Slope Stability 2020 - PM Dight (ed.)
 ISBN 978-0-9876389-7-7
doi:10.36487/ACG_repo/2025_74

Considerations for open pit to underground transition interaction

ECF Hamman *AngloGold Ashanti Ltd, Australia*

M Cowan *AngloGold Ashanti Ltd, Australia*

J Venter *AngloGold Ashanti Ltd, Australia*

JB de Souza *AngloGold Ashanti Ltd, Australia*

Abstract

A large volume of work is available in the industry on many aspects relating to the interaction between open pit and underground mining. Various authors have addressed the optimisation of the transition problem to determine the optimal economic point to transition from open pit mining to underground mining. Several papers have been presented on determining a suitable crown pillar to eliminate or minimise the interaction between open pit and underground mining, and several authors have presented on discrete, geotechnical interaction and challenges that were faced on certain mines.

There is, however, very little information available that has been collated into a suitable reference or guide for designers and practitioners to consult on the potential operational challenges that a mine may face. Thus, the need for robust due diligence processes/techniques, which can function as part of a mine's planning strategy, becomes essential to identify hazards that can impact production and amelioration options to mitigate and manage the risks.

These will be unique to the sequence of the open pit underground interaction, which can take any combination of the following forms:

1. *Scenario 1 – Open pit transitioning to underground; concurrent mining.*
2. *Scenario 2 – Underground mining below existing open pit.*
3. *Scenario 3 – Open pit mining through existing underground working.*

This paper provides an introduction in contextual information that practitioners, having to deal with open pit underground interaction, need to consider.

Keywords: *transition, open pit underground interaction, risk management, operational considerations*

1 Problem statement

In his paper, *In search of a design methodology for rock mechanics*, Bieniawski (1991, 1992) quotes the Accreditation Board for Engineering and Technology (1987) definition of engineering design:

> *"Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation. In addition, sociological, economic, aesthetic, legal and ethical considerations need to be included in the design process."*

Now consider a mining environment where various factors such as the highly variable nature of the groundmass, changing orebody interpretations, altering mine plans and actual excavated conditions, contribute to the level of complexity of the geotechnical engineering design that is required. The geotechnical engineer on a mine is therefore tasked to continuously use complex engineering design in order to manage one of the biggest risks on the mine; that of a rock mass instability.

Since an instability or collapse along a ramp need not be large to have a significant impact on production, the challenge is to develop a balanced (both optimised and robust) life-of-mine design with a risk management plan that suits the risk requirements of the mining company, whilst meeting acceptable, minimum safety standards. This means that there needs to be a good understanding of what drives potential failure mechanisms and how these different mechanisms can be controlled in a specific design option. The final design needs to be robust, repeatable and auditable but still maintain flexibility to cater for risks and opportunities.

On a normal operating mine, or for a typical project in the making, the geotechnical design will address ground control and inundation hazards for one particular mining method, where the aims and objectives are set and controlled by one technical team. This engineering feat is already a challenge for only an open pit mine; add the additional objectives and requirements for an underground mine and the complexity is significantly increased. There is a large volume of work available in the industry dealing with the many aspects relating to the interaction between open pit and underground mining, however, there does not appear to be any easily accessible reference for geotechnical design engineers and practitioners.

Various authors (e.g. Whittle et al. 2015) have addressed the optimisation of the transition problem to determine the optimal economic point to transition from open pit mining to underground mining. Several papers have been presented on determining a suitable crown pillar to eliminate or minimise the interaction between open pit and underground mining. Several authors (e.g. Brummer et al. 2006) have presented on discrete, geotechnical interaction, challenges that were faced on certain mines; typically dealing with mining through existing voids. As such, the design engineer and practitioner need to revert to their own experience, or rely on the experience of consultants, to define and mitigate the interaction challenges.

Thus, there is a need for industry knowledge to be collated into a suitable reference or guide for designers and practitioners to consult on the potential operational challenges that a mine may face. Such a guide should consist of a robust set of due diligence processes/techniques, derived from current industry understanding, case studies and technical references. These processes need to function as part of a mine's strategic and tactical planning systems to help identify hazards that can impact production, and amelioration options to mitigate and manage the risks.

The aim of this paper is to provide a basis for such a guide and to provide an introductory level of contextual information that practitioners–having to deal with open pit underground interaction–need to consider. It provides references to scenarios and papers that the author has found useful in providing guidance in open pit and underground interaction, which practitioners can use as a means to start a discussion.

2 Interaction/transition considerations

There are three unique scenarios that represent open pit and underground interaction:

1. **Scenario 1 – Open pit transitioning to underground**: This is the most likely to occur in the large open pit milieu. It represents the stages during which a new underground mine will be developed and begin production, while the open pit is still active and in the process of closing. During this concurrent mining stage, the interaction between open pit and underground management and technical personnel is critical. Examples of mines currently transitioning include Chuquicamata (Flores & Catalan 2019), Geita and Tropicana.
2. **Scenario 2 – Underground mining below/adjacent to existing open pit**: This scenario would follow on from above after the open pit has been closed. This may include a continuation of small and intermediate scale orebodies resulting in localised mining below or adjacent to the slope, which could result in localised instability, or massive orebodies mined through block caving or sublevel caving, which could break through taking out large portions of the pit. Examples of such mines

include Palabora (Brummer et al. 2006), Ekati and Diavik (Jakubec et al. 2017), and Grasberg (Freeport-McMoRan 2020).

3. **Scenario 3 – Open pit mining through existing underground workings**: This would typically represent a scenario where historical high-grade mining took place, leaving behind voids that may or may not be backfilled. The scale increase of open pit mining equipment has made it possible to mine large open pits at low grade, making closed historical underground mines viable targets. Typical examples of mines include KCGM (KCGM 2020), Cripple Creek & Victor (Leichliter & Larson 2013; Butts & Hague 1998) and Porcupine (Henning 2016). This could also represent a scenario where, during the transitioning phase, underground mining took place prior to a new pushback being implemented. Examples of mines where this happened include Sunrise Dam. A variant of this type of scenario is where artisanal mining targeting richer veins takes place prior to mining the next pushback. An example of such a mine is Siguiri in Guinea.

There are several synergies in challenges faced within each of these scenarios, however, this does not transfer to the final risk and mitigation options to be considered. The following overarching controls will be introduced below:

- Geotechnical model management.
- Voids management.
- Water management.
- Geotechnical monitoring.
- Operational management.

These overarching controls will be used as a rudimentary framework to communicate industry experience and provide processes/techniques for risk management suited to the different scenarios.

2.1 Geotechnical model management

Although lithological, alteration or structural models may be available, it is important to understand that the construction requirements imposed on these models are driven by the mining method.

The resolution required to proactively design in an underground environment is much higher than that for the open pit environment. The added degree of freedom introduced by the excavation hanging walls and backs in the underground environment makes understanding the spatial location, geometry and orientation of contacts and structure fabric essential. Interpreted geological contacts and boundaries moving only a couple of metres can result in significant changes in ground support requirements, which, in areas where changes in rock type cannot be readily observed by operators, may result in a safety incident.

In contrast, open pits require an understanding of geology over a much larger rock mass volume. Final pit walls are often located in completely different rock types than what the ore is hosted in. The orientation and continuity of large-scale structures can have a significant impact on the long-term stability of a design. A collapse, taking out open pit ramp infrastructure, often result in force majeure, whereas in the underground environment it is possible to regain access.

One exception to the rule is the ever-increasing footprint and depth associated with the modern, cave mining methods. Once the cave has broken through to surface, the crater itself represents a very deep and steep open pit scenario. The sheer scale of the modern cave and the final excavation warrants a more regional understanding than what would typically be done for a smaller scale underground mine. Flores & Karzulovic (2003) compiled a guideline for geotechnical characterisation, which discusses methods for the definition and characterisation of the main geotechnical parameters. It provides a comprehensive view of the methods, however, the focus is on porphyry copper deposits transitioning from open pit to caving.

The following section deals with some aspects that need to be understood and considered for the specific mining scenario.

2.1.1 Lithological model

The performance of a rock unit within one mining scenario does not guarantee similar performance under different mining conditions. Geometrical and orientation changes in the overall geological package can introduce biases within the unit.

For example, at Sunrise Dam gold mine, the main rock types are andesites and mafic units. While mining the open pit, the performance of these rock types were very similar and the scale of instabilities observed were limited to bench scale, mostly along the crests (Booth & Hamman 2007). Once the mine progressed to underground, the mafic was not intersected that often, however, the blocky nature of the rock mass did necessitate a change in ground support and mining activities where it was intersected.

2.1.2 Alteration model

Alteration is usually well defined in close proximity of the orebody, and not as much in the host rock. In the open pit scenario, how the level of alteration impacts the integrity of a rock type, generally becomes better understood as the pit matures towards end of life. Unless alteration introduces a significant change in rock mass conditions, the varying levels of alteration will typically be catered for in the design.

The large-scale of open pits, compared to local changes in alteration, and the impact of blasting on the slope will often mask the initial signs of changes in the performance of the altered rock mass. Transitioning from a large open pit to underground, or mining (pit or UG) near existing underground voids, will introduce elevated stress conditions. These conditions will manifest first in rock masses weakened by alteration.

For example, in Cuiaba Mine the alteration of the schistose host rock was not well understood until such time that the deeper underground drives located in close proximity to the stoping suffered induced stress damage (Costa et al. 2019). Once the different types of alteration were defined, demarcated in space and correlated to damage mapping done in the underground drives, it became apparent that the zones in the highly altered schist were more susceptible to rock mass damage due to mining-induced stress.

2.1.3 Structural model

Large-scale structures play a major role in hard rock, large-scale, open pit failures. As such, the degree of certainty on the continuity and condition properties of such a structure is much more important from a strategic, open pit, design perspective than underground, where local, tactical, design changes can usually be implemented without a major impact to the mine plan. Since portals are often placed within completed pits, the long-term performance of these known structural mechanisms can impact portal, underground infrastructure and access ramp placement.

For example, the Boston Shaker shear in the northern wall of Tropicana gold mine necessitated several design changes to deal with the potential production impact from a failure along the structure. Since the underground mine has been started, this structure has been intersected by the drives and has not caused any disruption. Based on the current understanding, it is anticipated that in the larger stopes, some dilution will occur due to the structure (Figure 1).

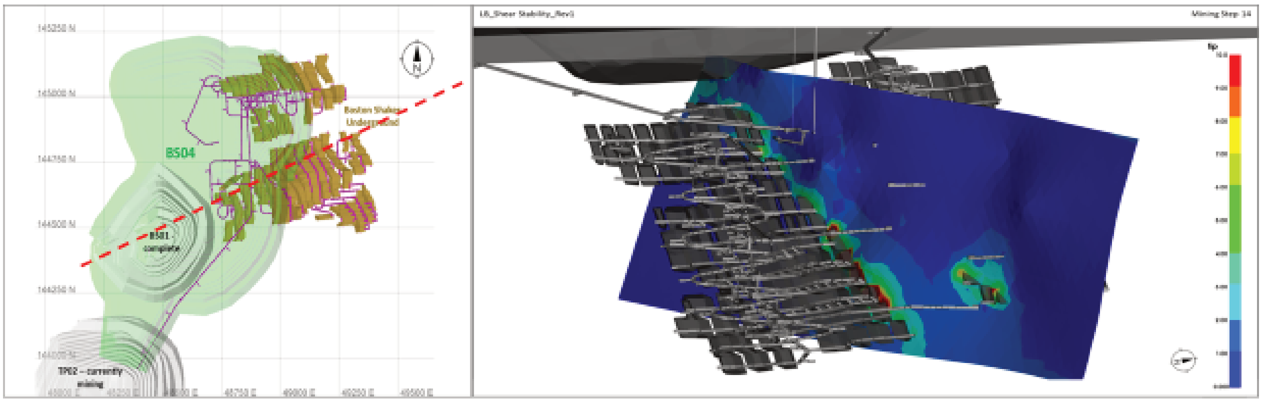

Figure 1 **Example of a large structure impacting active pits and planned underground mining**

2.1.4 Rock mass model

The one main difference between open pit and underground mining is the classification of rock mass data. Each method requires specific rock mass characteristics input, which leads to practitioners simplifying face mapping and logging processes to suit the preferred classification method. This introduces bias in the rock mass characteristics and makes a particular system more applicable to certain problems. Although it is good practice to use at least two classification systems, in reality, this is not often the case on an operating mine. As such, rock mass characterisation and classification data from open pits and underground mines are often not transposable. In the open pit environment, the preferred classification system used is geological strength index (Hoek 1994), whereas in the underground it will be rock mass rating (Laubscher 1990) for the cave mining types and Q (Barton et al. 1974) in the rest. The methods suggested by the ISRM (Ulusay & Hudson 2007, 2016), that deals with the rock mass characterisation and rock testing, is universal and has the capacity to cater for all the classification methods; hence, can be transferred between open pit and underground.

Furthermore, changes in material and structure properties within a rock unit, in particular where there is a difference in stiffness, will impact the behaviour in bordering excavations. In scenarios pertaining to the orebody, where the orebody may be stiffer than the host rock, or vice versa, the excavations and pillars will behave differently and even markedly pending the assigned stiffness.

For example, at Palabora, Brummer et al. (2006) demonstrated that the active instability in the north wall was most likely controlled by the pervasive joint sets, which formed wedges that daylighted into the cave region below the pit. Their finding was that the draw of ore in the cave zone was undermining the north wall, thus having direct control on the movement being experienced in the north wall. Even though faults were present, their analyses found that the joint sets were the controlling mechanism. Substantiating this finding meant having access to ta comprehensive rock mass model to use in the construction of the numerical model.

2.1.5 Hydrogeological model

In general, hydrogeological models within an underground mining environment will not have a similar level of detail as for an open pit. Understanding compartmentalisation and knowing where water-bearing structures and water retarding structures are located in and around the orebody are essential from an underground perspective.

The volumes of water to deal with from groundwater and surface runoff are usually much more significant in the open pit environment, thus a comprehensive understanding of how the water management fits into the production schedule is critical. Therefore, where any direct connection exists between underground excavation and the open pit, the underground will be at risk of flooding. Underground voids also complicate the prediction of water levels in the open pit, which impacts slope angles, but if well understood, can also provide an opportunity for more effective depressurisation resulting in potentially steeper slopes.

2.2 Voids management

This section deals with the planned/existing excavations and nearby voids that may be present. The main types of underground voids likely to be intersected by open pit mining methods are shafts (winzes), drifts (drives/ramps), service excavations and stopes. These underground voids may have been backfilled with material from the surface or underground. Timbers and metal rails are commonly found in the more historical voids, which can impact plant conveyor belts if fed into crushers.

Underground voids vary in size depending on the type of underground working. Drifts and shafts can range from less than one metre squared, or diameter, up to several metres. Stopes can be the most variable in size and geometry, ranging from narrow tabular stopes of a couple of metres to massive stopes of up to several tens of metres. Stopes and shafts have the highest risk potential for open pit mine operations due to the significant vertical extents.

Underground voids represent significant hazards to personnel and equipment operating in open pits. This includes areas where voids have intersected the pit surface or are close to intersecting it as demonstrated by De Beer (2015), Henning (2016), and Bar et al. (2018). The hazards include, but are not limited to:

- Sudden and unexpected collapse of the crown between the underground void and surface.
- Slope instability where stoping voids intersect the open pit perimeter or are located below the toe.
- Increased rockfall risk where voids act as catalysts for unravelling berms higher up.
- Personnel and/or equipment falling into unfilled or partially filled underground voids.
- Mobilisation of fill into adjacent voids, causing loss of integrity in rock mass.
- Loss of explosives from charged blastholes that have broken through into the underground voids.
- Overcharging of blastholes where explosives have filled voids connected to the blasthole, resulting in fly-rock, deflagration of explosives, or cut-offs with adjacent blastholes.
- Exploration drilling hazards where compressed air used to discharge rock chips can cause projectiles to dislodge from voids connected to the drillhole and impact personnel or equipment.
- Reserve uncertainties where the volume of ore extracted during previous mining may not have been well documented.

As such, it is important to accurately locate and survey existing voids, develop a suitable design to address the impact of the voids, and to compile a package of procedures and standards to deal with the void management risk on the operation.

2.2.1 Void geometry surveys

Accurate void wireframes are essential to manage the risk in designing and mining bordering excavations. Whether the designer is dealing with open pit or underground voids, which may or may not have accurate reliable surveys, it is important to appreciate that any 'known' geometries can change with future mining activities and could have changed in the past.

Several techniques (e.g. cavity autonomous laser survey, seismic surveys, geophysics and unmanned aerial vehicle drones) are available to confirm excavation size and geometry, providing evidence how it changed. This offer insight into the underlying mechanism, and how external drivers interacts to influence void migration.

2.2.2 Open voids

Old historical workings will likely consist of numerous open voids, ranging in size from small development drives to large stopes (Figure 2). More modern mines may have filled stopes, but the development and auxiliary excavations will still consist of open voids. These voids represent the worst-case scenario in the design and operation of an open pit (or alternate underground mine). In order to deal with this risk, the designer/practitioner needs to understand what type of voids may be present and where they are located.

Figure 2 Example of a large open void from historical mining

Very often, the pit slope can be mined safely through or adjacent to voids, due to the relatively small size of the voids compared to the overall slope. Although the void in the final slope may be stable, the portion being mined through in the pit floor presents a challenge in stabilising to enable equipment to access the area. Here, the crown pillar geometry plays a major role in stability. The challenge is to drill and blast the crown and collapse it into the void, while not posing a risk to the equipment and personnel having to traverse the area. This is a fairly simple exercise for drifts and narrow, flat-dipping stopes. Where larger, bulk stopes are present, the stable crown required often exceeds the maximum drilling depth for blastholes, making the filling of such stopes a technical complexity with major logistical difficulties.

2.2.3 Backfilled voids

The material used to backfill voids can range from loose rock to cemented fines, typically from mine tailings. Open voids in an active open pit are typically filled with waste or mineralised material blasted into the void, and pending the size of the void, this material may still experience some settlement as it consolidates under its own weight and open pit traffic.

Hydraulic fill has been used extensively in the past from as early as 1929 (McLeod 1992). It is a fine slurry reticulated into the underground stopes, which forms a compacted fill after the water has drained. There are several case studies dealing with mud rushes that have occurred after stope bulkheads failed, which highlights the inherent risk associated with historical mine stopes where hydraulic fill could still have a high level of saturation.

Cemented paste fill was used the first time in the 1980s at the Bad Grund mine in Germany (McLeod 1992). The addition of cement provided a means to hydrate the material and added to the strength and stability of the fill material. There are several examples in the industry where filled cemented stopes has been mined through and proved to be stable at bench scale (>30 m).

There are, however, a number of scenarios under which the fill material can be mobilised or squeezed out. This can be because of interaction between the underground void and the load imposed by the pit slope, or due to saturation and/or degradation of the fill material itself.

2.2.4 Crown pillars

The volume of rock between two adjoining voids is usually called a pillar. In the case where an open pit void is adjacent to an underground void, this pillar is called a crown pillar. The crown pillar is typically a mineralised rock mass, demarcating the ore that must be kept in situ to ensure long-term stability and to eliminate water ingress into the lower excavations.

Crown pillars are generally designed for a specific mine design scenario, and the design is usually for the final geometry (Carter 2014). When actively mining through the voids, crown pillars are formed below the floor between the open pit and underground voids, and the size and geometry of these crown pillars will change with each blast. This dynamic change in the crown pillar, due to the removal of rock mass material from mining or vibration shakedown, ultimately impacts the integrity of the crown pillar and presents a significant hazard to the mining operator.

As the crown pillar changes, so will the potential mechanisms that can impact the crown pillar or the surrounding voids or the pit slope. There is therefore a big onus on the designer/practitioner to manage the risk on the changing geometry of crown pillars.

The size of the crown pillar is also a significant contributor to the selection of transition depth from open pit to underground. The deeper an open pit, the higher the stress in the crown pillar, which increases the required thickness which impacts the project economics. The shallower an open pit, the more ore is mined underground but the thinner the crown pillar. Crown pillar stability characteristics should preferably be well-researched before deciding on the depth of transition.

2.3 Water management

As mines get larger and deeper, the regulatory authorities in most countries place increasingly tighter controls in the evaluation and management of water. Mining companies recognise that the sustainability of their businesses is, amongst other factors, dependent on the efficient management in the exploration, extraction and processing of mineral resources, including sound water management practices. In response, all mines should incorporate groundwater and surface water management programs at all stages of the mining cycles, and onwards into mine closure.

This section will focus on the requirements for stormwater and flood control management, which can be applied in open pit and underground operations where workings are linked to existing open pits, or open pits overlying underground operations, posing a risk of potential water inrush and inundation to the current mining operations.

The factors that need to be considered for the design of an appropriate water management system vary according to the regional and local hydrogeological setting, the mine plan, and local geology. Key components of water management include:

- Development of a conceptual hydrogeological model of the mining area.
- Estimates of groundwater inflow rates to the mine and subsequent dewatering rates to achieve depressurisation and maintain dry working conditions.
- Assessment of surface water runoff and dewatering rates based on storm design criteria.
- Installation of groundwater monitoring systems to monitor groundwater levels.
- Installations of dewatering infrastructure compatible with dewatering requirements.
- Maintenance of dewatering systems.
- Surface water management controls to minimise inflow of stormwater.

2.3.1 Climate

Understanding the climate and how the seasonal changes can impact operations is a key part of open pit mining. Knowing over which period/s the rainy season will occur and the expected rainfall intensity are important aspects in open pit mining since the design and construction of sumps and pumping infrastructure is largely based on understanding the local and regional precipitation of the area.

Since intense precipitation and thunderstorms pose safety concerns it can hamper open pit operations, thus seasonal factors are to be considered in the mine schedule. It often pays to understand precipitation on a storm scale, not just a calendar month or typical seasonal variation scale as these can hide real problems or overestimate risk.

Direct ingress of precipitation into underground mines do not generally occur, however, there are several cases where runoff was channelled through a holing into underground workings, resulting in flooding.

A case study is the crown pillar of a narrow, sub-vertical orebody that daylighted in the Cleo open pit, was mined during the rainy season. The breakthrough into the pit floor resulted in a 3 × 15 m holing. In the grander scale of things, this was a very small holing, however, the subsequent rainfall during a high-intensity event resulted in a flooded underground mine. Previous analyses of the latest seasonal trends showed it would be unlikely to have such a big rainstorm, however, when assessing the overall climatic trends, the rainstorm could be considered a typical 1:50 year event. Even though the holing was on a large flat area halfway down the pit, the amount of rainwater that was carried by the main haulage ramp was enough to break the water diversions in place and ingress into the underground.

2.3.2 Surface runoff

Water is shed as surface runoff whenever rainfall reaches the ground faster than it can infiltrate the underlying soil, and there is a surface gradient for flow to occur. Factors affecting the volume and rate of surface runoff during a storm event include the intensity, duration and temporal pattern of the rainfall and the infiltration rate of the generated runoff. Surface runoff is a major cause of soil loss by erosion, and thus it can impact depositions of finer materials.

Understanding the surface runoff and volumes is essential to the design of infrastructure to manage water runoff at mine sites such as culverts, diversion structures, sumps, pumping systems and catchment dams. These stormwater management systems play an important role in maintaining access routes and acceptable pit floor condition during wet periods. The design for the overall surface water management system should start with the prevention of surface water inflow from outside the pit boundary into the mining area. This is typically done by the installation of surface water diversion berms and culverts to divert water away from the pit. Where possible, rainfall falling within the pit shell should be channelled through collection trenches and directed to pit bottom sumps for transferring to surface. This process is usually accomplished using the pit sump pumping system, either via direct (single lift) pumping to surface or via a stage-pumping system, where staging stations are spaced with consideration to the manufacturer's pump performance curves.

Surface runoff is typically more prominent in open pit mining and as such, any underground excavations within the slope, or access portals/vent holings within the pit void, will be at risk from runoff entering the pit void.

2.3.3 Site-wide water balance

A comprehensive water balance model encompasses all the water cycles on a mine site as well as waters affected by the mine site as inter-linked components. The typical components to consider for a site-wide water balance are presented schematically in Figure 3.

The overall principles are similar in terms of how to manage in-pit water during mining of an open pit and after mining is completed and an underground access from within the pit is planned.

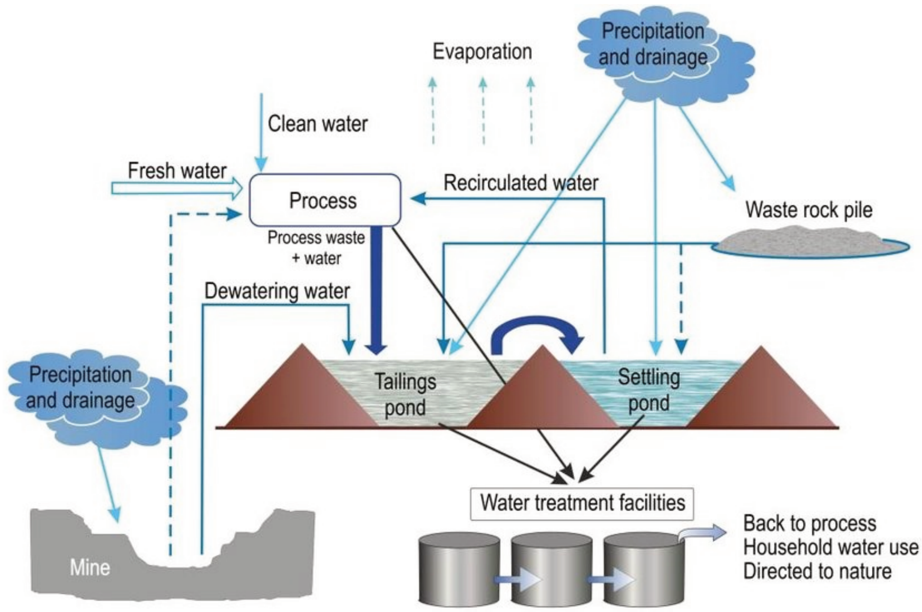

Figure 3 Example of different mine water sources and streams (after Kauppila et al. 2011)

When there is an underground mine that connects the open pit to the underground either by a portal/ramp, there are a few more considerations:

- The stormwater and groundwater infiltration to the open pit will still need to be managed within the open pit to prevent spill over to the underground workings.
- There is an increased risk of flooding the underground workings if water is not contained and pumped out of the open pit.
- The open pit closure plan cannot be completed until the underground mining is complete.
- The ingress portal/ramp to the underground must be located sufficiently above the pit floor to prevent flooding from within the open pit.

In certain scenarios, mining companies have intentionally allowed/directed stormwater through the open pit to the underground, reporting to purpose-built pumping stations. This was to allow for the uninterrupted mining of the open pits above the mined underground workings. This option does require more long-term water management after the open pits were completed. It also places restrictions on other underground activities such as paste fill.

2.3.4 Flood management

Flood management considerations include the risk of flooding at the mine site and the associated hazard to mine site personnel and infrastructure. It is essential that mine managers have, and understand, data on precipitation and flooding probabilities for their mine site. Potential hazards, flood damage and interruption to mining must be evaluated for a full range of flood events. Flood risk assessment is used to determine the spillway capacity of water storages, the freeboard of tailings dams and the discharge capacity of diversion channels as well as the open pits and underground mines.

Best practice principles for managing flood risk and flood hazard on mine sites include:

- Evaluating flood behaviour, peak flood discharges and peak flood levels across the mine site for a range of flood events (i.e. flood risks). Such 'flood studies' can be technically demanding and are best left to experienced hydrologists.
- Identifying mine site elements that the various flood events may affect and impacts.

- Evaluating the associated hazard to these elements. Hazard 'impacts' may range from nuisance (delayed access while road crossings are flooded), to economic (lost production) or ultimately, a threat to mine site personnel safety or lives.
- Developing a comprehensive and appropriate risk management plan for flood hazards. Four broad groups of flood management measures should form part of the plan:
  - Structural works, such as culverts, sand berms, causeways and river diversions.
  - Mine site planning considerations, e.g. locating key buildings and infrastructure in less flood-prone areas of the site.
  - Building controls, e.g. minimum floor levels so buildings and infrastructure that may flood are designed accordingly to minimise the likelihood of water influx.
  - Emergency measures, such as flood warning and evacuation plans.
- Flood risk management plans are specific to each mine site and integrate the four measures listed above. The expected life of mining operations is a key factor in shaping the risk management plan.
- Each mine site should have a signed off Flood Management Plan in place. This plan should provide the protocols with regards to emergency procedures such as communications and evacuation procedures to include all workplaces such as the mine, office, workshops, tailings dams, etc.
- The Flood Management Plan and emergency evacuation plan must be visible and communicated to every employee on the mine.

For example, at Obuasi in Ghana, several open pits were mined along the outcrop of the orebody, with a large crown pillar in place between the pit and historical underground workings. Illegal miners (galamsey miners) constructed a man-size shaft between one of these pits into an abandoned drive. During a large rainfall event, the pit was flooded from the accumulation of water from various surface source and subsequently the water entered the mine through this shaft. In these scenarios, bulkheads and pumping infrastructure need to be designed for water pressures and flows that may arise during the life-of-mine (Figure 4).

Figure 4 Example of an ageing bulkhead where the water level has risen past the drainage valve

2.4 Geotechnical monitoring

It is important to understand the failure mechanisms, or modes of failure, for both the immediate and long-term excavations and their impact upon one another in order to understand the potential impact to both equipment and personnel. This will determine what the monitoring requirements in terms of accuracy, resolution and frequency will be and to help decide the intervals at which the monitoring data needs to be collected, checked and reported on. These factors directly tie into the site-specific trigger action response plans (TARPs) that need to be compiled. TARPs may have triggers based on millimetres of movement in cases where movement dictates an issue, or triggers may be related to rainfall intensity or volumes in a sump at which point personal would move to a known safe location. Good guidelines on the design of monitoring plans can be found in Dunnicliff (1993) and Sharon & Eberhardt (2020).

2.4.1 Long-term slope stability

Open pits are designed for a certain life-of-mine during the feasibility study, and during operations, these design parameters are pushed further to optimise extraction. The design will seldom cater for the potential of having an underground operation that will be utilising the existing pit for access to the deeper orebodies.

The long-term slope stability now becomes a critical part in maintaining access to the underground as most mines that transition from open pit to underground will only have access from the pit. As such, the task of monitoring the existing open pit slopes, waste dumps and long-term stockpiles will likely fall onto the underground technical team, who have little appreciation of the slope stability hazards and pitfalls in monitoring open pit slopes. Therefore, providing the team with a means to appreciate and understand the importance of long-term monitoring of the slopes is critical. An additional complication is that open pits often use evacuation with subsequent re-establishment as a control based on monitoring data. Underground mines from in-pit portals may not be able to evacuate and may have to establish an ex-pit emergency exit for personnel should slope instability prevent portal access. The need may also arise for large excavation equipment to be contracted for clean-up operations as a site may no longer have open pit equipment once the pits are depleted. In general, the cost of managing a slope instability above a portal is much greater than the cost of the same slope instability only in an open pit.

For example, two large, flat-dipping wedge intersections were identified and analysed in the Betze Post mine (Rose & Hungr 2007). The larger wedge ultimately failed eight months after mining in the open pit was completed.

2.4.2 Ramp integrity

Access via ramps is important for open pit as well as the underground, where the mining method, economical constraints and orebody geometry allow for access via the existing open pit ramps. While the operating width required for an underground-only operation will be considerably less, there is still a need to understand, inspect for, and monitor the mechanisms along the length of the ramp. Normally, open pit ramps will require more maintenance during the rainy season as surface runoff can introduce significant scouring; a function often neglected once the open pit operations cease. This needs to be considered in the water management strategy as this will be impacted as well.

2.4.3 Portal access

Portals are usually established at the deepest part of the open pit, in close proximity to the targeted orebody. This is a high exposure area with all underground traffic passing through a small constrained area. It is often also the only access point for equipment, thus the financial risk associated with losing access through the portal is significant. In locating portals, the long-term stability of the targeted bench/slope and the surface runoff during rainfall events need to be considered and adequate water storage allowed for in the event of storms.

2.4.4 Laydown areas

Underground operations prefer to establish their laydown areas in close proximity to the portals and very often, this will be beneath the highwall next to the portals due to the limited space available. This poses a significant rockfall hazard and the exposure of personnel and equipment is usually much higher than in typical open pit operations. In establishing these areas, a comprehensive review needs to be conducted on the rockfall hazard and risk. This will require rockfall data from the open pit operating years to be properly collected and stored, and then communicated and transferred to the underground team.

2.5 Operational management

Operational management are the key to firstly develop working relationships between the workgroups and holistically review the site procedures and to integrate, in many circumstances, one set of systems or procedures in which the interactions occur, be it monitoring, traffic management and blasting activities.

It is important that the transfer of all forms of information is effectively communicated between workgroups for both the open pit and underground operations. This is a big challenge as mines expand/or transition to underground operations and the site personnel generally do not initially integrate well, primarily due to the lack of understanding of each workgroup's roles. In addition, the two workgroups commonly have different office locations and rely on emails for key communications. For this reason, it is important that combined meetings occur on a daily basis to directly deal with daily interaction matters that directly impact one or both the workgroups. This sets the focus on addressing the key operational hazards such as those associated with drilling and blasting activities, drilling/mining breakthrough, rifle holes and water management.

2.5.1 Knowledge transfer

This is arguably one of the most important tasks; that of the transfer of all historical and institutional knowledge pertaining to a mine. This instance excludes any specific geotechnical information, however, the items captured here are equally important from a geotechnical perspective.

In open pits, there is usually an intricate history where waste has been used to fill in depressions and raise ramps on the surround crest, and how water has been managed through intermediate sumps on wider berms and buried pipelines below ramps.

Underground workings have similar challenges with stopes and auxiliary excavations that were mined different to what was planned and possible to survey.

2.5.2 Traffic management

Although traffic management is largely a function managed by the operations or mining manager, there are several aspects that require geotechnical oversight. The communication of existing hazards along the ramps, training on geotechnical hazard identification, induction to reporting of rockfalls, cracks and support fatigue/failure, and training on alarming and associated procedures, rests with the geotechnical department. All these aspects contribute to the safe usage of the ramps and accesses in the mine.

2.5.3 Blasting

The design and detonation time of blasts in concurrent operations is largely a safety consideration. Exploration and grade control drilling often connect open pit and underground workings and are called rifle holes. Explosive gases and forces can push projectiles at high velocity between adjoining excavations, causing risk to personnel and equipment.

Open pit blasts are significantly larger in volume, charge weight and vibrations than those in underground mines. This can result in shakedown of loose material in stopes or drives, including freshly applied shotcrete, at greater distances from the blast compared to what is typically experienced in an underground mining scenario. As such, it is important to collect blast vibration data when operations are within 400 m of each other to establish site-specific specifications that will assist with decisions on when to remove personnel during blasting activities. Examples of direct hazards from blast initiation include rifle holes, gases, rock mass failure and small scats falling from tunnel backs or side walls. A single near-field blast system using a single uniaxial geophone is sufficient to collect the required vibration data to use to effectively and make timely decisions on personal movements for both the operations and to refine as more data is collected and interpreted.

Although underground blasts are smaller, they tend to occur in close proximity to the final pit slope, very often breaking through into the pit void, which can result in rockfall or localised failure. Underground blasts are usually designed for a solid rock mass and the mining engineers responsible for the design would not be proficient in a design where the blast adjoins a free face on a bench, which often results in the violent projection of material into the pit. It is the author’s experience that blast design and implementation crews do not perform well when carrying out work across applications, i.e. underground blasters perform poorly in open pits and vice versa (this is even evident across commodities) due to the different conditions and blasting requirements. It is better to have dedicated blasting crews familiar with the mining method.

Blast vibrations impact both operations in different ways. This is primarily due to the magnitude of blasting activities. Open pit blasts can be significantly larger in both volume and size to many underground operations with more tabular orebodies, however, smaller but more frequent.

2.5.4 Competency development

Mines transferring from open pit to underground (or vice versa) have the added litigious constraints to maintain the workforce. This requires retraining of operators and technical personnel alike. Within the geotechnical field, there is potential to transfer practitioners from open pit to underground providing that the complexity of the mining and geotechnical design can be managed.

The transfer for geotechnical practitioners must include a development plan over at least a two-year period to bring practitioners up to speed with technical and operational requirements for the new mining method.

3 Conclusion

Collectively, the considerations discussed in this paper demonstrate the need to fully understand and account for the complex interactions that can develop between open pit and underground mines. Considering that there is a finite amount of material that can be mined by open pit, there is an inevitable transition to underground and the success of this transition is anchored in understanding the interaction between existing and planned mining.

Furthermore, there is a need in the industry to collate learnings into a comprehensive guide for practitioners to ensure that the geotechnical risks are identified an aptly managed to ensure return on investment and maintain the credibility of the industry.

Acknowledgement

The authors thank peers and colleagues for their input in this paper as well as the management of AngloGold Ashanti for the opportunity to present this work.

References

Accreditation Board for Engineering and Technology 1987, *Fifth Annual Report*, Washington, D.C.

Bar, N, du Plessis, P, Nicoll, S, Welideniya, S, Ryan, C & McAllister, P 2018, ‘Risk management strategies for open pit mining through historic underground workings’, *Proceedings of 10th Asian Rock Mechanics Symposium*, International Society for Rock Mechanics, Lisbon.

Barton, NR, Lien, R & Lunde, J 1974, ‘Application of the Q-system in design decisions and appropriate support for underground installations’, in M Bergman (ed.), *Proceedings of the International Conference on Subsurface Space*, Pergamon Press, New York, pp. 553–561.

Bieniawski, ZT 1992, *Design methodology in rock engineering: theory, education and practice*, Balkema, Rotterdam.

Bieniawski, ZT 1991, 'In search of a design methodology for rock mechanics', in E Roegiers (ed.), Proceeding of the 32nd US Symposium on Rock Mechanics, Balkema, Leiden, pp. 1027–1036.

Booth, PA & Hamman, ECF 2007, 'Saprolites, structures and slope angles — applying site-specific geotechnical and mining knowledge to achieve the final design', *Proceedings of 6th Large Open Pit Mining Conference*, Australasian Institute of Mining and Metallurgy, Carlton, pp. 25–33.

Brummer, R, Li, H & Moss, A 2006, 'The transition from open pit to underground mining: An unusual slope failure mechanism at Palabora', *Proceedings of International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering Situations,* The Southern African Institute of Mining and Metallurgy, Johannesburg, pp. 411–420.

Butts, RA & Hague, PR 1998, 'Locating dangerous historic mine workings in the cresson open-pit mine with the aid of ground penetrating radar', *Proceedings of 11th EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems*, European Association of Geoscientists & Engineers, Houten.

Carter, T 2014, *Guidelines for use of the scaled span method for surface crown pillar stability assessment,* Golder Associates, Toronto.

Costa, LCB, Padula, RC, Pimenta, LMV, Pereira, RS & Peterle, DT 2019, 'Support and reinforcement damage initiation and design adjustments in a deep mine environment - case study: Cuiaba Mine, Brasil, MG', *Proceedings of the Ninth International Conference on Deep and High Stress Mining*, The Southern African Institute of Mining and Metallurgy, Johannesburg.

De Beer, CJ 2015, 'Mining an open pit over and through old sub-level caving operations at Kwaggashoek East Open Pit, Thabazimbi iron ore mine', *Proceedings of the International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering,* The Southern African Institute of Mining and Metallurgy, Johannesburg.

Dunniclif, J 1993, *Geotechnical Instrumentation for Monitoring Field Performance*, John Wiley and Sons, New York.

Flores, G & Catalan, A 2019, 'A transition from a large open pit into a novel "macroblock variant" block caving geometry at Chuquicamata mine, Codelco Chile', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 11, pp. 549–561.

Flores, G & Karzulovic, A 2003, *Geotechnical guidelines for a transition from open pit to underground mining*, International Caving Study ICS-II, Task 4.

Freeport-McMoran, 2020, *Indonesia Grasberg*, viewed 30 January 2020, https://www.fcx.com/operations/indonesia

Henning, JG 2016, 'Stability and access implications of open pit mining through old underground mine', *Proceedings of the 3rd International Symposium on Mine Safety Science and Engineering*, McGill University, Montreal, pp. 165–169.

Hoek, E 1994, 'Strength of rock and rock masses', *ISRM News Journal*, vol. 2, no. 2, pp. 4–16.

Jakubec, J, Woodward, R, Boggis, B, Clark, L & Lewis, P 2016, ‚Underground mining at Ekati and Diavik diamond mines', *Proceedings of the 11th International Kimberlite Conference*, Lucara Diamon, Vancouver.

Kauppila, P, Räisänen, ML & Myllyoja, S 2011, *Best Environmental practices in metal ore mining,* Finnish Environment, https://helda.helsinki.fi/bitstream/handle/10138/40006/FE_29en_2011.pdf?sequence=4&isAllowed=y

KCGM 2020, *Voids: An ever present hazard*, viewed 30 January 2020, http://www.superpit.com.au/about/mining/

Laubscher, DH 1990, 'A Geomechanics classification system for the rating of rock mass in mine design', *Journal of South African Institute of Mining & Metallurgy*, vol. 90, no. 10, pp. 257–273.

Leichliter, S & Larson, D 2013, 'Geometallurgy for two recovery process operations: At Cripple Creek & Victor gold mine', *Mining Engineering*, vol. 65, pp. 29–33.

McLeod, A 1992, 'Mineral heritage oration, Arnold Black and hydraulic fill', *Proceedings of the Australasian Institute of Mining and Metallurgy Annual Conference*, Australasian Institute of Mining and Metallurgy, Carlton, pp. 17–21.

Rose, ND & Hungr, O 2007, 'Forecasting potential rock slope failure in open pit mines using the inverse-velocity method', *International Journal of Rock Mechanics & Mining Sciences*, vol. 44, pp. 308–320.

Sharon, R & Eberhardt, E 2020, *Guidelines for Open Pit Slope Monitoring*, CRC Press, Boca Raton, in press.

Ulusay, R & Hudson, JA 2007, *The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974-2006*, ISRM Turkish National Group, Ankara.

Ulusay, R & Hudson, JA 2016, *The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014*, Springer, London.

Whittle, D, Brazil, M, Grossman, PA, Rubinstein, JH & Thomas, DA 2015, *Determining the open pit to underground transition: A new method*, The University of Melbourne, Parkville.