Mine Water and Rock Engineering – A Winning Partnership in Cave Mining

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Abstract

Bulk mining methods such as cave mining allow the production rates necessary to provide the needed near term supply of critical minerals to support the energy transition. Mine planning studies benefit from integration of rock engineering and mine water considerations to optimise and increase project value and limit project risks. This paper outlines a procedure developed to integrate these aspects. Each step of the process is described along with a case study demonstrating the value of the approach. The developed workflow can be used as a checklist to guide future integrated mine water studies supporting the development of cave mines.

Keywords: Mine water, rock engineering, integrated studies, ESG, Cave Mining

Introduction

In the drive to secure the world's supply of critical minerals, mining projects are being developed in more complex locations and at greater depth. Bulk mining methods such as caving are becoming increasingly common to allow the production rates necessary to secure suitable project economics and to provide the urgently needed near term supply of critical minerals to support the energy transition. Should appropriate geotechnical conditions exist, cave mining methods can allow for high production rates following a period of large initial investment in the substantial infrastructure development required to support this mining method. Consideration of water is essential for the successful development of these types of mining operations, both to limit production risks, costs, and safety risk as well as to meet Environmental, Social, and Governance (ESG) requirements.

When undertaking water management studies and design at deep underground cave mines, it is fundamental to consider geotechnical conditions throughout every aspect of the mine water study. In this light, a workflow has been developed to support full integration of geotechnical considerations into mine water aspects of cave mining studies. The workflow supports all aspects of a typical mine water study from site investigation through to development of the Conceptual Site Model (CSM), integrated modelling, risk management, planning and thereafter engineering of the water management scheme.

Although the integration of geotechnical and hydrogeological field investigations is common practice in the mining industry to limit drilling costs, the key value of this study was the production of a tested workflow which allows geotechnical integration through every aspect of a cave mining focused mine water study, thereby limiting project risk.

The developed workflow in this paper is expected to be used as a checklist to guide future mine water studies supporting the development of cave mines. A case study is used as an example of the workflow, applied to advance the development of a cave mining study and demonstrating the effect and importance of geotechnical integration to the outcomes of the mine water study.

Approach

Rock mechanics and hydrogeology professionals worked together to produce a workflow procedure to integrate geotechnical and hydrogeological programmes, to optimise data collection efforts and to feedback outcomes into integrated engineering designs. The procedure was developed over the course of a Front End Loading (FEL) 3 (Batavia, 1999) cave mining study and included the following steps:

1. **Integrated Field Investigation Design:** Consideration of integrated geotechnical and hydrogeological field investigations with feedback to hydrology and geochemistry.
2. **Integrated Interpretation of Field Data:** Delineation of mine scale faults and fracture network considering both geotechnical and hydrogeology significant fracture sets.
3. **Geomechanical Model:** Appropriate geomechanical modelling should be undertaken to understand the development of caving conditions over time and their effect on surrounding strata. Potential development of a Discrete Fracture Network (DFN) model (with feedback to Step 1).
4. **Integrated development of the CSM and water management concept:** Consideration of geotechnical ground disturbance in the CSM and water management conceptual design (with feedback to Step 1).
5. **Mine Plan Optimisation:** Optimisation of the mine plan and engineering considering the above integrated CSM and conceptual design (with feedback to Step 4 and Step 1).
6. **Integrated Modelling:** Outcomes of the optimised mine planning should be considered in water balance and geochemical modelling. Consideration of development of the cave and stress/strain conditions in the surrounding strata within the hydrogeological model (with feedback to Step 4).
7. **Inrush Assessment:** Hydrogeological model and integrated water balance should be considered alongside the geomechanical model to predict the potential risk of catastrophic inrush to the mine workings.
8. **Water Management Plan:** Consideration of the above in the development of groundwater control options and detail of the site water management plan (with feedback to Steps 5 & 7).
9. **Detailed Engineering:** Progression to detailed engineering and monitoring plan.

This process is represented graphically as Fig. 1 with each step discussed further in the following sections.

1. Integrated Field Investigation Design

Integration of geotechnical and hydrogeological field investigations is common practice to limit drilling costs. However, it is critical that these investigations are planned together, with appropriate feedback from conceptual mine planning,

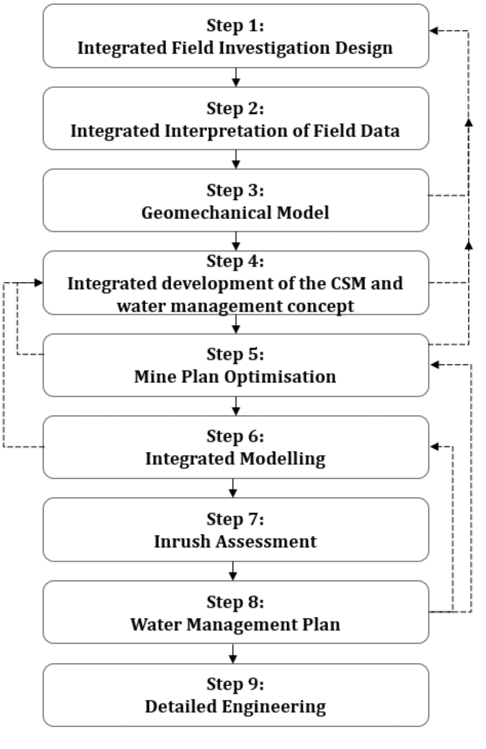

***Figure 1** Workflow Procedure with Feedback Loops.*

geomechanical modelling, and CSM development (Steps 3, 4 and 5 as above), and integration of hydrology and geochemistry studies. Not only can drillhole locations be optimised for combined data collection but they can be used for geological, geotechnical and hydrogeological logging, testing and instrumentation and water quality sample collection (for both geochemistry and hydrology considerations). Factors to be considered and planned for in design of these investigations include:

- Ground stability and suitability for various types of testing.
- Sampling and ability to investigate units and areas key to the mine plan and associated infrastructure.
- Positioning and suitability to install long term monitoring equipment (e.g. drill hole diameter and collar location).
- Need for high quality structural geology data collection aligned with hydrogeological parameter identification.
- Drilling and testing equipment limitations.
- Experience of local contractors in specialised testing and installations.

2. *Integrated Interpretation of Field Data*

Delineation of mine scale faults and fracture network considering both geotechnical and hydrogeology significant fracture sets (potentially DFN model).

High quality data collection of the mine scale faults and fracture networks is essential to cave mining studies. This information feeds into both geotechnical and hydrogeology analysis and understanding. The use of the information may be different since geotechnical analysis considers both open fractures and healed or infilled fractures as a critical part of the ground conditions predictions. Traditional hydrogeology analysis considers open or interconnected fractures as conduits to flow. However, as the cave propagates, disturbance of the blocks of rock is designed to cause a change in the stress/strain regime of the healed rock structures which may then become open or conduits to flow. The changes in the connectivity and openness of the caved area and surrounding rock affected by caving should be considered.

3. *Geomechanical Model*

Appropriate geomechanical modelling should be undertaken to understand the development of caving conditions over time and their effect on surrounding strata.

The extent and magnitude of ground disturbance expected from caving activities should be evaluated and fed into the development of the CSM and water management concept. One approach is to produce an integrated DFN model of the site considering these aspects however the suitability of this approach will be dependent on the site conditions and availability of suitable datasets.

Key outputs include:

- The footprint and magnitude of surface subsidence over time.
- The extent and magnitude of ground disturbance developed over time expected to cause a change in hydrogeological condition.

The calculation of these values can be site and materials specific.

4. *Integrated development of the CSM and water management concept*

Consideration of geotechnical ground disturbance in the CSM and water management conceptual design (with feedback to Step 1).

Consideration of geotechnical ground disturbance should generally focus on the following aspects relevant to groundwater and surface water management plans:

- At the surface via predictions of surface subsidence.
- Between hydrogeological units causing increased connection of the area to capture groundwater inflow.
- Causing increased infiltration rates from surface or other water bodies due to increased hydraulic connection.

The extent and magnitude of ground disturbance can affect:

- Positioning of surface infrastructure;
- Need for surface diversions around subsidence zones;
- Need for removal or decommissioning of potentially connected water storage facilities;

- Positioning of groundwater control infrastructure; and
- Potential effects on groundwater quality and discharge considerations.

Feed back to the ground investigation (Step 1) to allow the study to characterize:

- Areas relevant to surface infrastructure and surface water bodies;
- Targeted testing of structural features which may eventually be conduits to flow;
- Testing of units that may eventually be in hydraulic connection with other units which are currently disconnected; and
- Baseline water quality analysis and geochemical characterisation to approximate the predicted water quality and set discharge location and/or treatment requirements.

5. *Mine Plan Optimisation*

Optimisation of the mine plan and engineering considering the above integrated CSM and conceptual design.

The outcomes of the CSM and conceptual water management plan should be fed back and integrated with the mine planning works to:

- Optimise mine sequencing to achieve project goals such as minimising mine inflows during early time and staging water management infrastructure development to allow the mine to achieve ramp up production targets;
- Optimise mine infrastructure positioning to limit the potential need to relocate key mine infrastructure; and
- Appropriately consider water storage and discharge locations and treatment requirements.

6. *Integrated Modelling*

Outcomes of the optimised mine planning should be considered in water balance and geochemical modelling. Consideration of development of the cave and stress/strain conditions, which may be influenced by geochemical weathering, in the surrounding strata within the hydrogeological model (with feedback to Step 4).

Optimised mine planning should be integrated into the relevant water balance and geochemical water quality modelling so that all relevant aspects are considered.

If appropriate, the numerical hydrogeological model should aim to represent the relevant hydromechanical coupled effects induced by the cave mining when running predictive simulations. There are several methods to allow for this including consideration of a full integrated DFN model or by modifying the hydraulic parameters and recharge rates of equivalent porous media models according to the results provided by the geomechanical models. In particular, the model should represent the effects of the cave and strain zones, along with any surface subsidence over time if this information is available.

Predictive simulations should consider these changing conditions over time and their effect on potential inflows to the mine including the influence of hydraulic connections which may develop as the effect of cave related ground disturbance propagates. It is essential that modelling extends to cover the mine closure period as well as the extent of the propagation of geomechanical effects.

7. *Inrush Assessment*

Hydrogeological model and integrated water balance should be considered alongside the geomechanical model to predict the potential risk of catastrophic inrush to the mine workings.

The potential risks arising from the possibility of inrush or mud rush should be assessed as appropriate to be informed by the mine plan and predictive hydrogeology and water balance modelling. The assessment should include consideration of the potential magnitude and frequency of inrush events and associated safety and operational considerations.

The assessment shall consider:

- Any enhanced hydraulic connections between the mine workings and the ground surface associated with the cave and strain zone, and to the potential development of subsidence fractures or a subsidence zone at surface level; and
- The potential existence of additional preferential pathways for ingress of groundwater or surface water.

Outcomes of the assessment should feed into the project risk assessment and inform Water management and operational monitoring plans developed in Steps 8 & 9.

8. Water Management Plan

Consideration of the above steps in the development of groundwater control options, site water management plan and associated infrastructure.

Optioneering of water management solutions should consider the positioning of both groundwater and surface water management infrastructure in relation to the predicted ground disturbances. The hydrogeological model and water balance model ideally should be used to set performance specifications and assess options against other project requirements (e.g. the need for pre-dewatering of some mining areas) and will inform the inrush assessment (Step 7). The transient outputs of the model predictions are essential to develop this planning and mine plan optimization (feedback to Step 5) and should extend to consider mine closure.

9. Detailed Engineering

Progression to detailed engineering and monitoring plan.

Detailed engineering of water management infrastructure to consider the outcome of Step 8 including the progression of geomechanical ground disturbances from mining over time.

Detailed engineering should be advanced to consider the following integrated geomechanical and mine water considerations aligned with the requirements of the water management plan (developed in Step 8):

- Timing of decommissioning or lining of surface water bodies and storages;
- Design of surface water diversions and the mechanism for staged dewatering;
- Positioning and interaction of key infrastructure;
- Integrated design for closure and consideration of passive water management and passive treatment options;
- Consideration of the optimised mine plan, dewatering and mine safety infrastructure; and
- Controlling the quantity and quality of site discharges and the need for water treatment prior to discharge aligned with project requirements.

Monitoring plans should be developed and managed during operations and closure to consider timing and progression of the mine through the operations and closure period and associated ground disturbance. Typical monitoring considerations could include:

- Instrumentation and monitoring of surface water features and storages;
- Piezometric pressures in area of potential ground disturbances;
- Real time inflow monitoring within the mine at key locations and draw points noting that sudden changes in inflows can be an indication of inrush risk; and
- Changes in water quality and sediment loading which also can be an indication of changing geomechanical conditions; and
- Monitoring of changes in geomechanical conditions which also may provide early indications of changes to the groundwater or geochemistry regime.

Case Study

The above process was developed and tested while working on an integrated FEL 3 study of a deep cave mine by a collaborative team of geotechnical, rock mechanics, modellers, mine water professionals, and mine planners. The process was validated by this multidisciplinary team who were able to include the feedback opportunities indicated in the process to the benefit of the study. The following aspects were noted as being valuable to the project and study:

- A key aspect of development of the CSM was interaction of the cave with local water storages and the near surface weathered bedrock. Timing of this progression from the geomechanical model was essential to the assessment.
- This understanding directed field investigations and monitoring installation locations and positioning of key surface infrastructure.
- It also directed the requirement for pumping tests in the weathered bedrock zone to more accurately evaluate key parameters such as Storativity.
- This monitoring and the outputs formed a critical part of the hydrogeological mod-

elling input and allowed for an optimisation of the dewatering efforts by considering the option of pre-dewatering from the weathered bedrock zones which reduced pumping effort and also reduced the inrush risk.
- Mine planning options were also optimised to consider the advancement of development to allow staged implementation of the mine and associated dewatering infrastructure to achieve early time production targets limiting cost & schedule risks for the mine operator.

Study planning and timeline had to be updated to consider this integrated feedback and allow for associated updates to the field investigations, interpretation, mine planning and infrastructure design. This consideration should be built into the project schedule, which may be challenging given commercial pressure to meet cost-driven deadlines.

Conclusions

When undertaking water management studies and design at deep underground cave mines, it is fundamental to consider geotechnical conditions throughout every aspect of the mine water study, ideally with feedback to mine planning aspects. A tested workflow has been developed to support full integration of geotechnical considerations into mine water aspects of cave mining studies.

The procedure outlined in this paper has been shown to provide positive and integrated value in the development of the FEL3 cave mining study. The primary application is a proven approach to support the advancement of bulk mining methods underground with opportunity to optimise water management and mine planning aspects aligned with project focused business drivers, such as ESG aligned project metrics and limiting risks to production and schedule.

A case study has been presented as an example of the workflow, applied to advance the development of a cave mining study and demonstrating the effect and importance of geotechnical integration to the outcomes of the mine water and overarching FEL3 study.

Key success factors of the process were the close collaboration between project teams and the mine owner and the iterative feedback process through various phases of the study. Time allowance for this feedback should be built into the project schedule and/or considered as projects advance through study phasing. The developed workflow can be used as a checklist to guide future integrated mine water studies supporting the development of cave mines.

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