the centre of the mineral deposit.
- Deposit porosity is low and is estimated to be in the 0.1% to 0.5% range.
- Weathering of the upper 100-150 meters of the host or country rock has resulted in reduced permeability nearer to the deposit surface.
- South-westerly, shallowly dipping faults in the southern sector of the deposit provide a barrier to lateral groundwater flow with heads in this area not impacted by open pit dewatering operations.
- Permeability along the northwest trending Tongoloka-Batu Hijau Fault Corridor is enhanced.

As additional geological, geotechnical and hydrogeological information becomes available the hydrogeological model for Batu Hijau will continue to be updated and refined.

Mining
Development of the Batu Hijau open pit is being achieved by a conventional truck and shovel operation. The primary loading fleet currently consists of one hundred and eleven 240 tonne haul trucks, with loading provided by seven electric rope shovels.
The ore body is cylindrical in shape and is being mined in a number of concurrent, concentric phases. Currently the fourth, fifth and ultimate phases are being developed. The concentric nature of the phases and the geometry of the ore body mean that mine sequencing flexibility is relatively limited. In particular, in-pit haul road layouts are relatively inflexible and must be maintained in a spiral configuration. As a result, any larger scale slope instability cannot be left for an extended period and design changes would be required so that mining activities can continue.
The vertical advance achieved in any one mining phase is typically about 200 meters per annum (Figure 4), over its entire circumference. The cumulative vertical advance peaks at 600 meters over three concurrent phases. Open pit slope design criteria aside, the rate at which the deposit is being mined is relatively aggressive, with annual material movement generally ranging from 200 to 250 million tonnes over much of the open pit life.

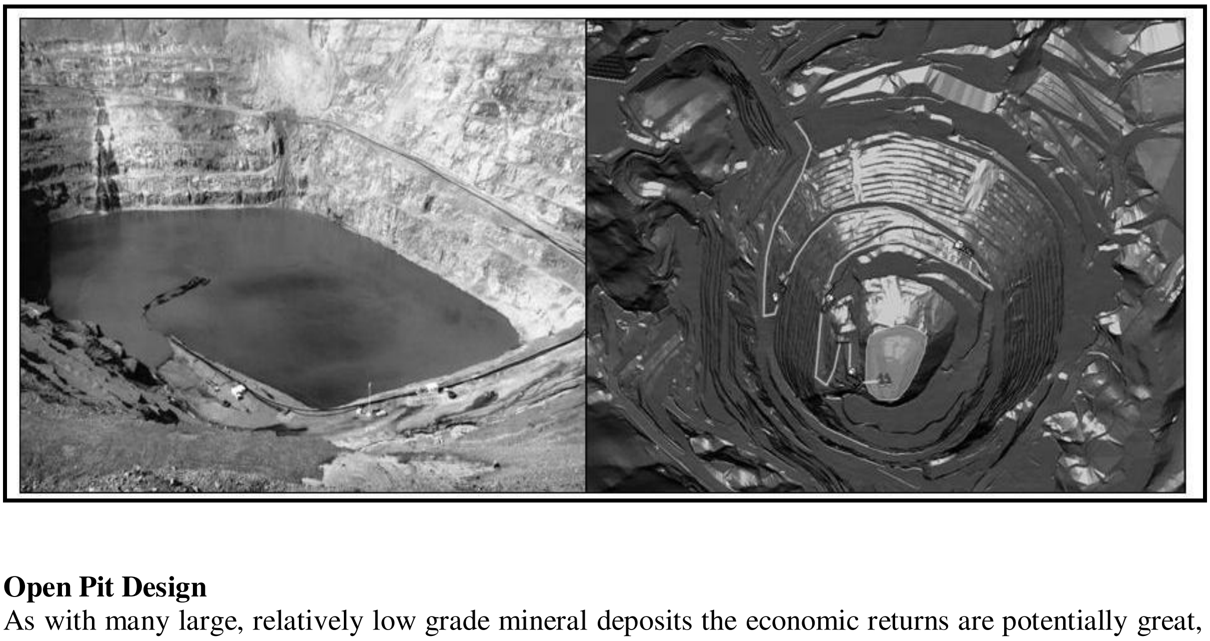
Open Pit Dewatering
In addition to the slope stability and operational issues generated by the high intensity seasonal rainfall events, a relatively large dewatering sump must be maintained in the bottom of the open pit; to which surface water run-off and groundwater inflows report. Due to the relatively low geographical elevation of the mineral deposit, mining is taking place below sea level, therefore water entering the sump must be pumped out and gravity drainage opportunities are nil.
The open pit is kept dry via a system of floating sump pumps coupled through HDPE pipelines to booster pumps installed in series on the edge of in-pit haul roads (Figure 5 and 6). Average sump pumping peaks in the wet season at about 40,000 m^3/day, of which about 50% is groundwater inflow. Sump pumping has been demonstrated to be the only practical means to accommodate large wet season surface water inflows; trials of in-pit wells undertaken in 2000 and 2001 demonstrated the impracticality of operating such infrastructure given the high vertical mining advance rates.

Figure 4 *Summary of open pit mining at Batu Hijau*



Open pit dewatering operations which commenced in 2001 have resulted in a maximum reduction in groundwater level of approximately 450 meters in the centre of the mineral deposit. However, the impacts to regional groundwater levels have been minimal, with typically less than a 20 meter fall in head 500 meters from the current pit crest. From 2001 to 2005 un-aided slope depressurisation has been achieved through the dewatering required to sustain open pit development, coupled with the relatively high permeability of the intensely hydrothermal altered rock mass around the centre of the mineral deposit.

Figure 5 *Open pit dewatering system at Batu Hijau*



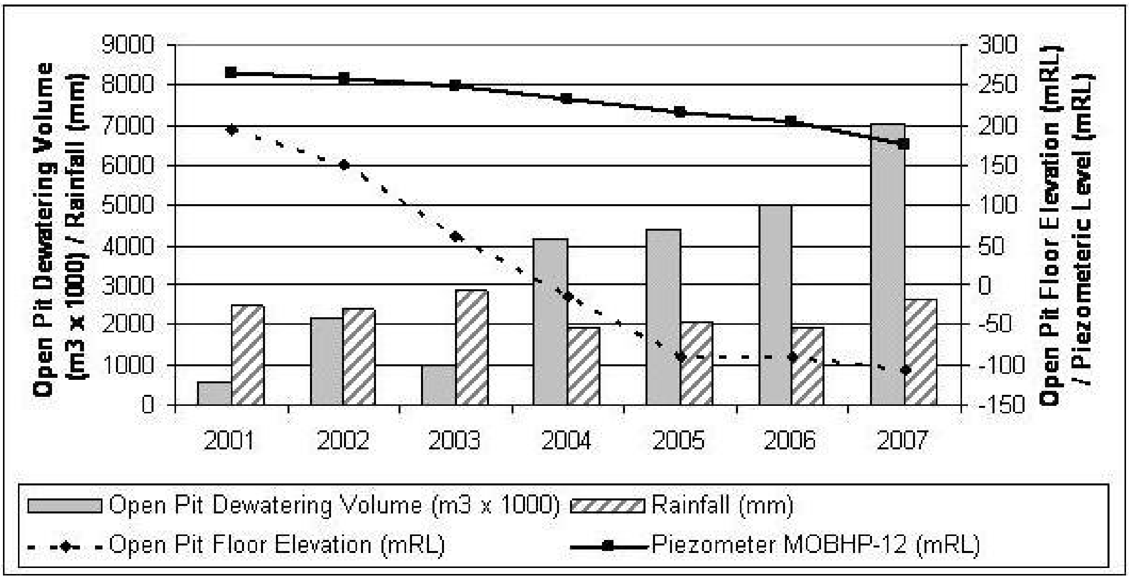
Open Pit Design

As with many large, relatively low grade mineral deposits the economic returns are potentially great, but relatively minor adjustments in specific variables (e.g. slope angles) have a significant impact on the minable reserve. At Batu Hijau, from a geotechnical perspective, the slope design philosophy and the associated programs adopted are very much tools implemented to reduce the risk to a level acceptable to the owner.

Recommended open pit slope design criteria for use in mine planning at Batu Hijau have caveats associated with them (Leech, 2007), including:

"Acceptable" levels of slope depressurization can be achieved – although somewhat difficult to quantify, the assumption is that a "more is better" philosophy is accepted and adopted.

Figure 6 *Open pit dewatering summary from Batu Hijau*



Although the statement could be construed as being vague, it highlights the commitment required to establish and maintain an integrated mine dewatering and slope depressurization program that will lead to an increase in the likelihood that mine plans can be achieved, and at an acceptable level of risk. Programs that lead to the establishment of reliable hydrogeological models in a relatively complex hard rock, large open pit mining environment often take years to develop, and must be sustained and improved upon so that relatively reliable predictions can be made.

Horizontal Drains

The construction of horizontal drains began at the Batu Hijau mine in 2004, when a small-scale trial was undertaken to evaluate their potential effectiveness in aiding and accelerating the slope depressurization process. The results of the trial (Golder 2004) suggested that there was minimal potential for substantially improving the "natural" rate of depressurisation using horizontal drains, primarily due to the higher rates being achieved with the rapid advance of the open pit.

In response to a relatively large-scale slope failure (Figure 7), where groundwater pressures appeared to play a significant role, a horizontal drain construction program totalling about 1,500 meters was completed. This program followed the construction of three standpipe piezometers, which were installed with the objective of determining what benefit the horizontal drains would have in terms of reducing groundwater heads behind the failed slope.

As a result of apparent benefits of this program, NNT made the decision to commit to a longer term program of horizontal drain construction and from 2006 to 2007 a total of about 98,000 meters were completed.

From early 2006 a contracted, specialist directional drilling rig has been used to drill and complete horizontal drains. The constructional plant (Figure 8) consists primarily of:

- Vermeer™ D50x100A Navigator drill rig.
- ELGI™ 350psi/1100cfm screw compressor.
- Air Research™ 350psi/1200cfm booster compressor capable of compressing air up to 900psi.
- Various support trucks, etc.
- Safety features including enhanced rockfall protection, self-loading drill rod carousels, etc.

Figure 7 Slope failure (height about 100 meters) at Batu Hijau in May 2005

Figure 8 Contracted directional drilling rig in operation at Batu Hijau

A typical horizontal drain is constructed as follows:

- Set up Construction Plant at the rig site as per guidelines and standard operating procedures.
- Collar hole at 5^{o} above the horizontal.
- Drill 8” (200 mm) conventional open hole hammer top hole up to a length of 5.5 meters.
- Run 6” (150 mm) OD PVC Surface Casing and fully grout the annulus.
- Drill ahead at 5 ½” (140 mm) by conventional open hole hammer to a length of 350 meters.
- Run 1 ½” (40 mm) OD Schedule 80 PVC blank and machine slotted Production Liner.

Typically, working on a double 10-hour shift basis a 350 m long drain is completed in a day.

Over the 2006 to 2007 period the total average cost per meter of horizontal drain constructed was about US$44, comprising:

- Direct contractor costs (drilling, running casing/liner, work time, rig moves, etc) US$37.
- Diesel fuel US$2.
- Construction consumables and materials (casing, liner, grout, etc) US$5.

A pragmatic approach to horizontal drain construction has been developed with drilling taking place primarily from in-pit ramps. The drilling plan is coordinated with both the Mine Engineering and Operations groups to ensure platforms and safety barriers are constructed prior to drill rig moves. In some locations just a single drain is drilled perpendicular to the slope. In other locations, a fan of 4 to 6 drains are drilled from a single platform (Figure 9), primarily to reduce the interference with mine operations but also to reduce the drilling contractors exposure to various hazards.

Figure 9 *Multiple horizontal drains completed at Batu Hijau from a single drilling platform*

Initially the horizontal drain program at Batu Hijau focussed on areas where historical slope instability had been prevalent, with the logic being that depressurisation of those areas would lead to enhanced stability. In some instances horizontal drains were drilled which yielded very low groundwater flows and this was initially interpreted to reflect very low rockmass permeability, rather than possible pre-drained conditions, suggesting additional, more closely spaced drains were required to achieve adequate depressurisation. The misinterpretation was primarily due to there being insufficient groundwater monitoring infrastructure in particular areas or the data available was not being reviewed to a required level of frequency or detail.

Monitoring Methods

In order to address the issues of inadequate groundwater monitoring data and differing groundwater head distribution resulting from variability in rockmass permeability, a series of vibrating wire piezometer (VWP) sensor installations was initiated in 2006 (25 completed to the end of 2007 out of a total of 30 monitoring points).

The initial VWP installation program utilised conventional open hole hammer to drill holes to depths up to 400 meters. However, this was relatively unsuccessful and the program was completed using conventional core drilling methods. These holes were then completed with up to four VWP sensors each, and grouted following the reasoning and methodology of Mikkelsen and Green (2003). A thorough review of the data from these completions was undertaken about six months after completion, and determined that in the majority of cases the grout seals were inadequate with the

groundwater levels being measured often reflecting a standpipe style head and not the piezometric head. The inconsistency of the seals was determined to be the result of inappropriate site methodology, poor grout mixing, inadequate pumping capacity and/or equipment. In order to address these issues, the VWP design and installation process was revised and modified.
Subsequent to the review VWP sensors are installed in core holes (Figure 10) that form part of ongoing geological and geotechnical drilling programs. The use of smaller diameter holes coupled with the ability to set the VWP sensor through the coring rods typically results in more consistent settings at the planned depth and significantly less grout volumes required. The coring rods are pulled before the grout is injected down a sacrificial tremmie pipe, and grout injected through the bottom of the pipe until returns are seen at the surface. Following the assessment of a number of different material types to serve as the tremmie, the Batu Hijau site has selected a standard NPT threaded ¾" ID galvanised iron pipe, which is supplied in three meter lengths. At installation, the first two lengths of tremmie pipe are perforated, which act as ports allowing injected grout to exit the tremmie pipe, thus increasing the likelihood that the VWP sensors are fully grouted. Typically two VWP's are installed per core hole, with the deeper (5,000 kPa) sensor set 200 to 300 meters below the estimated piezometric level and the shallower (3,000 kPa) sensor 40 to 50 meters below the estimated piezometric level (Figure 11).

Figure 10 *Installation of a Vibrating Wire Piezometer at Batu Hijau in a core hole*

A second but less frequently utilised methodology is the installation of a single VWP sensor in a horizontal drain. This method uses the same ¾" ID galvanised iron tremmie used for core hole installations, but is significantly more labour intensive than is the case for vertical or steeply inclined core holes. When installed in a horizontal drain the tremmie pipe, complete with sensor must be pushed by hand (Figure 12). There are physical and safety limitations as to how far the sensor and tremmie string can be pushed before the frictional resistance becomes too great (a setting of 280 meters has been achieved).

Monitoring Results
A view, commonly held is that if on completion groundwater emerges from the collar of a horizontal drain then it is successful and if not, it is unsuccessful. Undoubtedly these two generalisations are often correct, but they should not be used as the sole basis for evaluating the success or otherwise of a horizontal drain program.

Without adequate groundwater monitoring, assessing the relative success of horizontal drains is not possible. By evaluating groundwater head data collected at monitoring sites located behind a slope that the horizontal drains have been installed, a thorough understanding of the relative success of the program can be reached. To illustrate this, three examples from the Batu Hijau program are presented:

Figure 11 *Typical design of a Vibrating Wire Piezometer at Batu Hijau in a core hole*

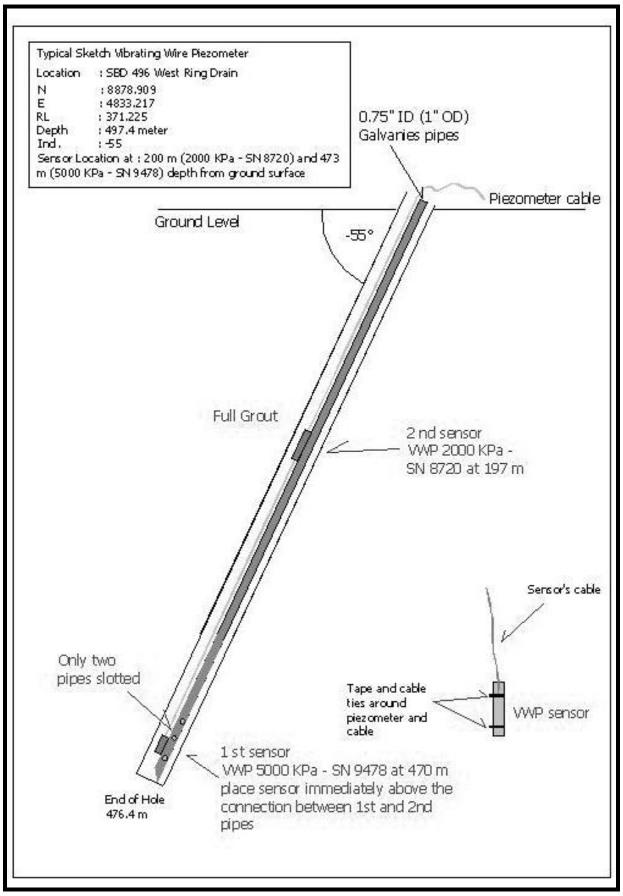
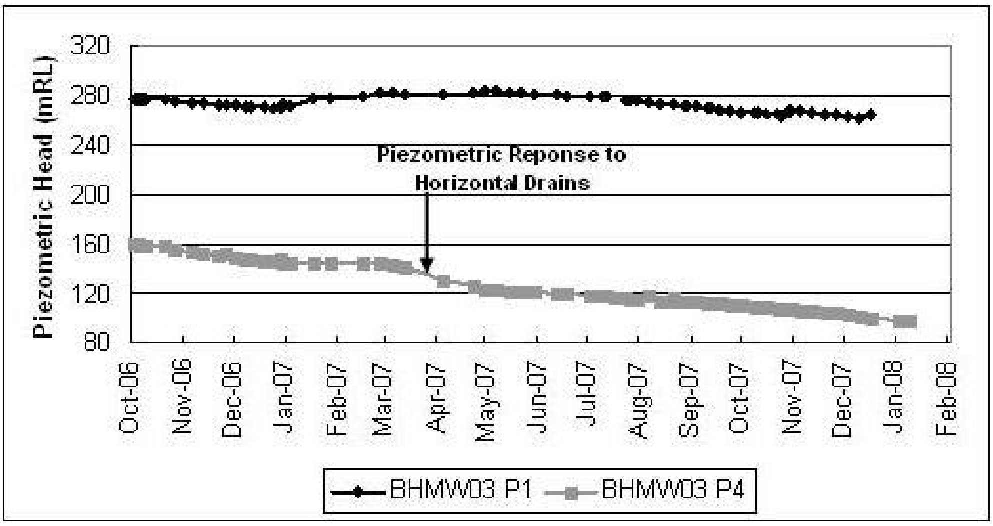


Figure 12 *Installation of a Vibrating Wire Piezometer at Batu Hijau in a horizontal drain*

1. Northwest Sector
Early in 2006, a series of nine horizontal drains were drilled into the northwest slope of the open pit at an elevation of approximately 165 mRL, with no individual drain producing more than one litre per second. At the time these drains were drilled there were no suitable monitoring points to evaluate drain performance and the value of their installation was questionable. Later in 2006 a multiple sensor VWP (BHMW03) was installed at the crest of the northwest slope. Subsequently in March 2007, additional horizontal drains were completed at approximately 0 mRL, with individual drains yielding up to 10 litres per second. Monitoring of the VWP sensors clearly shows the positive impact these horizontal drains had on the piezometric head distribution in this sector of the open pit (Figure 13). Whereas the deeper sensor recorded a fall in head of 25 meters over a two month period, no such effect was observed in the shallow sensor. At the time when the initial horizontal drains were drilled at 165 mRL, the groundwater head in the area was later estimated to be at about 175 mRL. With such a small hydraulic head (± 10 meters), only limited groundwater flows could have reported from the horizontal drains, suggesting that the open pit slope above 165 mRL was essentially depressurized prior to horizontal drain installation.

***Figure 13** Data from Vibrating Wire Piezometer BHMW03 at Batu Hijau*



2. Northeast Sector
In mid 2006, a relatively large area of slope instability had developed in the northeast sector of the open pit and it was believed that depressurisation of this failing rockmass would improve stability. As a result a number of horizontal drains were completed at an elevation of approximately 165 mRL, but yielded very little groundwater flow and this supported an interpretation of low rockmass permeability. The nearest monitoring point used to evaluate horizontal drain performance was about 600 meters behind the horizontal drain collars and showed an elevated but stable groundwater head. In late 2006 a multiple sensor VWP (BHWM06) was completed within the open pit, collared at about 165 mRL, which indicated that groundwater heads were significantly below the drain collars. Subsequently in late March 2007, additional horizontal drains were drilled into the slope from approximately 0 mRL and again in December 2007 additional drains were drilled at -45 mRL. Groundwater flows from individual drains was considerable, at up to 20 litres per second. Monitoring of BHMW06 clearly indicates the positive effects that both the March 2007 and December 2007 horizontal drain installations had on the piezometric head distribution in this sector of the open pit (Figure 14). Extrapolation of the BHMW06 data back to early 2006 suggests that the initial drain program was undertaken into an area of the slope that was largely depressurized at the time. Additionally, during 2007 core drilling combined with VWP installations undertaken further behind the horizontal drain collars indicated that a previously identified fault zone provided a hydraulic barrier between the well drained rockmass on the hangingwall from that of poorly drained on the footwall.

3. Southwest Sector
   In mid 2006, horizontal drains were completed in the southwest sector of the open pit at an elevation of approximately 255 mRL, with no individual drain producing more than one litre per second. A lesser number were completed from 315 mRL, two of which exhibited very high (about 20 litres per second) but short duration groundwater flows over a few weeks, supporting the interpreted presence of very low permeability, shallowly dipping faults in this area of the deposit. Due to the absence of any suitable groundwater monitoring infrastructure the extent of any depressurisation was not well predicted. In late 2006 and again in mid 2007 multiple sensor VWP's were installed to evaluate the impact of the horizontal drains. Monitoring of a dual VWP completion (BHMW07) confirmed the presence of high groundwater heads in this sector of the open pit. However, it was apparent that open pit development, pit dewatering, and the construction of horizontal drains had no positive impact on slope depressurization. In December 2007, five horizontal drains were completed, with two terminating in very close proximity to BHMW07 to determine if a specifically targeted horizontal drain program could effectively reduce groundwater heads. Two drains initially yielded very substantial groundwater flows estimated at 50 to 75 litres per second for about two days, rapidly reducing to about five litres per second. Although a reduction in groundwater head was expected, a review of the monitoring data (Figure 15) indicates that there has been no positive impact on slope depressurization, but wet season recharge is taking place. Confidence in the hydrogeological model for this sector of the open pit is relatively low and additional work is ongoing. However, it does highlight that initial impressions are not always correct and good monitoring infrastructure is critical for accurate interpretation.

Figure 14 *Data from Vibrating Wire Piezometer BHMW06 at Batu Hijau*

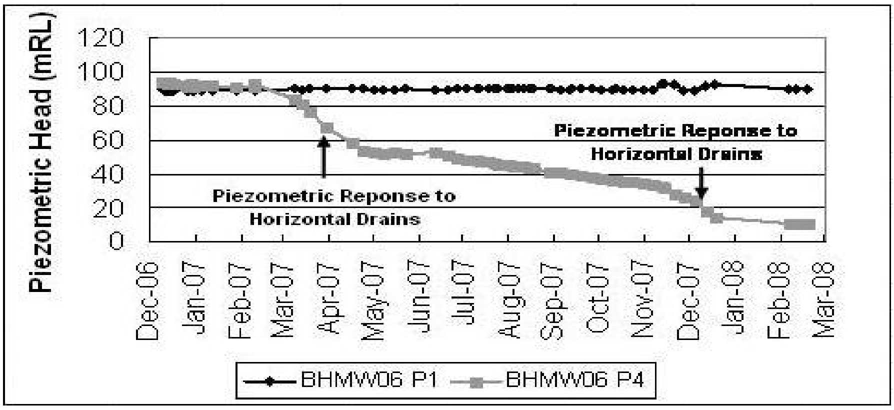
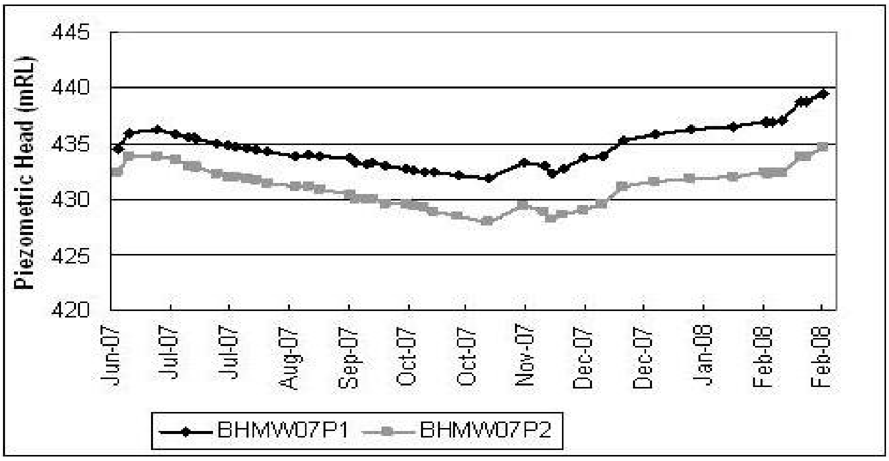


Figure 15 *Data from Vibrating Wire Piezometer BHMW07 at Batu Hijau showing no response to horizontal drains*



Conclusions

The Batu Hijau open pit and mining operation has reached a level of maturity whereby past performance is a strong indicator of what the future holds. The geotechnical and hydrogeological understanding and models of the mineral deposit developed pre-mining have been modified and revised as more reliable data, including operational impacts has become available. This understanding and the reliability of the models will continue to evolve and develop throughout the life of the mine and in to closure.

In order to assist in the optimization of the mineral deposit and the associated open pit slope design criteria, depressurisation is of significant importance. From an initial understanding that little or no advanced depressurization can be viably achieved, the program at Batu Hijau has evolved rapidly, sometimes with execution taking precedence at the expense of hydrogeological understanding. The open pit slope depressurization program has been centred around the construction of horizontal drains and implementing a monitoring program, which has to some extent involved trial and error, particularly with respect to the construction of multiple sensor VWP's. However, to optimize the slope depressurization program at Batu Hijau it will not simply be an exercise in constructing "enough" horizontal drains, as operational experience and monitoring have shown that the process is more elaborate. As the slope depressurization program at Batu Hijau has evolved a few lessons have been learnt:

1. It is essential that adequate groundwater monitoring infrastructure be installed prior to the execution of a horizontal drain drilling program, to assess whether it is appropriate.
2. For relatively deep installations, monitoring infrastructure construction must be carefully executed so that there is confidence in the data generated.
3. That the horizontal drain program be well integrated with the geotechnical and geology programs so that costs can be minimised and more importantly the quality of data interpretation improved.

Acknowledgements

Authors would like to thank PT Newmont Nusa Tenggara for approving the publication of this paper, and to those who reviewed the drafts.

References

Leech SJ (2007) Updated Open Pit Slope Design Criteria – July 2007. Unpublished Internal Memorandum prepared for PT Newmont Nusa Tenggara.

Golder Associates (2004) 2004 Slope Depressurisation Trials Batu Hijau Copper Mine. Unpublished Consultant Report prepared for PT Newmont Nusa Tenggara.

Mikkelsen PE, Green GE (2003) Piezometers in Fully Grouted Boreholes. Symposium on Field Measurements in Geomechanics, FMGM 2003 Oslo Norway.