

Hydrogeological Model Development and Horizontal Drainhole Effectiveness for Slope Stability

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ABSTRACT

The presence of ground water, particularly pore pressures can have a significant detrimental effect upon slope stability. Successful open pit slopes, particularly in tropical environments, depend on a good understanding of the hydrogeological model and the development of appropriate depressurisation strategies. This paper presents the development of the hydrogeological model and depressurisation methods used at an open pit mine in Southeast Asia. The overall aim of the study was to reduce the number of horizontal drain holes installed while maintaining effective depressurisation objectives and achieving the projects economic and environmental goals.

A field observation program was conducted during wet season to support the study. The observations identified both lithology and structural controls on hydrogeological conditions within the open pit. This paper describes the resulting conceptual hydrogeological model, which is based on existing mine development data, recent groundwater monitoring and horizontal drain hole (HDH) installations. Preliminary model sectors were created to direct HDH design, including depth and spacing. These have then been tested against ongoing groundwater monitoring. This paper also presents the development of pore pressure trigger levels for areas where depressurization is insufficient and has implications for slope stability. Ongoing work is focused on the validation of the HDH design sectors.

Keywords: Open Pit Mining, Hydrogeological Model Development, Depressurisation, Horizontal Drain Hole, Slope Stability

1 INTRODUCTION

It is well understood that pore pressures contribute to most significant large scale slope failures (Read and Stacey, 2011; Beale and Read, 2013). Beale and Read (2013) describe the impact of ground water by the following: *“The presence of groundwater has a detrimental effect on slope stability. Water pressures acting in the pore spaces, fractures or other discontinuities in the materials comprising the pit slope will reduce the strength of those materials and may therefore have a large influence on the performance, safety, and economics of a mining operation”*.

Open pit mines are commonly located in geologically complex environments in diverse climates around the world. To develop an adequate groundwater and surface water management plan, a degree of understanding is needed of the deposit's geology, structure, rock mass and hydrogeology to inform the conceptual hydrogeological model. The case study site is in Southeast Asia, a tropical environment wet seasons from May to October and dry seasons from mid-October to April. The deposit is situated in a mountain province and is positioned in a topographic low at a confluence of a regional river system.

This paper presents the application the development of a conceptual hydrogeological model and review of existing depressurisation performance. The aim of the study was to use the model to optimize Horizontal Drain Hole (HDH) design as the existing installation program is considered to have high human, environmental and financial costs.

2 EXISTING DEPRESSURISATION DESIGN

The existing site horizontal depressurisation hole (HDH) program is a grid design with 50 m spacings and typical lengths of 100 m to 150 m. A historic dewatering bore was also established prior to mine development in 2009, located in the northern sector of the pit, within a karstic limestone unit.

Depressurisation began in 2009 with the majority of HDH installed within volcanic tuff and siltstone units. Pit progression remained consistent from 2010 through to 2016 with total depressurisation drilling fluctuating between 5,000 m and 12,000 m annually. Mining progression accelerated from 2017 through to 2021 with the peak HDH installation occurring during 2020, with a total of 47,000 m.

3 METHODOLOGY

The open pit's geotechnical model was used to inform the basis of the hydrogeological model to optimise the HDH design. The characteristics of the geology, structure, rock mass and hydrogeology of the site were analysed to develop the model. The sections below present the key characteristics of the geotechnical model assessed.

3.1 Geology

The copper–gold (Cu-Au) deposit is described as a porphyry-skarn ore system, believed to be of Late Triassic age, related to subduction and island arc magmatism. The lithologies forming the primary geotechnical units are as follows:

1. Granite
2. Limestone
3. Interbedded calcareous siltstone-sandstone
4. Siltstone
5. Andesitic lapillic tuffs
6. Diorite intrusions, which are associated with faulting.

The distribution of the units are shown in Figure 1. Packer testing, where pressurised water is administered to the rock mass to ascertain hydraulic conductivity, was undertaken for each of these units.

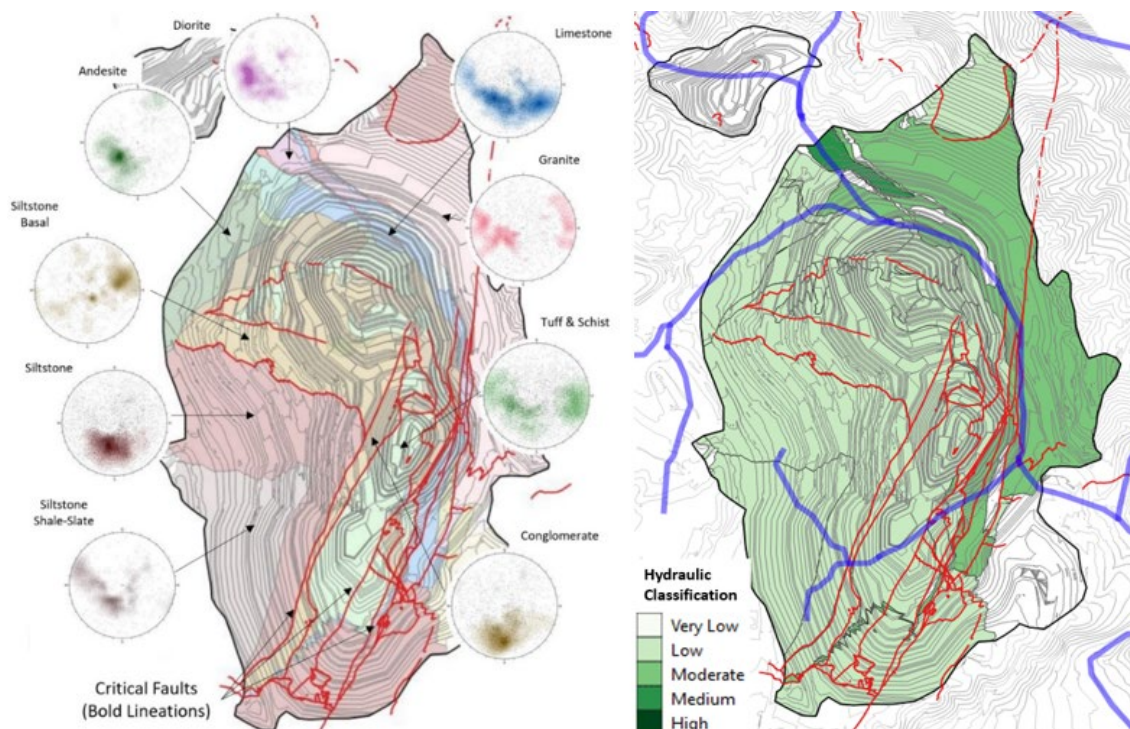


Figure 1. Lithology and the main structural elements of the case study site.

3.2 Structure

Geological structures were assessed to identify persistent anisotropic defects either consistent through the rock mass or defects that comprised a considerable reduction of the rock mass or material. Faults and shears were identified as reduction in rock mass, while bedding and foliation were identified as consistent anisotropic defects. Persistent structures such as faulting, shearing, bedding, or foliation were

observed to be either a conduit (enhance permeability) or barriers (reduce permeability). Faults were further assessed based on geotechnical and hydrogeological importance and were classified based on four categories (Table 1). An over all rating was derived with faults achieving a rating over 12 being identified as a critical fault.

Table 1: Critical Fault Criteria

Rating	Fault Condition	Persistence (m)	Orientation	Confidence ^a
1	Healed	<100	>500m from pit	0
2	Narrow (<1m thick)	100 – 500	Perpendicular to the pit wall	2-3
3	Fragmented/Sheared	>500	Oblique to pit wall	>5
4	Clay/Gouge	N/A	Parallel to pit wall (>50m)	>5
5	N/A		Parallel to pit wall (<50m)	N/A

^a Number of fault condition observations across a fault trace. Observed in either open pit mapping or boreholes.

3.3 Rock Mass

Understanding of the rock mass properties was imperative to the formation of the geotechnical model. To delineate the properties of the rock mass specific to the site, a review of existing literature and reports was undertaken. Site based data pertaining to the rock mass was reviewed. The rock mass was classified based on the level of oxidisation. Finally, the site-specific engineering properties of homogenous, heterogeneous, and anisotropic rock masses were identified.

3.4 Hydrogeology

Understanding the surface water and ground water characteristics was critical to implementing an effective HDH design. To identify surface water catchment and groundwater flow regimes, existing data relating to groundwater flow was assessed, including:

1. The paleo mining surface for post water drainage channels
2. Site specific recordings of ground water flows post heavy rainfall events
3. Flow readings from HDH's
4. Vibrating wire piezometer (VWP) measurements of pore pressures within the rock mass.

Finally, H_u values were derived from the VWP results whereby the H_u value was defined as a numerical assessment of the pore pressure behaviour irrespective of pressure head vs sensor depth. The assessment was conducted to identify confined aquifers that may be situated behind the pit wall and pose a risk to slope stability.

4 RESULTS

4.1 Geology

The lithologies at the case study site were characterised as a fractured rock aquifer, where most groundwater located in fresh rock is stored within fractures, joints, and cavities. Site based data included 103 packer tests were carried out within the surrounding rock mass through two campaigns. A 2014 campaign, consisting of 72 tests and another campaign in 2020 consisting of 31 tests, Figure 2.

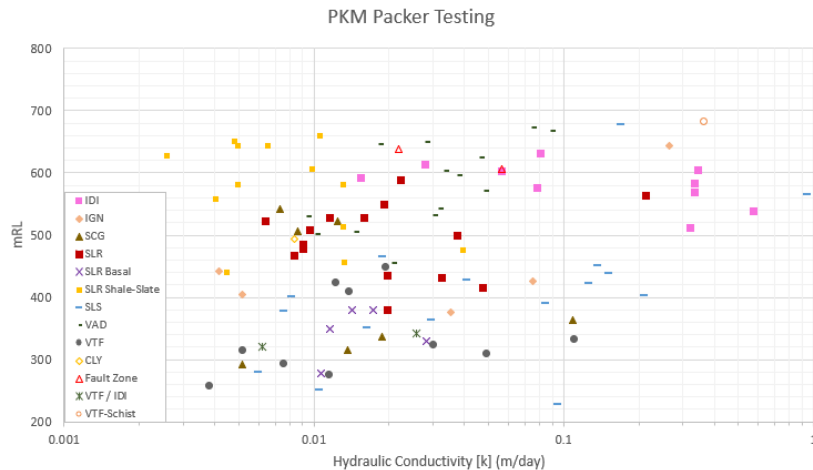


Figure 2. Packer testing results conducted between 2014 and 2020 at the Cu-Au deposit.

The packer testing indicated that most of the rock mass is of very low to low permeability. Diorite, granite, and limestone exhibited moderate to medium permeabilities associated with the eastern fault corridor, (Figure 1). The limestone was karstic, with zones of solution cavities which provide the most significant groundwater aquifer. It is noted that the 2014 testing had limited information on the characteristics of rock mass tested, with most of the testing occurring along the eastern fault corridor.

4.2 Structure

Two main structural elements, also referred to as critical faults, were identified as important for the conceptual hydrogeological model and are shown on Figure 1. These are:

1. A series of northeast-dipping thrusts. The two primary surfaces are the North and South Thrusts. These are located to the west of the pit and separate the siltstones from the Tuff and Schist.
2. A series of north-northeast trending, steeply dipping structures that form a zone in the eastern part of the pit called the eastern fault corridor. These post-date and offset the thrust faults.

Analysis confirmed conduit faults were present along both the eastern fault corridor and along the siltstone/conglomerate faulted contacts. Assessment of core photos, logging descriptions and HDH flow rates indicated that barrier faults were present along the limestone faulted contacts between both the siltstone and granite.

4.3 Rock Mass

Three oxidisation zones were identified as relevant for the conceptual hydrogeological model: completely oxidised (CO), partially oxidised (PO) and fresh. The upper CO consists of silts and clays from completely weathered bed rock units. The unit was described as a porous medium (intergranular) clay alteration with low permeability. The PO zone was characterised by moderately weathered to slightly weathered parent rock. The unit was described as a fracture flow, high permeability rock mass.

Fresh rock mass was characterised by fresh parent rock and was divided into three subgroups for hydrogeological assessment. The subgroups identified were as follows:

1. Homogenous: comprises igneous, conglomerates and tuff units. Characterised as having preferential flow occurs through joints.
2. Heterogeneous: comprised of the limestone unit. Characterised as having preferential flow through the medium to highly permeable rock mass and along discrete defects. Karsts are characterised as discrete vertical features which act more as a surface water feature than groundwater feature.
3. Anisotropic: Bedded and foliated units including shales and schist. Preferential flow occurs along persistent defects (bedding or foliation).

4.4 Hydrogeology

4.4.1 Hydrogeology - Surface water

The open pit is in a tropical climate where ground and surface water management have a large influence on mining operations, planning and management. The average annual rainfall from 1987 to 2019 was 2,525 mm where annual totals range from 1,547 mm (1992) to 3,738 mm (2005). The pre-mining water table was recorded between 4 mBGL and 9 mBGL. The deposit has a large surface water catchment located to the north to northwest of the pit and is estimated to be 5 km². The principal catchment for the area flows from the north-western corner of the pit and is then diverted along the north and eastern pit walls. Several tributaries converge with the principal catchment before exiting through the eastern pit wall. The principal stream was predominately unlined at the time of the study and flowed along excavated channels in transitional, faulted, medium permeable granite. The project concluded that surface water management has an important role in depressurisation at the site.

4.4.2 Ground Water and Hu Assessment

Since mining commenced about 160 VWP sensors have been installed across the various geotechnical units. The pit has been mined as a series of cutbacks resulting in many VWP's and HDH holes being destroyed between 2017 to 2019. Limited VWP data is available for the upper weathered (CO, PO zones).

Hu is a geotechnical pore pressure coefficient. It is a simple factor between 0 and 1, by which the vertical distance from a point in the soil of rock mass to a water surface is multiplied to obtain a pressure head. Hu values were derived for the site from the 160 VWP sensor readings. The results were able to directly compare with the assumptions used in the slope design. It was observed that for some units the VWP pore pressures exceeded both the assumed conditions and hydrostatic conditions (Hu =1), Figure 3.

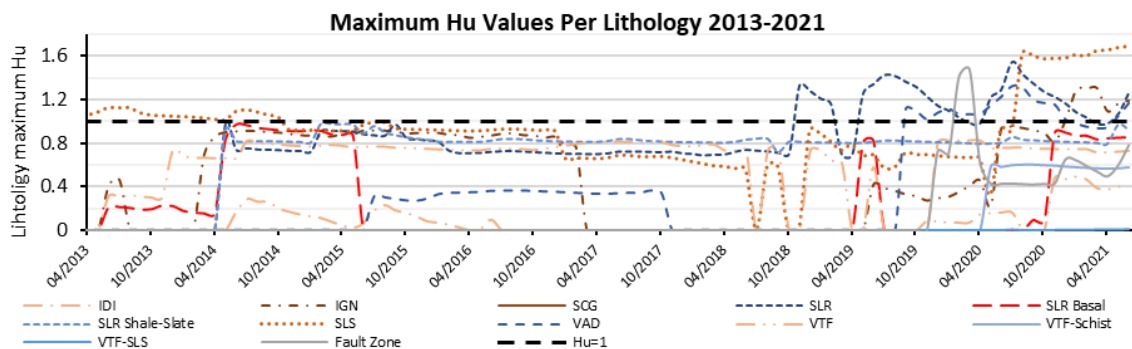


Figure 3. Maximum Hu values recorded per lithology from beginning of Mining to July 2022

For each VWP noted to exceed the slope design assumptions, a review on the location and consequence to slope stability was undertaken. No excessive pore pressure result had an immediate effect on slope stability. Further investigation was recommended to aid understanding of the increased pressures.

5 DISCUSSION AND CONCLUSIONS

This study found that the pre-existing HDH design achieved adequate depressurisation and groundwater conditions. However, the design required a large quantum of drilling, with substantial cost implications. In addition, there was inadequate monitoring of structurally complex locations such as the eastern fault corridor. The pre-existing design, with the unlined diversion drain allows surface water to infiltrate the moderately permeable rock mass units allowing recharge of pore pressures.

The hydrogeological model is presented in Figure 4 and considers specific components such as structure, anisotropy and surface water. The resulting HDH program included:

1. Completely Oxidized Zone: HDH spacing to remain at the 50 x 50m spacing with hole depth reducing to 100m. Recommendation of periodic flow ratings and observations.

2. Eastern Fault Corridor: HDHs only drilled to target Category 5 faults. Recommendation to increase monitoring behind these faults to confirm depressurisation targets are met.
3. West Wall Anisotropic Zone: Preferential flow along bedding. Targeted HDH drilling, perpendicular to bedding dip. Recommendation to continue monitoring through the West Wall hydrogeological units.

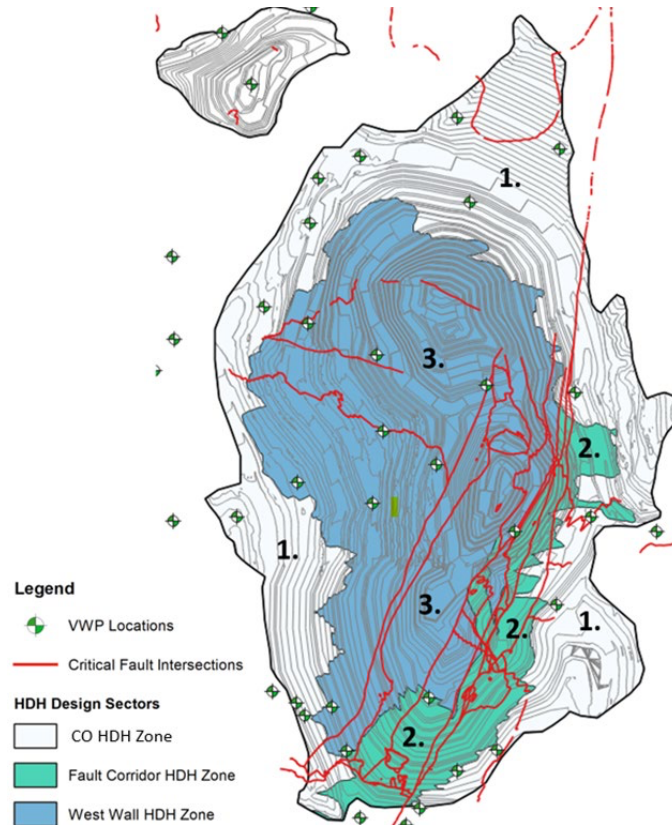


Figure 4. Hydrogeological depressurisation drilling sectors

Limitations to this model included restricted data regarding HDH flow rates and draw down responses unmonitored by VWPs. This led to difficulties in assessing the effectiveness of the HDH hole. Further work recommendations included:

1. VWP installation locations be selected along 2D cross-sections to understand pressure head gradients through various geological units.
2. Additional groundwater monitoring and permeability investigation be undertaken in the oxidised zones.
3. Ongoing permeability testing and installation of VWPs through the oxidised zones is warranted.

This study has illustrated that optimisation of specific components such as structure, anisotropy and surface water will greatly improve depressurisation outcomes whilst decreasing drilling requirements.

6 ACKNOWLEDGEMENTS

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