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Mechanical-flow coupled simulation of a proposed multi-panel sublevel shrinkage

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Abstract

Sublevel shrinkage mining can be applied as a derivative of the sublevel caving (SLC) mining method. In this context, an otherwise conventional SLC approach utilises the continuous introduction of tipped rock backfill into the blasted void to assist in stabilising the hanging wall, footwall and sidewalls of the orebody while the mineralised zone is extracted. The shrinkage methodology is primarily suited for thick, steeply dipping deposits in strong rock with low caveability. Shrinkage projects have several advantages over conventional caving, such as reduced development waste haulage costs and lower surface environmental footprint. However, the shrinkage methodology also carries risks. One major risk factor is the potential for increased dilution due to the dynamic nature of ore and backfill mixing within the cave zone. Dilution might have a very significant impact on the project economics, although it cannot be quantified empirically due to the unique geometry, rock mass characteristics and mine design of each orebody. In this case study, Beck Engineering and Newmont Corporation have collaborated to investigate the feasibility of a sublevel shrinkage caving method using numerical techniques. This particular mining methodology and mine geometry is a unique case study for mechanical-flow coupled modelling. The main objectives of the simulation were to forecast hanging wall damage, rock mass stability at the critical excavations as well as ore recovery. The simulation required an innovative and unique implementation of the LR4-FS4 mechanical-flow coupled simulation framework to realistically simulate the complex physics involved. This paper discusses the complexities of the mine design, the novel simulation approach that was applied for the project, and a selection of the model results focusing on critical infrastructure stability and ore recovery.

Keywords: *sublevel shrinkage, flow simulation, coupled modelling, backfill, simulation aided engineering*

1 Introduction

Sublevel shrinkage (SLS) is a mining method primarily suited to thick, steeply-dipping or vertical orebodies within a strong and competent host rock of low caveability. Although relatively infrequently utilised, the SLS technique has been applied in Australia in the past (Mackay et al. 2014). SLS is also currently being implemented at a small number of sites worldwide, including Newmont's Subika Underground Mine in the Ahafo region of Ghana. In this particular case study, Newmont and Beck Engineering have investigated SLS mining as an extraction method for another gold deposit within Newmont's resource portfolio. The proposed SLS mine design is almost identical to a longitudinal sublevel cave (SLC). The main difference is the tipping of unconsolidated waste rock backfill into the top of the cave via a system of shafts and an open pit tip-crest. Within the SLS, tipped fill would flow dynamically within the cave column as further ore extraction and draw-down occur from the production levels. The extraction-style of SLS should be differentiated from shrinkage stoping and stoping under rockfill (SURF) given the much larger size of the SLS production cavities, especially the thickness, by the SLC-style of ring production blasting from parallel oredrives mined in retreat and by the fact that instability of the hanging wall and crown is expected to occur over a broad area of the orebody. The instability induced by a SLS mine is of a limited severity, given the inherently low caveability of ore deposits compatible with the SLS technique.

The tipping of backfill into the SLS cave serves several objectives. Firstly, the backfill provides a means of support to the walls of the production cavity and to a lesser extent the backs, thus limiting potential for caving-induced subsidence. This is especially important where strict management of surface subsidence impacts is required. Backfilling also provides a convenient means of disposal of waste rock generated by mining, such as development muck. Disposal of this material into the cave avoids some of the mining costs associated with rock haulage. It also minimises the environmental, logistical and financial impacts related to the construction of large waste dumps on the surface.

Although the tipping of waste into the void has some significant benefits, it also introduces risk. One major risk in SLS mining is dilution of the ore caused by preferential draw of tipped waste material through the cave flow column, which then reports to the production drawpoints and eventually the ore processing system. The likelihood of tipped fill dilution migrating through the cave column and to the drawpoints could be expected to follow similar behaviour to dilution in a block cave, which in that case depends upon the nature of the material, such as the particle size, strength properties as well as the fines content (Castro et al. 2022). Dilution would also depend upon the geometry of the shrinkage cavity and the resulting complexities of rock particle flow within the cave. The relative tonnages, schedule and location of production draw and backfill tipping can also be expected to significantly influence the dilution potential.

The physical complexity of the SLS mining method creates economic risk that cannot be quantified using generic empirical methods, given the unique characteristics of each mine. As such, numerical methods with dynamic flow-simulation coupling may be the best available tool to forecast the physical and economic performance of the SLS-type mining operations in quantitative detail.

2 Mine design and excavation geometry

Beck Engineering recently worked with Newmont to simulate a proposed SLS operation consisting of four independent mining panels. All panels are intended to be operated simultaneously. The geometries of the proposed mining zones are large and complex. The four panels collectively span a 2.4 km strike length of the mineralised zone and are each separated along strike by regional pillars in the order of 75 to 150 m in length (Figure 1). All panels are planned to be mined according to a longitudinal extraction strategy with an SLC-style continuous retreat, with 2.6 m long rings. The northern and southern SLS panels have a single direction, end-to-end retreat towards the centre of the deposit. The central SLS panels will both apply a centre-out mining approach, with dual end accesses. The depth of mining ranges from 50 to 725 m below surface, with high stress conditions and seismicity expected during the mine life.

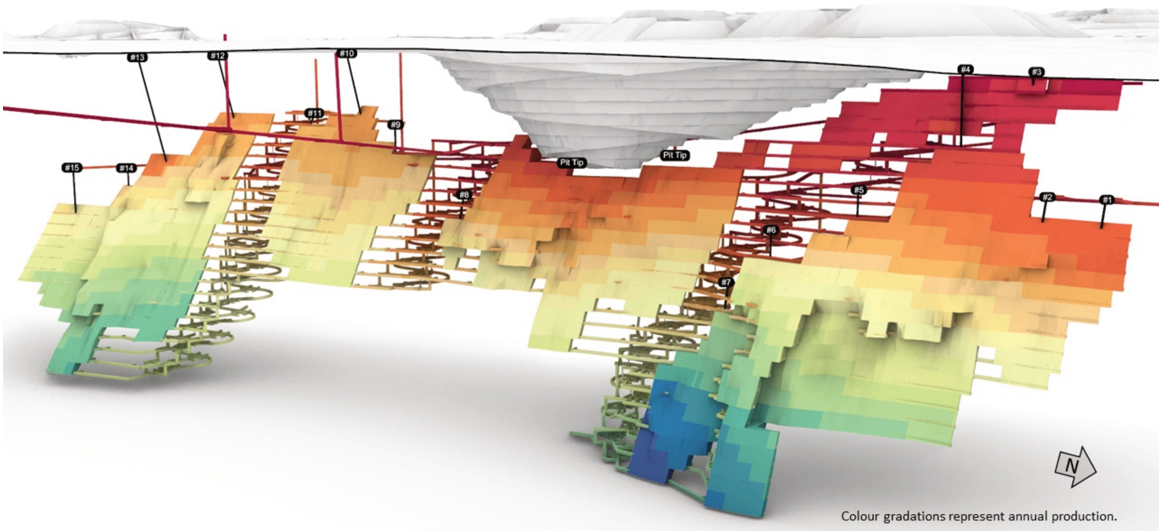

Figure 1 Excavation geometry of the proposed sublevel shrinkage operation with four panels

The mineralised extraction zones are all steeply dipping and range considerably in width, strike length and overall height. The mining zones are up to 80 metres in width at the centre and narrow to approximately 10 metres at the margins. The planned cave shapes created by ring blasting also contain numerous undercuts, crown steps, sills and funnel-shaped geometries, which stand to impede and complexify the flow of unconsolidated backfill material within the cave (Figures 2, 3 and 4). This will affect the successful recovery of ore as well as the ability of the tipped material to rill uniformly and to fully support the cave walls.

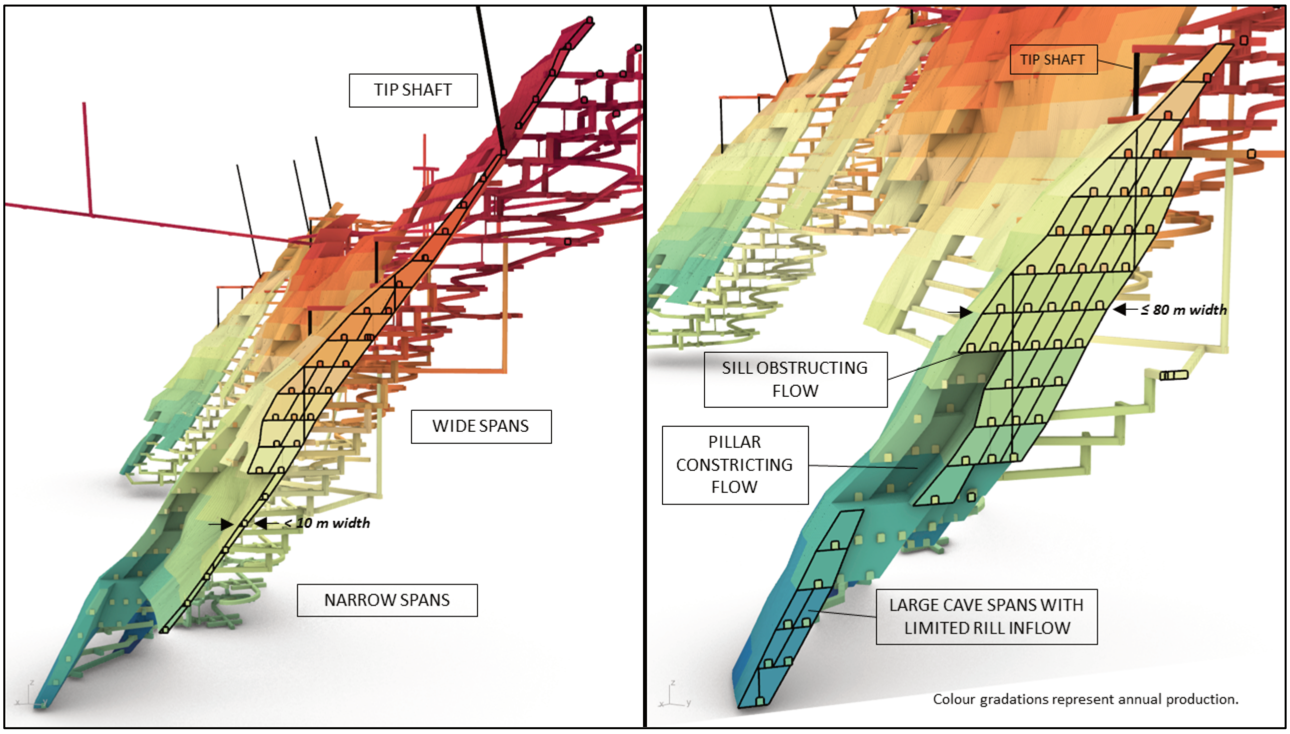

Figure 2 Clipped sections across strike showing the geometric complexity of the SLS panels

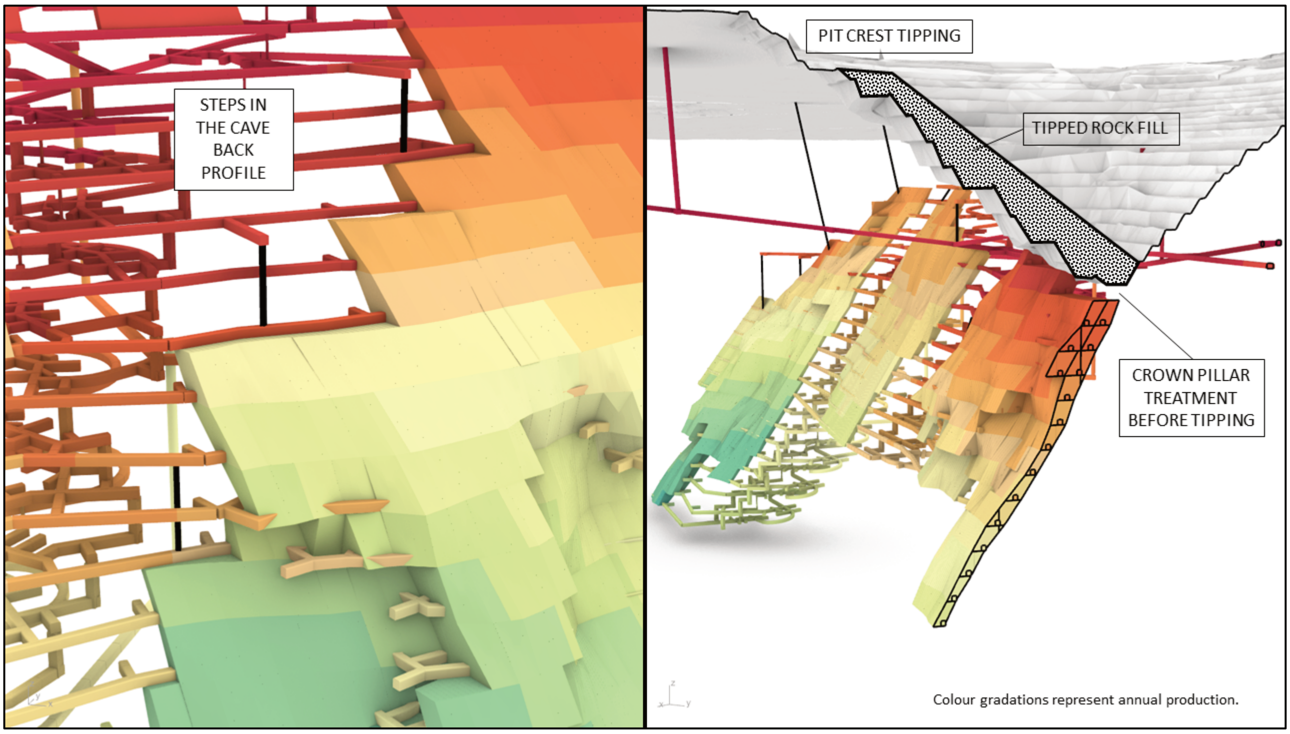

Figure 3 Perspectives of the geometric complexity of the SLS cavity and in-pit tipping scenario

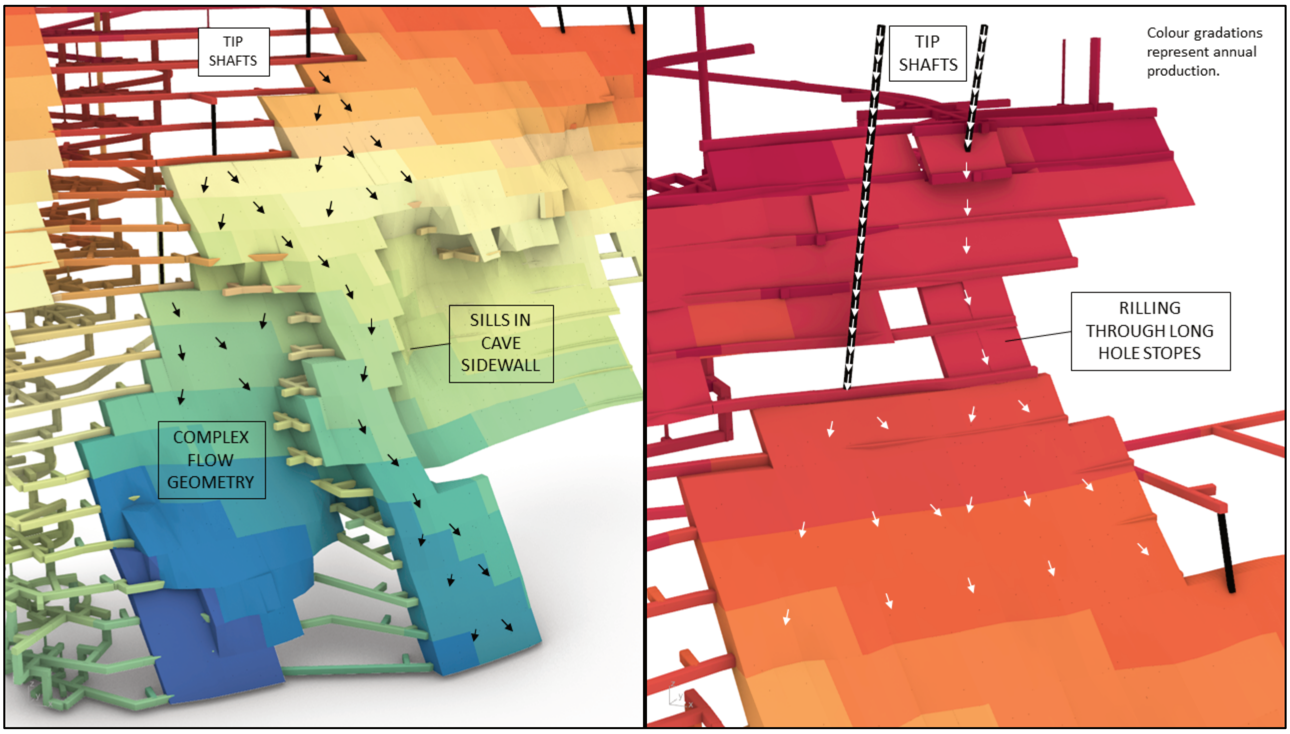

Figure 4 Examples of complex and constricted backfill flow paths through the SLS void geometry

Tipped backfill is proposed to be inserted into the cave via a system of 15 shafts, including both underground and surface tipples. A 500 m long tip-crest is also intended to be operated at the existing open pit, which overlies one of the caving panels (Figure 3). Due to the low caveability of the deposit and the limited rock mass damage forecast in the numerical model, it is planned to pre-fracture the crown pillar between the pit and underground production cavity using explosives. This will promote caving of the crown pillar such that an opening of sufficient width and strike length will form at the surface for tipping. This is crucial to avoid potential cave stall below the pit and ensure that the size of the unsupportable region of the hanging wall at the north and south ends of the pit will be minimised. Seven levels of narrow-vein open stopes are also planned above the northern SLS panel. Some stopes will have constant through-flow of tipped backfill material, acting as conduits for fill flow into the SLS cavity below (Figure 4).

The major accesses development of the mine is all located in the footwall of the deposit. Numerical modelling indicated a minimal risk of caving-induced subsidence or damage interaction with the production workings. However, some mine-critical development is necessarily positioned at least partially into the hanging wall, including several of the backfill tipping shafts, their tipples and the shaft access development. The position of some tipping infrastructure in the hanging wall of the orebody is necessary to provide direct access above the planned cave back for fill tipping. In most cases, the tipping shafts are either located on the surface or several sublevels above the cave breakthrough. However, some tipples are unavoidably located within one or two sublevels of the cave back design, and the long-term stability of these facilities requires detailed assessment and risk forecasting.

3 Numerical simulation methodology

The numerical modelling approach utilised for this project was strain-softening dilatant discontinuum finite element following the LR4-FS4 framework with a generalised Hoek–Brown yield criterion. The LR4 constitutive framework (Levkovitch et al. 2010) was applied in Abaqus to forecast the mechanical behaviour of the rock mass and geological structures. It included the 3D geometry of the mining excavations, sequenced in quarterly mining steps to capture the realistic stress path. The material properties of the model were assigned to the lithology domains of the deposit using the latest geological wireframes. The discontinuum formulation used cohesive (zero volume) elements to model discrete geological structures. These elements were free to dislocate, dilate and degrade in order to realistically capture the behaviour of the structures, including those influencing hanging wall stability. The entire structural model of the mine was included in the simulation without simplification.

The FS4 flow solver was applied for the flow domain of the simulation. The flow domain is defined as the volume of the blasted rings and open pit. FS4 is a physics-based particle flow simulation based on an open-source theory originally developed by Macklin et al. (2014) for the computer graphics industry and adapted by Beck Engineering for mine-scale flow simulation applications. FS4 allows the evolution of realistic cave phenomena at high resolution. It includes particle to particle kinematics and dynamics, and enables higher resolution of granular flow and cave maturation which can more realistically replicate complex cave behaviour, when compared to previous FE-CA coupled simulations.

This case study of shrinkage caving was a unique example of LR4-FS4 implementation. The planned mining method involves a combination of cave flow influencing processes which are very rarely simultaneously encountered in mining operations and which, to the authors' knowledge, have not previously been numerically simulated. Features of the simulation included:

- Longitudinal SLC-style orebody extraction.
- Introduction of waste rock backfill into the stoping voids, subject to controlled volumes and schedule.
- Backfilling via multiple shafts at various elevations and positions along the orebody strike.
- In-pit backfilling across a 500 metre-long tip-crest, linking directly to the underground flow zone.
- Complex flow of material across sills, adjacent crown overhangs and steps, through wide spans, narrow spans and also funnel-type geometries of the large-scale cavities.

The spatial scale of the mine, the geometric complexity of the production cavities and the various backfilling methods meant that the FS4 simulation was necessarily implemented according to a simplified coupling framework. Specifically, the flow domain for each extraction step was limited to the geometry of the blasted SLS rings and open pit and this geometric shape was exported to FS4. The FS4 definition of granular particles representing blasted in situ rock was then created within the limits of the production rings. Particles were removed from the production cavity at the drawpoint locations based on the scheduled ring tonnages for each quarterly mining period. New particles representing backfill were then added to the simulation by spawning them at the top of the flow domain in controlled volumes. For fill introduced via the shafts, the particles were spawned at the approximate position where the shaft would breakthrough into the cave back. For the in-pit tipping, particles were spawned uniformly, initially, along the strike length of the tip-crest.

As new particles were spawned to represent backfill, the flow evolution was allowed to settle within the new excavation geometry. The volume representing the newly settled muck pile was then exported back to the FE mechanical solver as a wireframe. This was effectively a one-way coupling to define the muck pile-supported and unsupported (i.e. airgap) portions of the stoped cavity. Confinement of the hanging wall was simulated in the model following the realistic rilling limits of the waste fill material and based on the scheduled draw and fill volumes. This process was repeated for all excavation steps in the simulation.

A series of initial model runs following this approach were conducted to test and optimise the initial assumptions regarding the backfilling volumes for each tipping shaft and the pit. The intent of the test runs was to optimise the fill volumes for each mining step in the model and ensure that the final model maximised the hanging wall support provided by the rilling cave material. This approach assumed choke-feeding of the shrinkage cave with the maximum possible backfilling volume. The initial simulated fill schedule was set to match 100% of the total draw. The quantity of fill distributed to each tipping point was initially estimated by summing the scheduled draw volume from all production rings below the tipping point within half the lateral spacing to the adjacent tipping points in each mining panel during each mining period. In order to avoid the spawned fill particles 'surging' into the flow domain in large quantities, the quarterly mining steps were broken down into one excavation step and nine fill steps. This evenly distributed the fill particles into the flow domain over time. The rilling of the waste fill was reviewed after each test run, and additional fill particles were manually assigned to the tip points until a desirable fill volume was achieved (Figure 5).

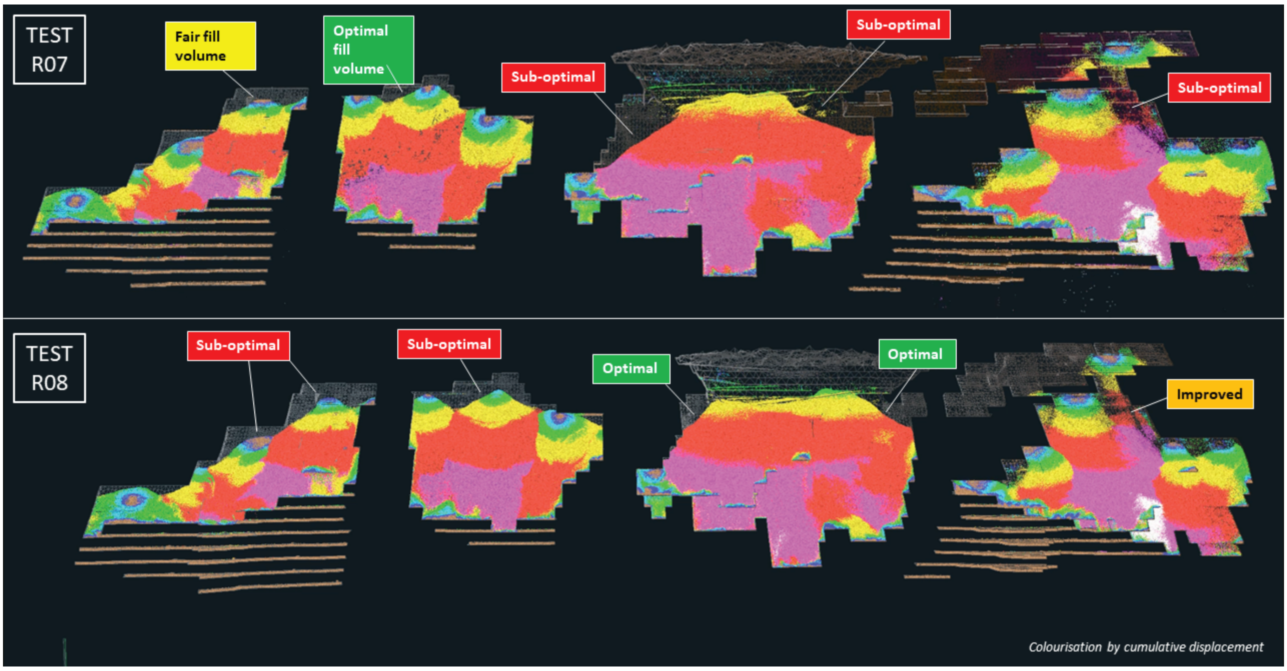

Figure 5 Calibration of fill particle spawning rates to achieve optimal backfilling of the shrinkage cavity

A particle (voxel) diameter of 1.5 m was implemented to simulate realistic flow within the narrow span margins of the shrinkage void and to minimise the risk of flow blockages forming in the simulation. It was not computationally possible to implement a regular SLC-style cave-coupling framework whereby the FS4 flow domain would be allowed to grow beyond the ring blasting zone, as the number of 1.5 m diameter voxels required to cover the entire mine-scale geometry was simply too great to process. This meant that cave growth was not explicitly allowed to develop in this model beyond the design of the SLS ring limits, as it would otherwise in a regular SLC coupled model. Instead, the caving potential of the host rock was inferred from the plastic strain forecasts. While different to Beck Engineering's usual SLC coupling method, this modified LR4-FS4 coupling approach was the only available approach, considering the scale and geometric complexity of the excavation geometry and the small FS4 voxel size that was compatible with it. The approach was appropriate, given the high strength, good quality rock mass conditions and low caveability. It was considered to provide the best possible holistic assessment of both hanging wall stability and dilution/ore recovery for the complex, large-scale, multi-panel SLS extraction geometry.

A grade tracking task was conducted after the completion of the final optimised simulation, with each 1.5 m diameter particle in the FS4 flow domain being assigned a grade value. Particles representing the blasted in situ rock within the limits of the production rings and ore development were assigned a grade value based on the block model nearest-neighbour (Figure 6), whereas introduced fill particles were assigned a nil grade and treated as dilution. Statistical outputs from the FS4 grade tracking included total production tonnes, total recovered gold, total recovered waste (i.e. blasted material below cutoff grade), total recovered dilution (i.e. tipped backfill), waste percentage of total recovery and backfill percentage of total recovery. The recovery statistics were available at the scale of the individual production rings and for the total mine plan, thereby providing a detailed quantitative forecast of the complete recovery performance.

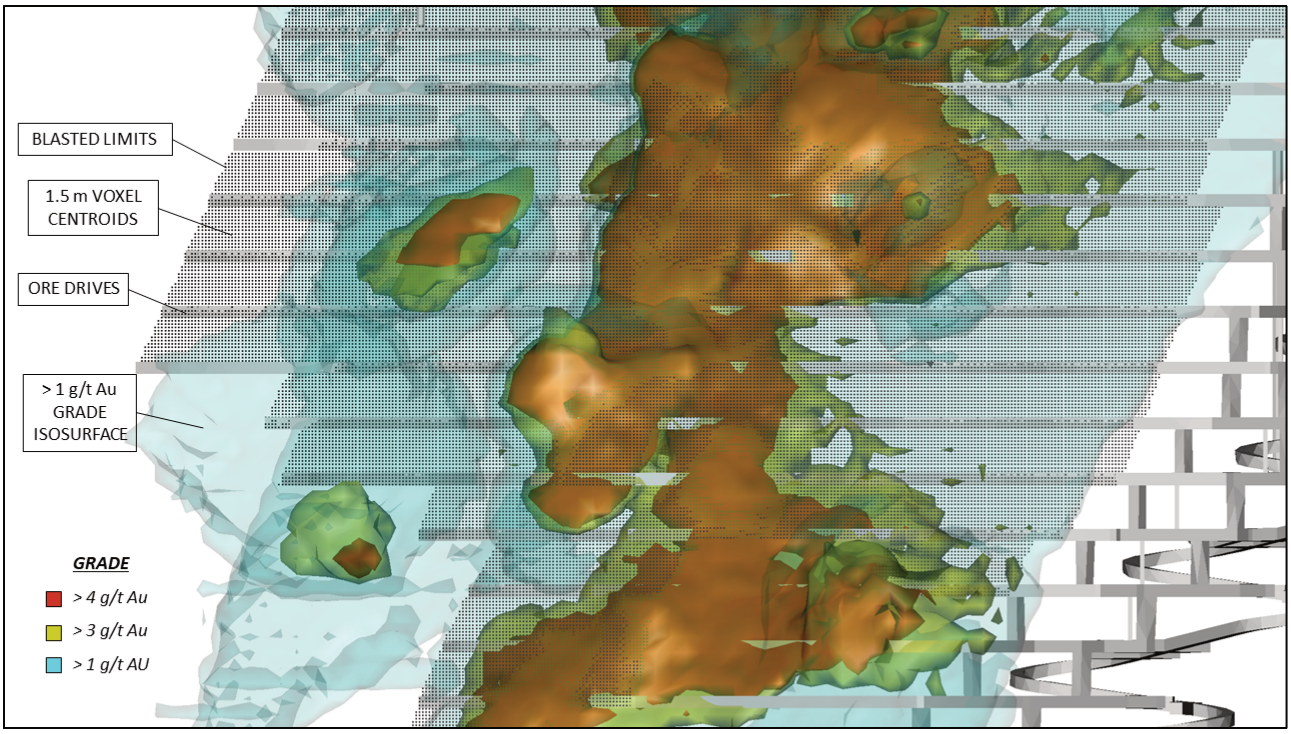

Figure 6 Grade-designated FS4 voxels within the planned production cavity

4 Simulation forecasts and interpretation

The main objectives of the simulation were to forecast hanging wall damage, rock mass stability at the critical excavations, such as the tipping shafts, and ore recovery. These objectives all relied on the simulation's ability to realistically forecast both the draw and rilling performance of the material within the cave.

4.1 Hanging wall stability

Figure 7 presents a volume rendering of the rock mass damage severity to the hanging wall of the orebody at the end of the planned mine life. Damage severity is represented according to a colour scale linked to thresholds of plastic strain. In order to identify the least stable zones, only damage of an early stage of yield or greater has been shown in Figure 7. The forecasts indicate the damage to be most significant where the hanging wall remained permanently unsupported by the cave fill. Importantly, the cumulative hanging wall damage to the end of the mine life has been forecast considering the realistic evolution of the unsupported cave cavity, using the planned draw and tipping schedules, rather than by a simple empirical rill angle assumption applied at the shaft locations. Identified zones of severe hanging wall damage included the abutments of the open pit, especially at the south end where the SLS cavity undercuts the pit wall as well as the upper hanging wall of the most southern SLS panel close to the tip shafts. Also forecast to experience significant damage are several regions of the northern SLS panel, particularly in the regions between tip shafts on the upper sublevels and also one broad zone close to the deepest part of the mine where a cave step-out is planned. This zone has a narrow funnel geometry to the main cave, which restricts the flow of rilling towards the northeast. The simulation results highlight the importance of the horizontal spacing of the tipping shafts when the cave crown is relatively flat. Large shaft spacings increase the unsupportable hanging wall and thus lead to elevated long-term damage, which might lead to adverse shaft performance over time.

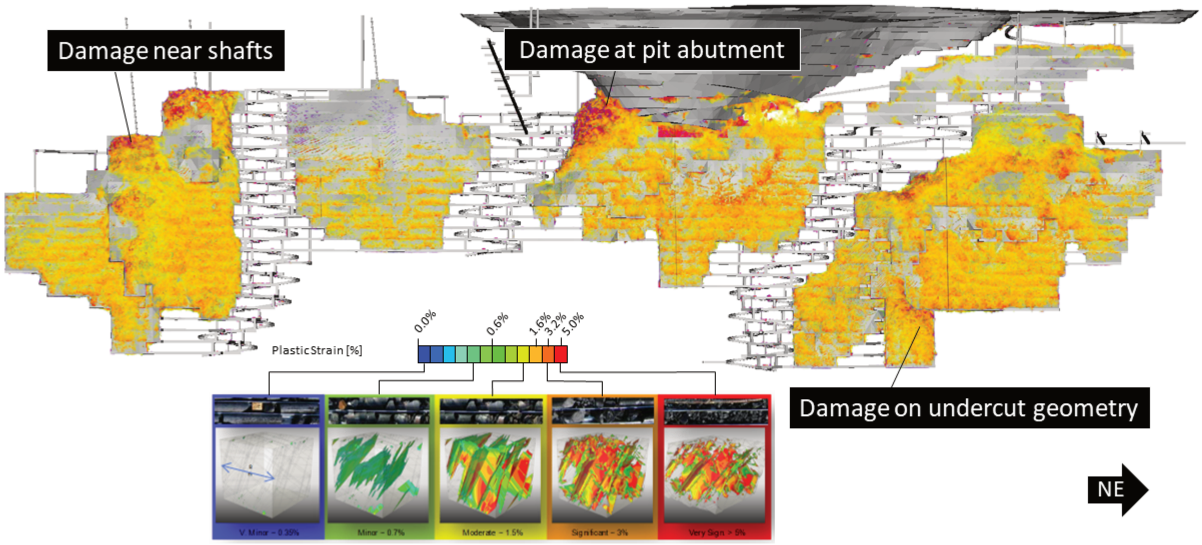

Figure 7 Forecast hanging wall damage of an early yield severity or greater at the end of the mine life

The damage forecasts on the hanging wall, as illustrated above, can be compared to the physical limits of the waste fill rilling illustrated in Figure 8, which shows a visualisation of the final simulation results with grade tracking. This figure shows the physical limits of the waste fill within the sublevel shrinkage panel beneath the open pit. The FS4 particles are colourised by increments of grade. The simulated limits of the rill identified that permanently unsupportable portions of the hanging wall would occur at both the northeast and southwest corners of the open pit. These regions resulted in a higher severity of rock mass damage, often to a late stage of yield when compared to the nearby fill-supported parts of the hanging wall. However, damage beyond the production ring limits was not to a significant depth that would be indicative of a caving response, instead indicating that only moderate break-back of the hanging wall should be expected. Figure 7 also illustrates the horizontal distribution of spawning FS4 particles as they are created and allowed to settle into the excavated zone.

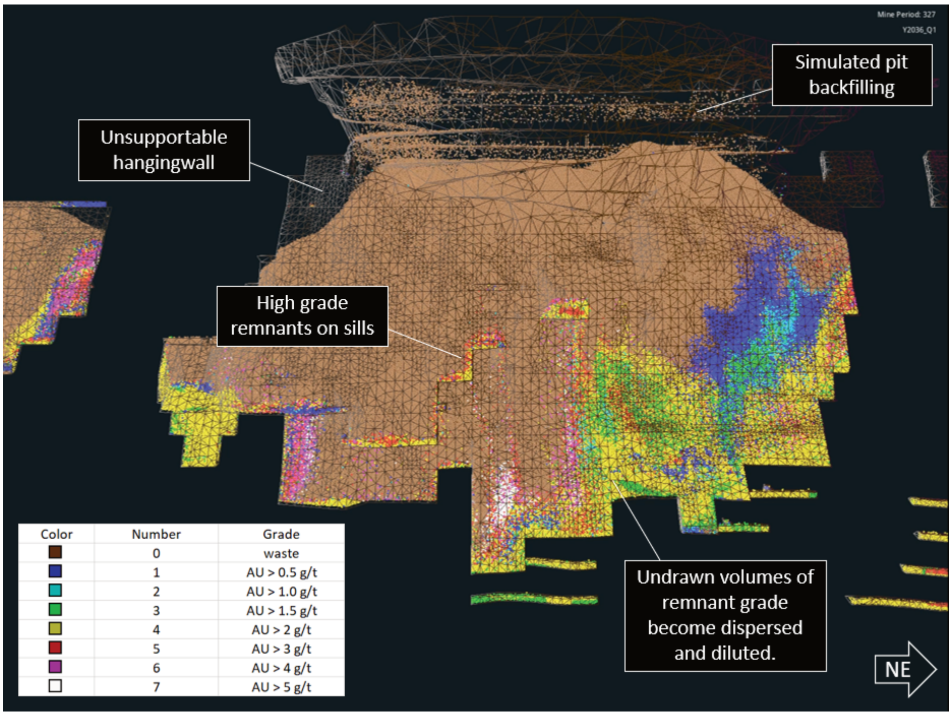

Figure 8 Forecast backfill rilling angles, underdrawn ore zones and grade-bearing remnants on sills

Evident in the grade-tracking of the flow simulation was a large undrawn zone of grade-bearing material in the northern portion of the mining panel. This material originally formed the crown pillar between the underground shrinkage mine and the open pit, although it was not included in the original production schedule. The FS4 simulation showed the gradual caving of this material from its initial position above the sublevels until eventually coming to rest nearer the base of the flow domain at the end of the mine life. Prior to mining the SLS, the crown pillar material was one to two sublevels in total height when in situ. By the end of the mine life, the process of drawing down the ore was forecast to have vertically dispersed the crown pillar material over approximately seven sublevels.

The crown pillar material was progressively diluted due to differential rates of draw along strike, as well as the vertical mixing of the ore and tipped backfill. Visualisation of the more complex draw and flow pattern behaviours provided an appreciation of the mechanisms, location and severity of the dilution processes that would likely occur within the shrinkage cave. With this in mind, strategies for minimising the adverse dilution effects, such as modified draw schedules for specific regions, could be incorporated into the final mine plan and schedule. One significant conclusion of the simulation was to schedule the recovery of this crown pillar ore very early in the LOM. This would be required to commence immediately after the crown pillar treatment. Although recovery of the crown pillar would ideally be completed as quickly as possible to avoid dilution with the fill, the necessity of a protective muck pile blanket above the early SLS drawpoints was recognised, and a staged approach would be required to the crown pillar recovery. Another interesting observation from the FS4 simulation results in this same region of the mine was remnant high grade ore left on sills created by the blasted production cavity (Figure 7). Although not immediately necessary for this feasibility level assessment, the rings from which this grade originated could be identified in the simulation and additional draw scheduled there for the final mine plan, thereby ensuring that minimal, if any, valuable ore remained unrecovered.

Another noteworthy flow phenomenon identified through visualisation of the FS4 simulations was sudden flows of material caused by rill stand-ups on the vertical steps in the cave profile. As shown in Figure 9, the stepped profile formed by the SLS rings on adjacent levels and current spacing of the tipping shafts were forecast to cause sizeable unsupported cavities to form above the rill pile, even with tight choke filling practices. At the base of these cavities, the tipped fill from the nearby shaft(s) would accumulate vertically at the cavity sidewalls. Any significant draw event from the production rings directly below the vertical step in the back would trigger flows of rill from the upper cavity to the lower adjacent one with relatively high speed and volume. Depending on timing and specifically whether grade bearing material was exposed in the rill pile of the lower cavity, these sudden flow events could have implications for ore dilution and ought to be avoided or mitigated as much as possible. At a detailed mine design and scheduling phase, all such events could be identified in the simulation with close monitoring of the forecast flow patterns. Once identified, both the draw and tipping schedules for the corresponding mining period could be adjusted to minimise any adverse dilution effects. Figure 9 also provides another example of undrawn grade requiring revision of the draw schedule. At this particular time, the draw schedule has caused a particularly sharp contrast between > 5 g/t Au high grade ore and tipped fill to form within the waste fill above the most recently mined sublevel. More broad zones of undrawn ore are also visible further along strike. The FS4 simulation allowed these underdrawn regions to be identified for draw schedule optimisation and value recovery.

Figure 10 presents a wireframe view of the two most northern production panels of the SLS mine. Streamlines of simulated flow for approximately 1 in every 600 particles within this region of the flow domain are also shown and colourised according to total displacement. The streamlines illustrate the complexity of the flow paths for both grade-bearing and unmineralised backfill material, which in many instances can be observed to move several hundred metres vertically through the cave column. Constriction of flow is evident in a funnel-shaped cave geometry of the lower north, resulting in only partial filling of the shrinkage cavity and a large unsupportable hanging wall zone at approximately 600 to 675 m depth below surface. The simulated rilling limits for this zone influenced the rock mass damage forecasts, which were used as the input to an assessment of hanging wall overbreak based on an empirical method established by Cepuritis (2011). This overbreak analysis was preliminary, but it did assist in establishing more realistic overbreak forecasts to inform the overall ore recovery and project economics.

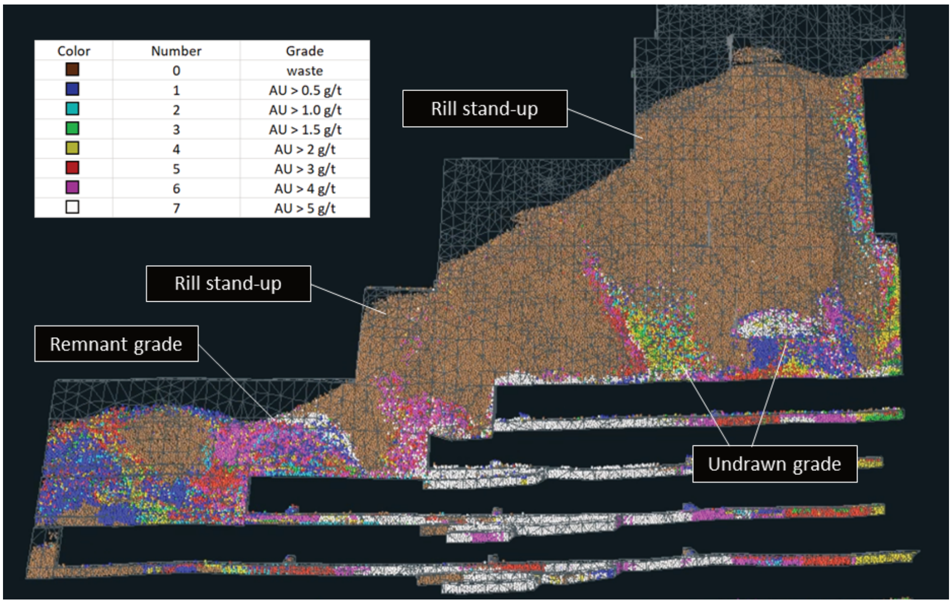

Figure 9 Example of backfill stand-ups on the cave sidewall with sudden large-scale rill flow potential

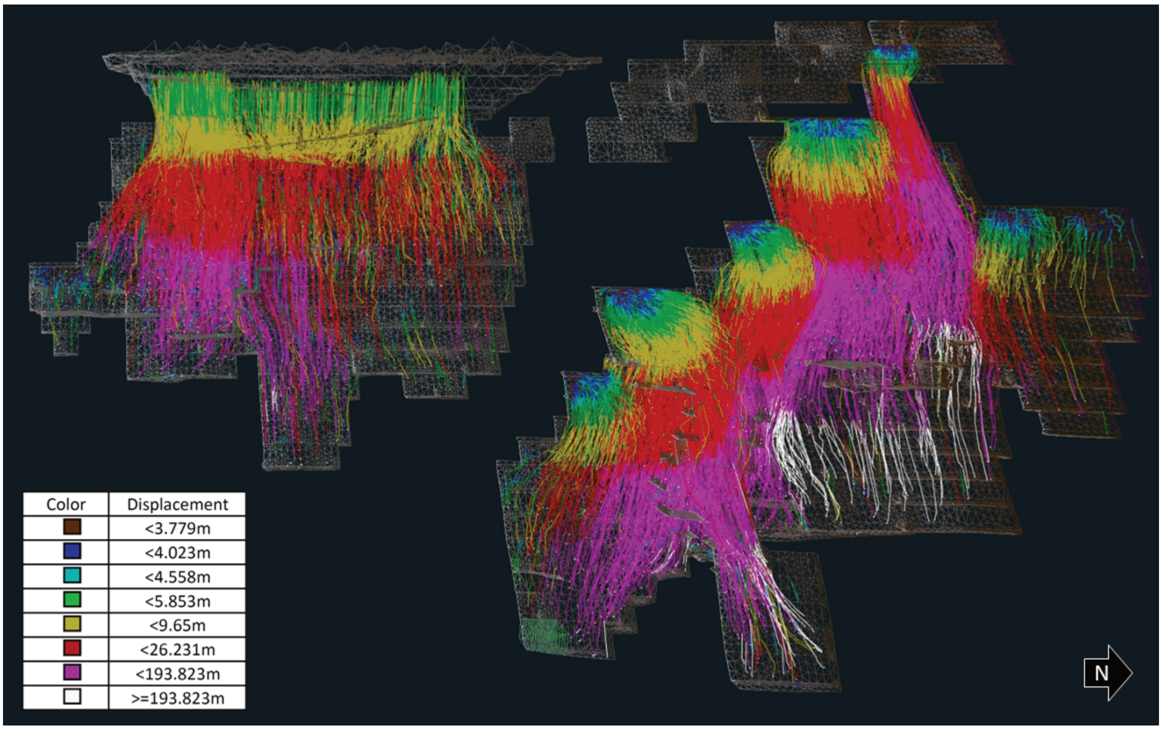

Figure 10 Streamlines of particle flow through the complex geometry of the SLS cavities

4.2 Shaft stability

The backfilling shafts are critical pieces of infrastructure in any SLS mine design. If caving is forecast to adversely affect any of the shafts, then the feasibility of an SLS strategy could be invalidated. Critical instability on any of the shafts during operations could prevent cave backfilling and present a severe mine plan disruption or even a fatal flaw affecting orebody recovery. Forecasting hanging wall and cave crown damage adjacent to the shafts is therefore a critical aspect of the mine stability assessment. In both reality and the 3D simulation, the extent and severity of rock mass damage depend on the evolution of the unsupported spans formed above the cave rill. The use of a flow simulation to define the unsupportable spans is considered the most realistic means available. End of LOM damage forecasts in some of the more heavily deteriorated hanging wall zones are illustrated in Figures 11 and 12. Figure 12a also shows fill rilling.

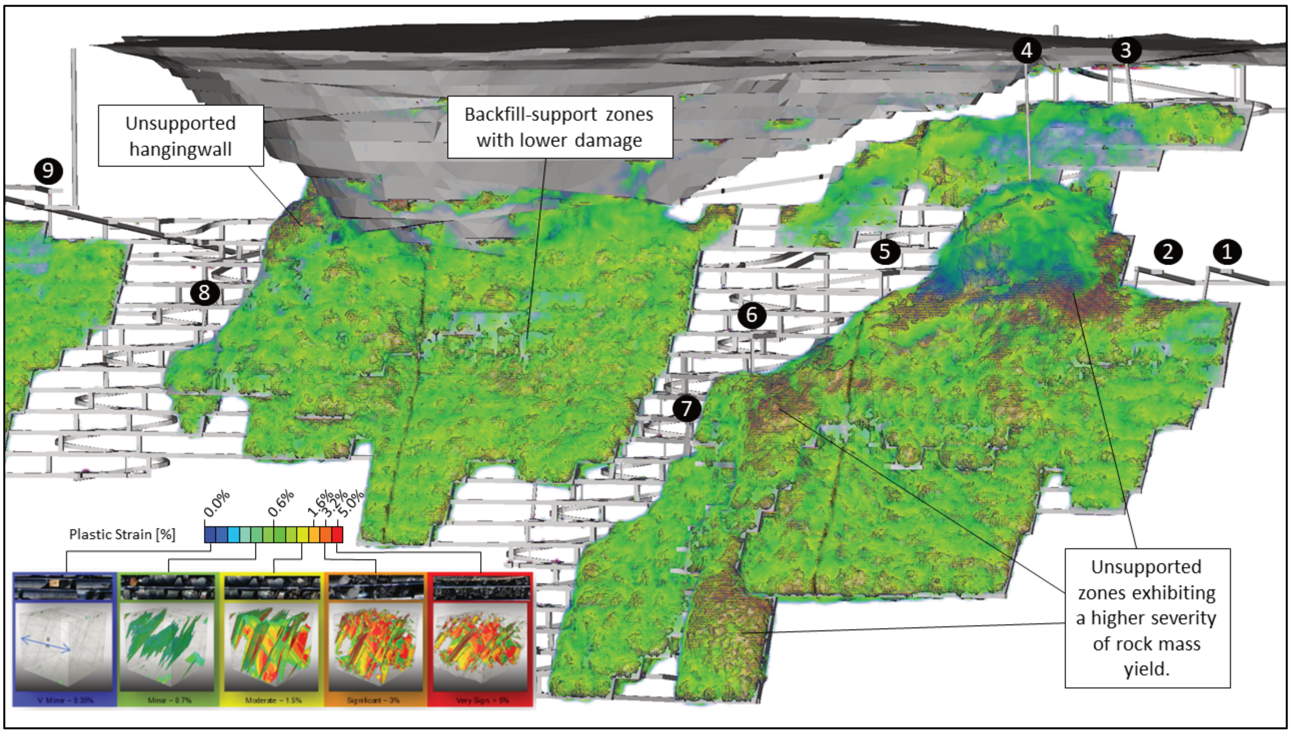

Figure 11 Forecast rock mass damage in the hanging wall adjacent backfill shafts 1 to 9

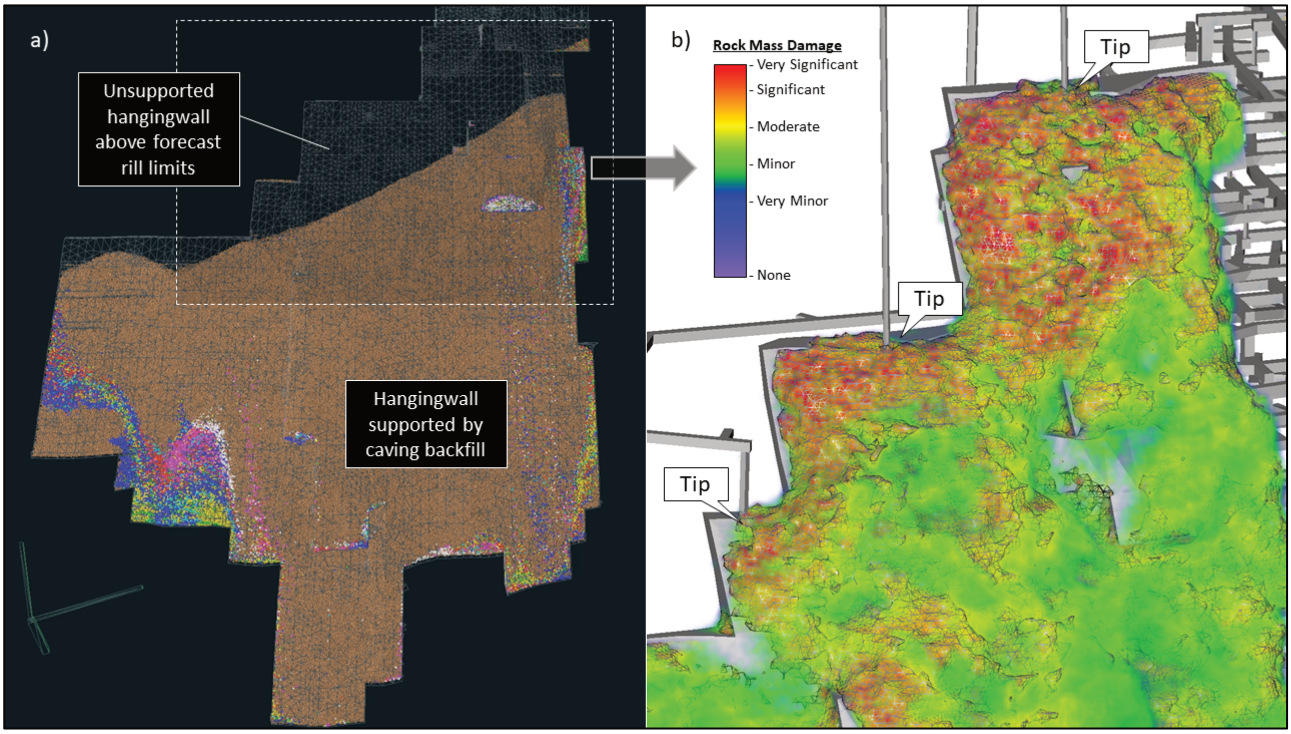

Figure 12 Forecast rill limits and the resulting severity of rock mass yield in the unsupportable hanging wall

The results demonstrate hanging wall damage to late-stage yield above the unsupported spans but only to a relatively shallow depth beyond the production rings. The damage severity is consistent with a forecast of sloughing off the hanging wall up to several metres, but it does not progress into the hanging wall to such a depth that implies caving instability. The expected impact on the shafts could therefore be characterised as localised overbreak at the base of the shaft around the hanging wall breakthrough. Given the high strength, massive rock type, this severity of damage would present an almost negligible risk of adversely affecting tipping operations or impacting the safety of the grizzly higher up in the mine.

4.3 Ore recovery and backfill dilution analysis

The draw was simulated by permanently removing a tonnage-dependent volume of FS4 particles from the flow domain, and the assigned grade value for each particle was logged as recovered for the relevant production ring. This grade tracking process permitted a detailed ring-by-ring recovery forecast for both metal and tipped fill, with total and average recoveries for each ring and the whole mine reported from the grade tracking outputs. Figure 13 shows the forecast backfill dilution as a percentage of total production draw tonnes for all rings on all sublevels. This illustrates the regions of the mine where the planned production draw is forecast to result in an unfavourable ingress of dilution to the drawpoints. Excessive dilution is evident in a relatively low percentage of the production areas, although the zones of elevated dilution do correlate to regions of higher grade. The results indicated that the current draw schedule is likely to include unnecessary levels of overdraw in those regions, which could be optimised for the final mine design. In practice, rings would be decommissioned under geology control, although the FS4 simulation assists to refine the project schedule and economics, with more quantitative physics-based detail and fewer assumptions.

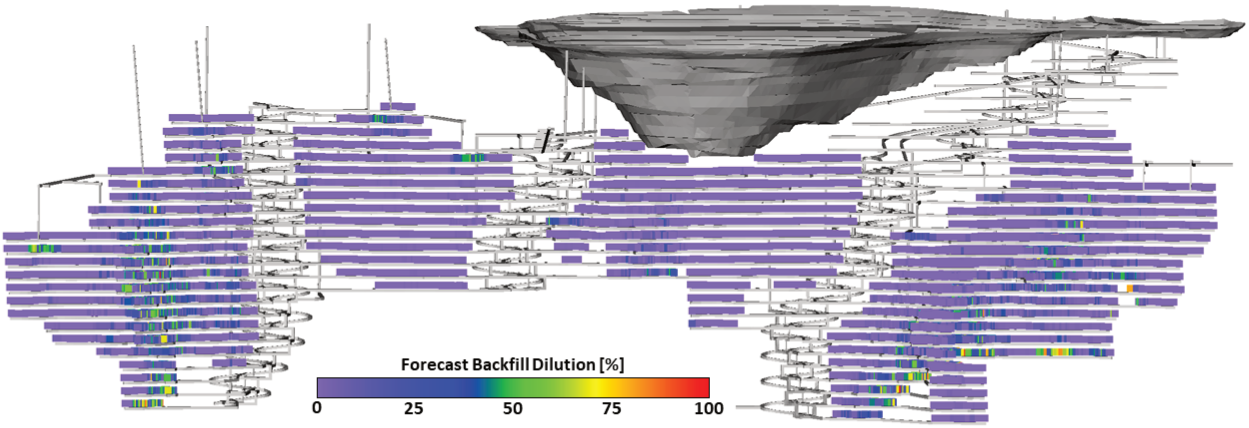

Figure 13 Forecast tipped backfill dilution as a percentage of total draw tonnes for all production rings

Average grades were reported and this data provided a clear definition of the planned mining regions that were forecast to yield recoveries below the cutoff grade. As illustrated in Figure 14, significant portions of the margins of some mining panels had a forecast average grade below the cutoff and could therefore warrant reconsideration of their inclusion in the mining plan. The FS4 simulation indicated that there was considerable scope to optimise the physical extent of the mine plan in order to remove these zones, avoiding the uneconomic mining regions and associated mining costs. This level of detailed forecasting was achieved with quantitative consideration of the influence of the backfill material on the recovery.

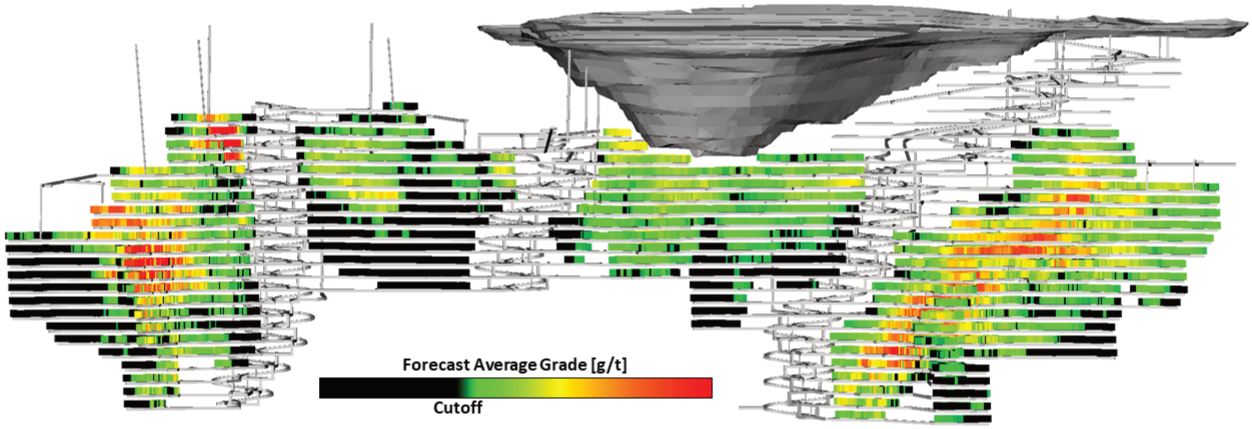

Figure 14 Forecast average grade for all production rings showing cutoff

5 Summary of mine planning benefits

The use of a numerical simulation enabled several key uncertainties of the sublevel shrinkage method to be quantitatively forecast with improved confidence. Arguably, the most important and difficult factor to quantify was the total recovery, which, critically, included a physics-based estimate of backfill dilution. Recovery analysis of the simulation revealed a life-of-mine average gold grade forecast that was slightly higher than the original assumption. The increase, measured in tenths of a gram of gold per ore tonne, had an appreciable impact on the overall project economics and brought a finer resolution to the comparison of the sublevel shrinkage with an alternative primary-secondary stoping option that was also being considered for the orebody. Also available for mine planning were the model output data of backfill tonnages per drawpoint per mining step. This data could be used to allocate backfill material to the drawpoints, with costing of the load and haul logistics able to be completed more accurately. As discussed earlier, further flow calibration work would be required before using the simulation to cost the final mine design.

6 Improvement opportunities

Several improvement opportunities have been identified that would assist to increase the accuracy of future model forecasts. For example, the variable density of the real in situ rock ought to be captured in the numerical model at the input stage using a density block model with as much 3D resolution as possible. The variable density functionality in FS4 was not available at the time of this project in late 2021, but it has since been implemented and now forms part of Beck Engineerings standard LR4-FS4 coupling framework. Furthermore, some relevant measurements of the density of the tipped fill material should be conducted and used as inputs to the model. The assumed density of the rock materials within the flow domain significantly affects the input/output of flow particles, which is based on schedule tonnages. Any uncertainty in density will therefore introduce draw or tip volume error. It would also be advantageous for the FS4 flow simulation to incorporate a distribution of particle sizes that reflects the natural variability of the actual waste fill, rather than implementing a single 1.5 m voxel size. Simulation of fall-off material fragmentation using a particle-division or breakdown criteria would also increase realism. Finally, calibration of the flow simulation results, such as rilling angle, to the measured characteristics of similar SLS operations would also improve the simulation accuracy.

7 Concluding remarks

Despite having several economic and logistical advantages over other underground mining methods in certain orebodies, SLS utilising an SLC-style mine design is a rarely applied mining technique within the industry. At the present time, there are only a small number of mines operating an SLS-type extraction worldwide. The Newmont Corporation is currently operating the Subika mine in Ghana using the SLS approach and is also considering the technique for other orebodies in their resource portfolio. SLS mining is applicable for low-caveability deposits, and the introduction of backfill to the cave provides hanging wall support, reducing the potential for hanging wall instability and large-scale caving. However, this benefit is accompanied by the potential for ore dilution. It is suggested that due to the unique nature of each orebody and the complex nature of cave flow, dilution in an SLS mine cannot be realistically quantified empirically, and thus a dynamic flow simulation of the detailed mine design, including draw schedule, is considered to be best-practice. The flow simulation approach described in this paper was a unique implementation of the LR4-FS4 numerical framework and a case study on which further simulation improvements can be built.

The simulation served to significantly reduce engineering and economic uncertainties in the mine plan, in particular the extent and severity of hanging wall stability as well as ore recovery. The distribution of backfill throughout the tipping infrastructure was also quantified to a degree that improves mine planning forecasts of mining duration and costs. Nonetheless, as with any novel approach, there are improvement opportunities that have been identified. For example, the assignment of variable density to the particles of the FS4 flow domain based on measured data would allow more realistic forecasting of the drawn tonnages and volume changes within the stoped void and hence the necessary backfilling quantities. Calibration of the physical characteristics of the flow domain material, such as rill angle and density, against existing mining operations of a similar nature would also add considerable value and realism to the simulation. Overall, the dynamic flow simulation approach provided more confidence and resolution to the mine planning phase than would otherwise be available, and further innovations can be made to further refine the methodology for this application.

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