Integrating Hydrogeology with Geotechnical Engineering

John Waterhouse[1]

[1]*Golder Associates Pty Ltd, 1 Havelock Street, West Perth, WA 6019, Australia, jwaterhouse@golder.com.au*

Abstract

Integrating physical hydrogeology with geotechnical engineering is a valuable part of slope design in mines and can be a critical safety aspect, particularly in underground mining.

This integration is not always carried out adequately. Designs are being made with assumptions about drained conditions or with simplistic assumptions about hydrostatic pressure distributions within saturated rock masses below a "phreatic line".

For new projects, perhaps the first aspect to consider is whether the highest water pressure likely to occur would affect stability. Designs for mines with strong and poorly-fractured rock masses may be essentially independent of groundwater pressures. Weak, layered sedimentary rocks may be extremely sensitive to groundwater pressures This consideration is the first point of integration of hydrogeology with geotechnical engineering.

Slope design and underground design and support can be optimised without compromising safety with a proper understanding of the magnitude and distribution of groundwater pressures around mines.

Understanding the distribution of groundwater pressures requires adequate hydrogeological investigation and conceptualisation. Measurements of groundwater pressures are essential. Numerical modelling may be important to predict groundwater behaviour as a mine is developed and after closure.

Integration of the disciplines requires good communication.

Keywords: geotechnical engineering, hydrogeology, mining, slope failure, inrushes

Introduction

Integrating physical hydrogeology with geotechnical engineering is a valuable part of slope design in open pit mines. In underground mining hydrogeology can be important in designing access drives, mine workings and roof support. Groundwater conditions may be a critical safety aspect regarding inrushes of water.

In the past and perhaps now, this integration is not always carried out adequately. Designs are still being made with assumptions about drained conditions. Simplistic assumptions are made about hydrostatic pressure distributions within saturated rock masses or soils below a "phreatic line" or "phreatic surface".

For many years, some hydrogeologists like me have worked to provide stronger integration of hydrogeology and geotechnical engineering in the mining area.

Why do I think this is important? What are the key issues and how should we think about hydrogeology in association with slope stability?

The first aspect to consider with any new mining proposal is whether the highest water pressure judged likely to occur would affect stability. Estimating the highest likely water pressure may be a matter of hydrogeological judgement, given the setting within which the mine will be developed or into which it will be extended.

Which rock mass conditions will be independent of the probable groundwater pressure conditions? This question is a geotechnical matter, providing the first point of integration of hydrogeology and geotechnical engineering in a mining project.

Designs for some mines with strong and poorly-fractured rock masses such as fresh, metamorphic and plutonic rocks will be essentially independent of groundwater pressures. Others, for example in weak, layered sedimentary rocks, may be extremely sensitive to groundwater pressures. This consideration is the first point of integration of hydrogeology with geotechnical engineering.

Safety is a key issue. Water pressures that exceed those included in design calculations can cause failures which, if sudden, can kill people. Every effort must be made to avoid sudden failures and catastrophic water inrushes in underground and surface mines.

Apart from safety, slope design and underground design and support can be optimised with a proper understanding of the magnitude and distribution of groundwater pressures around mines. Such optimisation may be a key economic aspect of a mine, making the difference between a feasible project and one that fails economically.

In some situations, numerical modelling is essential to predict groundwater behaviour as a mine is developed and after closure. However, most mines are not managed with models but by observation and measurement. The value of a good numerical model can be in focussing attention on areas of potentially high groundwater pressures, where piezometers are most needed.

Integration of the disciplines requires good communication. In the author's experience, this must often be driven from the hydrogeological side to the engineering team. Perhaps the best, most recent publication on the subject of groundwater and mining, at least for open pit mines, is that of Beale and Read (2014). This comprehensive book is readily available from the publishers.

This paper provides a few examples, hoping to stimulate further action to improve communication of hydrogeological information into design of open pit slopes and underground mines.

Example 1: A shallow, groundwater-related slope failure

The photograph shows the complete loss of a small, shallow gold mine, where ground movements destroyed the only economically-viable design. The failures occurred in saturated clays, themselves in-situ, completely weathered metamorphic rock. So why did the slope fail?

The cause of the failure was groundwater pressures in weak material. Those pressures were accurately predictable by knowledge only of

1. the depth of the mine below the local water table
2. recognition that the low relief terrain with low hydraulic gradients would allow hydrostatic assumptions to be used to predict pressure with depth below the water table.

In this instance, the groundwater pressures that caused the slope failures probably did not exceed 300 kPa (about 30 metres depth below the water table. The failures were

Photograph 1: *Circular failure in saturated, extremely weathered Archaean rock*

attributable to mining downwards faster than groundwater pressures could dissipate.

Example 2: A deeper groundwater-related slope failure

Photograph 2 and Figure 1 show another complete loss of a small gold mine as a result of mining below the water table in weathered to fresh metamorphic rock. The cause of the failure was an incorrect assumption that the water table was deeper than the bottom of the slope and that, therefore, there were no groundwater pressures to consider in the slope design.

In this instance, the water table elevation was easily predictable by a consideration of the regional hydrogeological setting, even without drilling. There was a nearby salt lake and its bed elevation would have been similar to the water table elevation at the mine. The bed elevation of the lake was tens of metres higher than the bottom of the slope.

Photograph 2: *Structural failure in weathered to fresh Archaean rock*

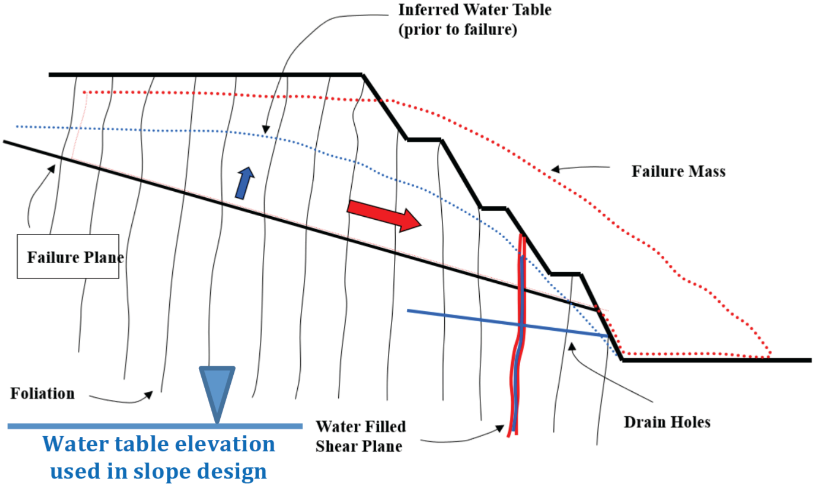

Figure 1: *Diagrammatic section showing slope failure and groundwater assumptions*

Example 3: Catastrophic inrush to underground mine

Figure 2 shows the location of a catastrophic inrush to an underground mine. In this instance, there were progressive signs of instability in a stope roof (a geotechnical matter) several hundred metres below the water table. Earlier mining of shallower parts of the deposit had not intersected any cavities in the rocks that formed the roof of the mine. However, the final part of the deposit to be mined was faulted laterally and located directly beneath the cavernous limestone.

The consequential risk of the hydrogeological setting was that any roof instability had a risk of a catastrophic inrush of groundwater. Maybe this recognition would have led to a more focussed geotechnical study?

The failure occurred suddenly, with a very high rate of groundwater inflow (maybe 50 m^3/s over the first hour). Fortunately the inrush happened overnight when no-one was working underground. The mine flooded completely and was lost.

Example 4: Pore pressure distributions

The simplest conceptual model relates groundwater pressure to the depth of mining below the water table using the simple equation $P = \rho gh$. This condition can apply well in low relief terrain where equipotentials are vertical and groundwater movement is horizontal.

As soon as a mining void is created below the water table, flowlines towards the mine perturb the flow field and reduce the pore pressures to some extent, at least near the mine.

In high relief terrain, the vertical component of natural groundwater movement also means that the equation $P = \rho gh$ is invalid, typically over-estimating pore pressures. In these cases, numerical modelling has a place in making estimates of the distribution of pore pressures with time and with mine development. Figure 3 gives an example of a modelled head distribution at a mine in high relief terrain, with steep gradients. Near the modelled position of the

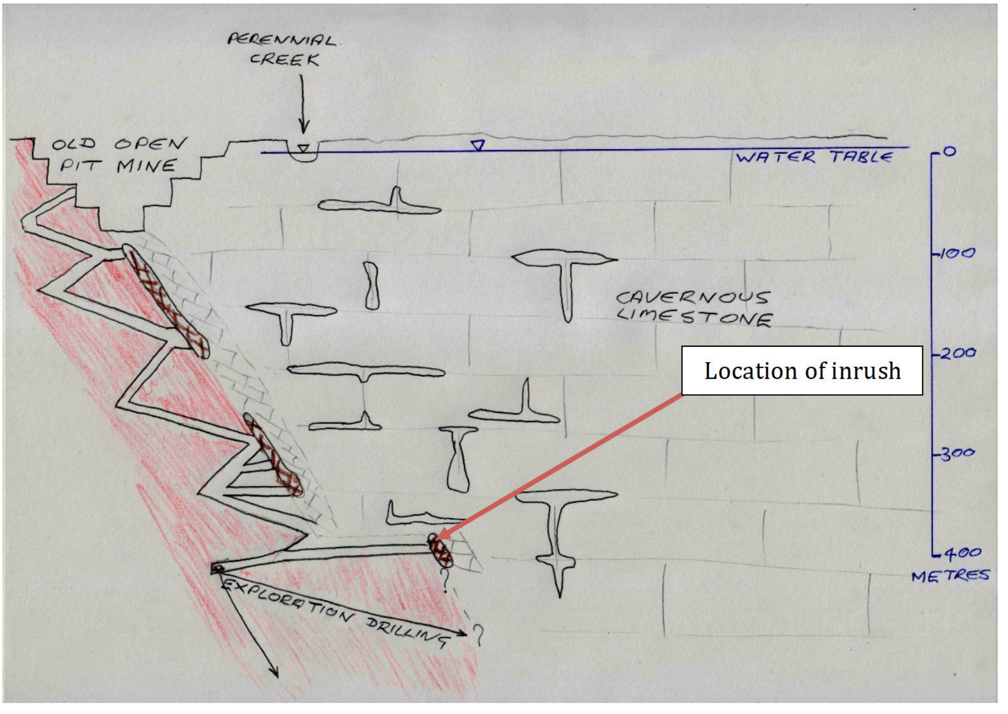

Figure 2: Diagrammatic location of the inrush to the underground mine

water table the steep head gradients mean that the pressures below the water table are in places lower than given by the relationship P = ρgh.

One consequence of over-estimating pore pressures can be over-conservative slope design, leading to excessive mining costs. Equally, good numerical modelling with an appropriate distribution of calibration data from piezometers located behind areas of active mining, can point to areas of stability risk. It is those areas which deserve priority in measuring grounwater pressures.

Discussion

The paper's examples present two open pit slope failures caused by groundwater pressure and one catastrophic groundwater inrush. All three mines were lost at great cost to the owners and the loss of contractors' or employees' jobs. There were no injuries or fatal accidents in these cases.

All were caused by hydrogeological factors.

In most situations where rock strengths are moderate to low or when structurally-controlled failures are possible, groundwater pressures in walls and floors of open pit mines and in the rock mass around an underground mine should be understood and measured. This information needs to be communicated to the geotechnical engineers who design these aspects of a mine.

The fourth example illustrates that there are circumstances where numerical modelling is important in providing a distribution of estimated pore pressures for input to stability analyses. This hydrogeological information, expressed as pore pressure distributions, leads to optimised slopes that still can have acceptably low risks of failure.

One underlying message from this paper is about communication. Hydrogeologists need to understand how to communicate effectively to engineers, who have a different background and culture to many people with science backgrounds. Effective communication of good information and of

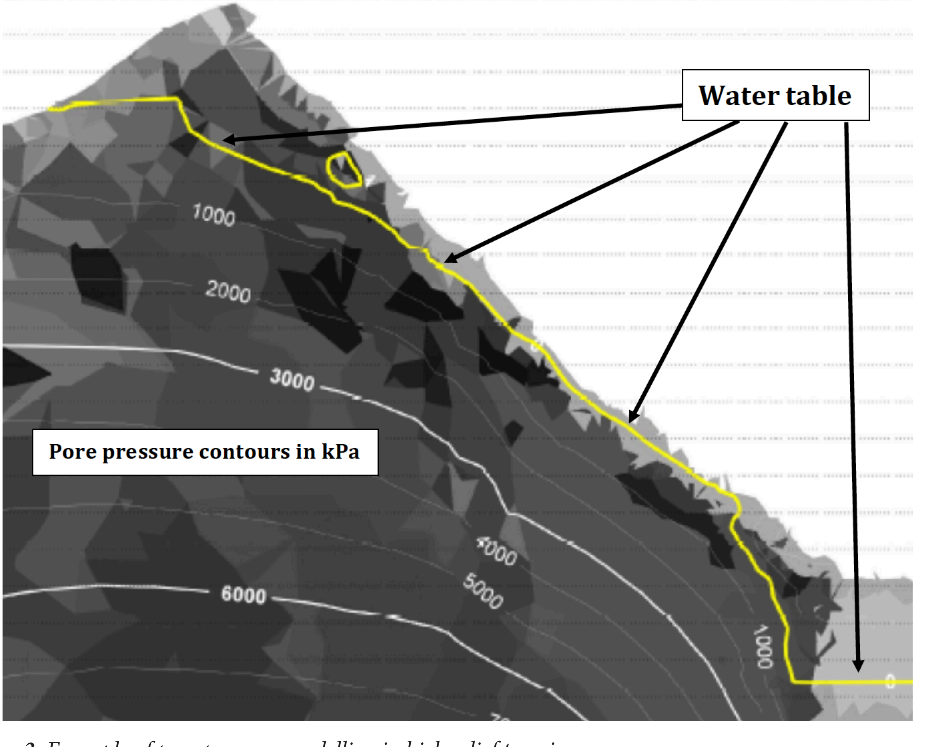

Figure 3: Example of pore pressure modelling in high relief terrain

uncertainty can bring respect and good team work.

A parallel issue is discontinuities in the distribution of ages through our ranks.

Time distribution of professional experience

Groundwater-related issues in slope stability are not a new topic. Relevant papers can be found decades ago in the literature. However, the lessons seem to need repeating by older practitioners and re-learning by younger practitioners year after year.

In areas of mining where professional employment is affected by fluctuating demand and prices (industrial metals such as iron, copper, nickel etc and precious metals such as gold), there are time bands of missing experience in our professional groups. For many years I have had 15-20 years more experience than practically all of my colleagues. Mining engineers with whom I work report the same gap in years of experience in younger professionals. This fluctuating demand for professional skills may not apply in long-term mining situations such as decades-long contracts to supply coal for power stations. However, in the commercial world of mining commodities for which demand fluctuates, professional employment fluctuates too.

To conclude….

I urge all of us in the physical hydrogeology area to continue to work hard to bridge the gap between science and engeering. We must communicate effectively with geotechnical engineers, in their language, if they are to respect hydrogeological advice and we are all to achieve the best compromises between mine stability, safety and economics.

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References

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