Simulation Aided Mining Engineering: collaborative monitoring, modelling and planning

David Beck and Charles Lilley
Beck Engineering Pty Ltd, Sydney, Australia

ABSTRACT

Open access to forecasts of mine performance by all members of the mine planning team, in the form of open databases of technical or financial simulation results has been considered risky in the past, with a concern that the results will not be understood or will be misused. However, some modeling techniques allow very high similitude forecasting of performance and the results can potentially be presented in a form that is unambiguous and which all engineers can be more easily trained to understand. With some effort, sufficient reliability and quantifications of error are possible to overcome many of the issues.

Allowing more members of the planning team to have direct access to forecasts of mine performance - across rock mechanics, economics, geology and production - will promote awareness of the issues across disciplines and will act as a mechanism for improving mine designs. The models will also be more easily integrated into quality assurance programs, by providing a framework for understanding measurement results.

The sufficiency requirements for undertaking Simulation Aided Mining Engineering will be presented, included some conclusions about requirements for training, quality standards and software development.

1 INTRODUCTION

Endeavors in the field of mining engineering are effectively divided into two broad categories: design (including research and development) and operations. Frequently, these roles occur in isolation, or with insufficient feedback. A first great opportunity exists to merge design and operations, so that the entire life of a mine becomes an ongoing design process, continuously evaluating performance and conceptualizing and implementing improvements.

Both processes - design and operations - start with an objective to achieve some mining outcome using limited resources, so necessarily include constraints arising from the particular circumstances and the environment. The solution always involves compromise, but if the compromises violate essential constraints such as safety or stability requirements, the mine will eventually fail. No unsafe mine is economic.

The job of the engineering team - geologists, surveyors, engineers, accountants and managers - is to properly appreciate the objective and the constraints, while taking full advantage of the remaining design freedom to achieve the best bottom line. The art is to manage compromise within the constraints, while still achieving the essential elements of the objective.

There is second great opportunity for any engineering team who can better manage the compromise between our objectives for economic returns and the constraints imposed by the physics of the real world to arrive at a better design.

2 WHAT IS SIMULATION AIDED ENGINEERING?

Ideally, the process of 'scientifically measured compromise' (design) would rely on exact, accepted calculations and field measurements of sufficient resolution and there would be a readily identifiable, optimal engineering and economic outcome: for every resource there would be one ideal answer. If the answer were found to be sub-optimal during operations, by comparison of expected with actual performance, quality control process would ensure the design would be adjusted appropriately.

Unfortunately, there are some complications:

- There is much uncertainty about the environment and even sometimes the objective and this uncertainty persists for the life of any mine - it is only the resolution of our uncertainty that changes.
- Initial design takes place before all facts are known and before the complexity of the environment is measured. Operations always proceed in a data limited fashion
- Design decisions, especially those made rapidly without a complete appreciation of the environment, are easily compromised by empirical biases.
- Typical mine planning workflows tend to be based on empirical tools and too often, design templates from other operations. This has some benefits, in that some learning's can be transferred, but relies on considerable homogenization - measured field data is averaged and reduced until mines fit the empirical norms.
- The generic designs that sometimes result may fail to adequately target the site specific vulnerabilities, while enlightened designs that target local circumstances and inhomogeneity are often penalized during concept selection stages for being unlike the 'norm'.
- Most tools - numerical and empirical - for assessing performance cannot quantitatively differentiate between mining options with much certainty, so the differences are dealt with qualitatively. A qualitative design disadvantage is easily traded off against other qualitative advantages. A quantitative measure of performance is usually harder to dismiss.

The uncertainties, complexity and biases mean that in any mining engineering design problem, there is a large number of differentiable, potentially feasible solutions. The engineering team must consider these, having first imagined them, and select from among them by balancing the compromises necessary to achieve the objective within the constraints.

Simulation Aided Engineering is a concept for leveraging computer based design tools to improve the engineering and design work flow.

For complex mines, it can be thought of as providing the virtual test laboratory for testing the bottom-line performance of various courses of action at every stage in the engineering process, using the best available information, constrained by the known physics at the time. It should also ensure that impossible, fatally flawed designs and decisions do not progress.

Its purpose is to ensure:

- that the constraints of the physical and fiscal world are properly appreciated at every stage from planning to operations, while
- considering uncertainty and
- promoting rapid progress towards a more optimal outcome.

In concept, SAE, using high similitude[1], physics based predictive tools differs little from best-practice non-SAE engineering which would have always used best possible information and tools to constrain design.

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[1] Similitude is a modelling term that means 'similarity' in terms of scale, dimensionality and physical response. In essence, compatibility between modelled and measured behaviour that is reproduceable, properly constrained and emergent consequent to the composition and inner workings of the modelling analysis.

SAE is simply an update to account for the rapidity with which computations can now take place and the complexity[2] which can now be captured with very high similitude.

If integrated to its fullest extent, SAE for mining should result in more reliable mines and better trained personnel.

2.1 SAE and PLM

SAE may be especially successful if implemented as part of a greater package of Product Lifecycle Management (PLM) and Change Management (CM).

Product Lifecycle Management is a business concept to develop a product or design, to manage it and its lifecycle including analysis results, measurements, quality standards, change, production information and uncertainty. It is essentially a systematic, controlled concept for managing designs and related information, especially relating to the use of computers to aid fast, easy and trouble free finding, refining and utilization of data for daily operations (Saaksvuori and Immonen, 2008).

For mines, SAE is a tool for integrating coupled information (such as strength, stress, strain and structural information for rock mechanics problems) while PLM is the process of collecting, sharing, storing, utilising, evaluating and acting on that information.

The parts go together: SAE ensures the data is considered in a rational way, PLM ensures the data is available and considered, CM ensures that the continuous process of design improvement is reflected in the mine.

In this paper, SAE is the main focus but it would rely on effective PLM and CM.

3 SAE IN THE LIFECYCLE OF A MINE

There are several classes of SAE tools for mining:

- Stress-strain-hydrology simulation tools: primarily numerical tools that evaluate the connected nature of different aspects of the environment, to quantify the effects on the mines performance, and to estimate the effect of the mine on the environment.
- Productivity and scheduling tools: tools for generating and maintaining mine designs.
- Geological modelling tools.
- Integrated financial modelling tools.

In each area, technological advances have enabled rapid, high similitude simulation of mine performance with fewer assumptions.

Conceptually, given the pace of best-practice modern simulation, design scenarios should be able to be tested in real time, or across shifts without significant modification to existing planning procedures if there is a sufficient investment in training and hardware.

During the mine life-cycle, these rapid simulation tools can typically be used as follows:

- When there is more than one differentiable, potentially feasible course of action (for example, different methods) or scenario (is there a large fault transecting the orebody?), the effects on design performance and the bottom-line can be assessed quickly.

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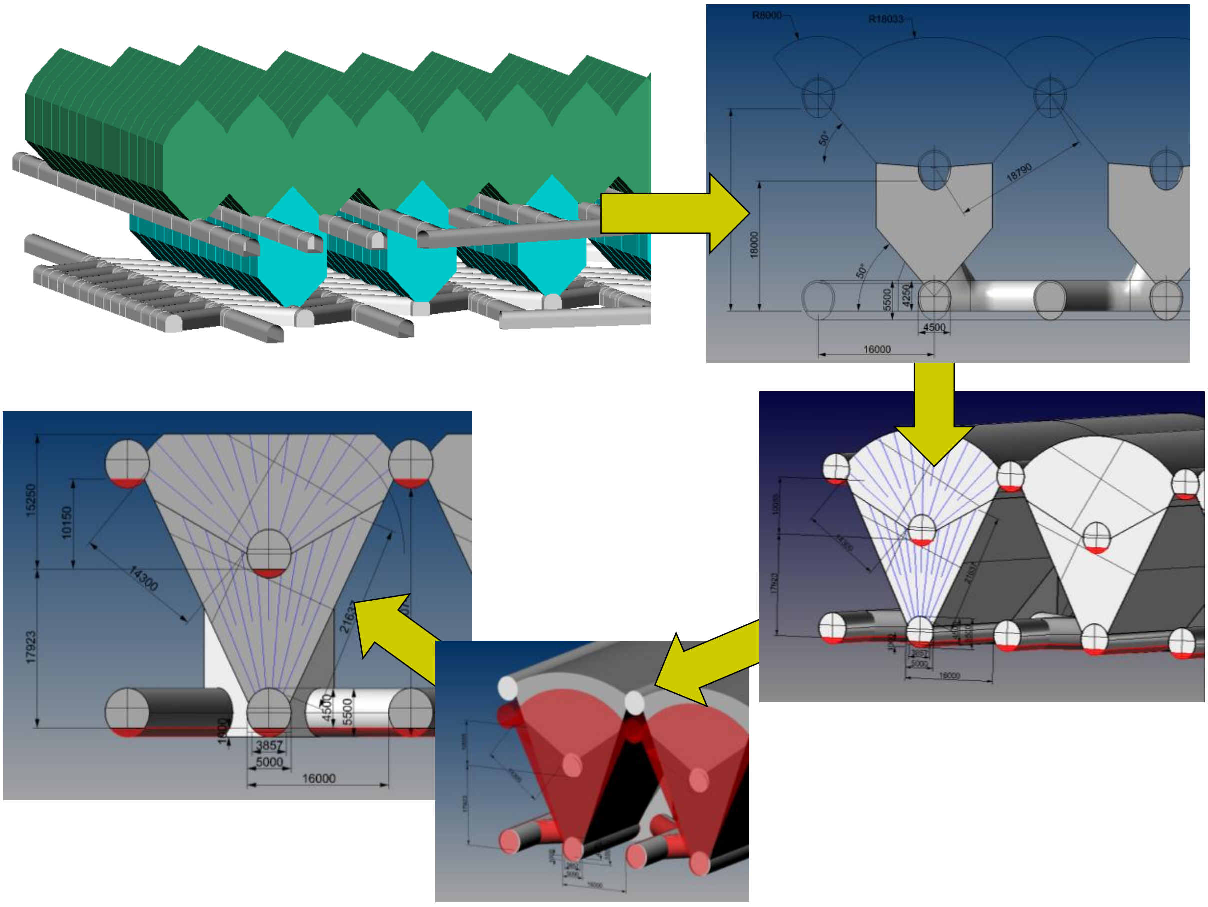
[2] Complexity in the context of SAE for mining can be thought of interconnectedness. Disparate length scales, parts of problems and physical processes coupled in some way evolve complexity. The physics of these couplings in most cases is well understood, though computing the equilibrium or dis-equilibrium that results has sometimes been too difficult. With increasing computer power, many of these complex problems can now be simulated with high similitude.

- The simulation and experience based process should identify or quantify the engineering, financial or other vulnerabilities of the design or the scenario and the range of expected performance for all options (probabilistic analysis is best of all).
- The possible plans should be modified <u>within constraints</u> including financial considerations, by adjusting the concept to manage vulnerabilities, or else by adding control measures.
- The bottom line range of outcomes, including potentially extreme events can be compared to the project objectives and the higher objectives of the organization to determine the best course of action.
- The concept or scenario can be re-tested and modified iteratively until a technically, socially and economically feasible option is achieved or the particular scenario is exhausted and rejected

Using modern computational capacity, this process can be repeated hundreds of times throughout the design process to iterate towards an optimal design, schedule and field measurement program while ensuring that at each stage, the governing physics and economic realities of the situation are properly considered. In a standard, non-SAE workflow, much fewer design iterations are possible and the precision of forecasting is generally lower, so such detailed optimization is not usually possible.

An example of pre-feasibility stage design optimization using SAE is shown in Figure 1. The figures shows key design milestones in the evolution of a potentially feasible concept. At each indicated step, a vulnerability was identified that was targeted in a subsequent design iteration, with strain softening, dilatant Finite Element modelling (stress and deformation modelling) used to assess improvement. Sufficiency requirements for stress and deformation modelling are discussed briefly in a subsequent section.

Figure 1 Iterations of a design concept for trough caving



Between the first and second design step in the example, changes to the undercut were made to promote undercut pillar stability and between steps 2 and 3 the ring design was simplified to improve blast reliability and flow. Final stages were to improve the blast design until eventually, the calibrated simulation tools indicated performance and reliability within pre-determined limits.

Without SAE tools, the process may have been stopped at stage 1 as the first proposal was qualitatively sound, without fatal flaws. The end result of the more detailed SAE process was a design much closer to production readiness and for which there was a bespoke field measurement program, designed specifically to target particular vulnerabilities and finalise the design.

Only some of these potential issues would have been clear to the mine had the process not been rigorously followed, even though they would have had more impact on the performance of the original design than the more reliable SAE design. In particular, there were subsequent design elements that were able to emerge much earlier and in a more considered way, owing to the rapid development of the design rules for the undercut and extraction level facilitated by SAE.

The effect on the schedule was probably a 6-12 month reduction in the time taken to realize the final design, and the key benefit of SAE in this case is thus early optimization through the rigorous consideration of more aspects of the problem.

A second example of an SAE process is where more information will be needed to finalise a design decision. This is actually the more common scenario in mining.

In these cases, the benefit of the rigorous, physics based SAE process will be that the particular decision should be able to be framed around something that can be measured, and a last safe moment to commit to one plan or the other. The SAE process should assist in identifying the particular measurements that are required to make an optimal decision.

If sufficient data can be collected to justify a less conservative course of action before the last safe moment to make a decision, then this information can be sought and used later to follow an optimal course of action. If not, the option that is safe regardless of the circumstances - the base case - is selected.

This kind of decision making for data limited mine planning and design problems consists of several steps, discussed in detail in Beck 2006:

- Identification of strategic vulnerabilities and environmental variables for all options. This phase involves identifying things that might go wrong, or data that still needs to be collected, that may influence the plan that is to be selected. SAE tools can assist in identifying, or quantifying the vulnerabilities of each option.

  For vulnerabilities likely to affect the feasibility of a concept, a most dangerous, most likely and a safest outcome should be identified. Alternately, if sufficient information is available, the range of outcomes should be defined statistically.

- Once vulnerabilities are identified for a concept, the range of outcomes for that vulnerability should be assessed using the sufficient SAE tools to determine whether the concept can inherently manage the problem. If the affected concept can be modified, this should occur before prior consideration.

- If more information is required to enable the decision to made, or if a decision is to become part of the concept, then control measures, decision points (DPs) and implementation schedules must be developed. A decision point is a set time when a decision will be made based on incoming data. The LSM is the Last Safe Moment to make that decision before the opportunity to change to avoid the problem is no longer available.

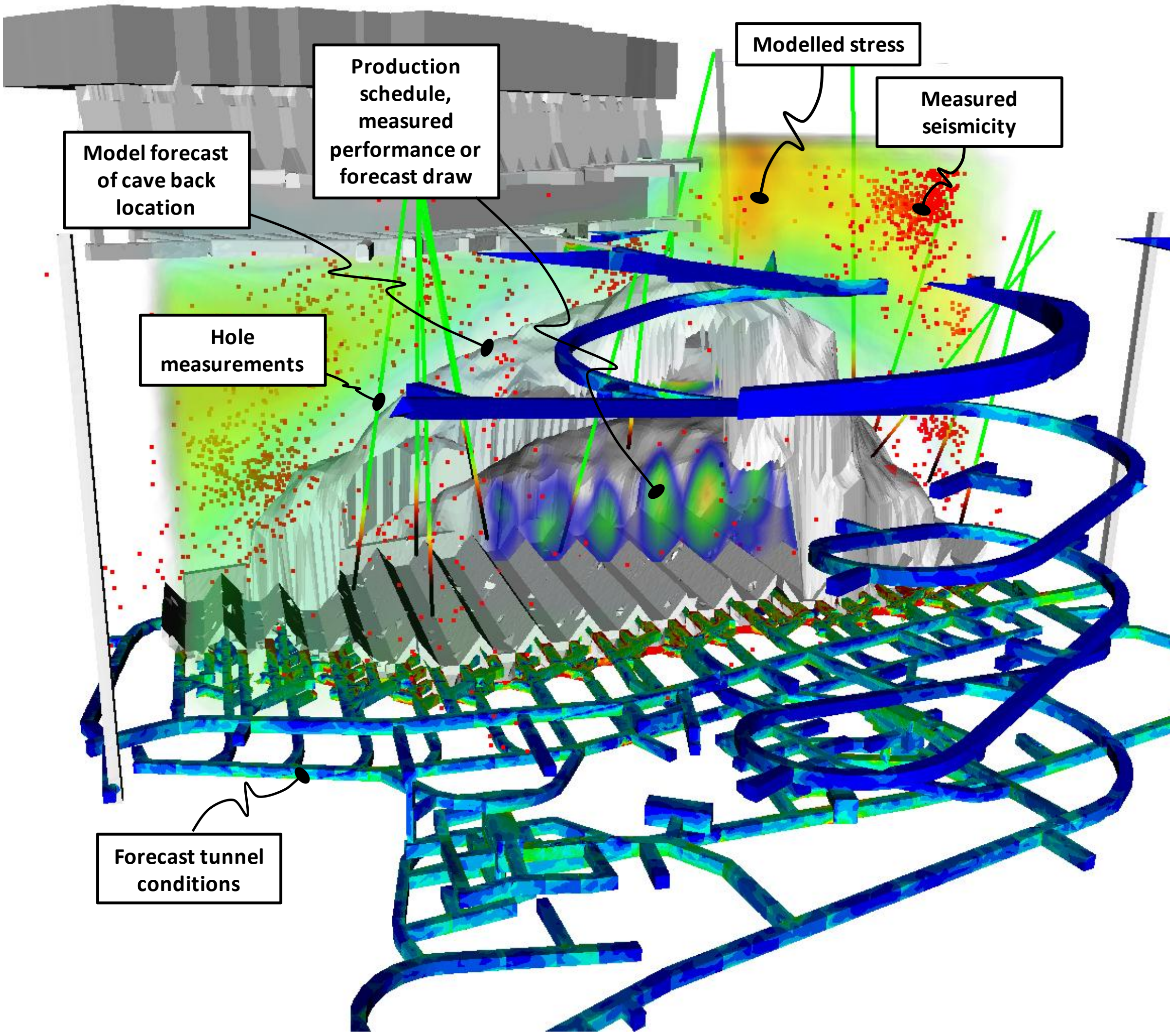
- Generally, all design concepts in mining require a schedule of DPs and LSMs in order to manage vulnerabilities within acceptable levels. A classic example is from slope monitoring. The slope must be monitored regularly enough to allow the modified plan to be implemented should the slope become unstable. If the slope monitoring is infrequent, the pre-cursors to failure occur too close in time to the failure for contingencies to be implemented or if there is insufficient time to implement the design change before the slope failure becomes inevitable, the objective for the pit may not be reached.

- The LSM for the implementation of the design change becomes the DP, by which time all data must be selected to make a good decision. Rather than wait for the data, the planning process can continue, and these requirements simply become a part of each concept.

3.1 Sufficiency requirements for SAE tools

The main sufficiency requirement for SAE tools is that they sufficiently quantify the problems being assessed: the design options need to be able to be differentiated accurately and quantitatively using the tools in a planning timeframe. For rock mechanics simulations for example, the hazards of complex rock mass phenomena such as induced seismicity, excavation instability and potentially extreme deformation phenomena need to be properly quantified before the time when a design decision must be made. For the example in Figure 1, the tools were first tested against their ability to replicate current mine conditions to ensure that they were sufficient.

Figure 2 Example of data from multiple sources visualised in a 3d collaborative workspace



For general SAE, including non-rock mechanics issues, the tools must be quantitative, field validated and the hazardous phenomena or rare and occasional adverse events must emerge, or at least the factors that contribute to them must be accurately forecast, emergent from the model as a function of properties and inputs that can be measured or engineered.

SAE tools for mine design must therefore have the following characteristics:

- They must be quantitative.
- They must capture the governing physics of the environment they are simulating
- Must be field validated to replicate the extent, magnitude and timing of deformation and energy changes with a verified level of precision. This means that the accuracy of forecasts of physical phenomena that can be measured in the real world should be quantitatively correlated with the equivalent phenomenon in the model or software.
- Outputs must have a resolution matched to the decision being made
- Field validated
- Hazardous phenomena must emerge in these models as a function of the measured properties of the deeper mining environment.
- The outputs of the analysis must be able to be integrated into the mine planning and operations - this means that the forecasts of performance have to be transparent, rapidly produced and communicated.
- Results should be reported in quantities that the rest of the engineering team can understand and use, for example tonnes per day, time, rehabilitation rates or event probability. The common feature of these particular examples is that they are in the same units as the mine would use to report its performance.

The process for SAE tool validation is as follows:

- Quantitative, high similitude, probability based calibration - model quantities must match field measurements (modelled metres of movement must sufficiently match measured metres of movement, timing and magnitude of forecasts seismicity must be sufficiently correct).
- Each tool will require rigorous testing and measurements.
- Examples of field measurements that can be used to validate SAE tools from rock mechanics are:
    - Modelled and measured subsidence: the extent and magnitude of subsidence, including the timing should be able to modelled with a low error in a high similitude SAE tool. The resolution, correlation coefficient and expected error should be defined.
    - Seismicity: the occurrence of seismicity, in terms of activity levels versus time and space can be quantitative forecast using measures such as Dissipated Plastic Energy (DPE) in high similitude FE models.
    - Drive closure or damage is easily measured, and if undertaken over a wide enough area can be compared to modelled drive damage.
    - Cave geometry can be measured, for instance using extensometers, open holes and passive tomography and compared to forecasts from coupled FE-flow simulations
    - Cavity surveys of stope overbreak can be compared to material instability (velocity, damage or displacement based criteria)
    - Measured pore water pressure can be compared to modelled pore water pressure

    - Movements in pit slopes should be replicated in 3d, with a defined resolution and precision.
- Field tests across a range of environments should be used show the tools are able to project into diverse environments. To do this, the tools should be proven across different areas of the mine, or a range of environments in similar mines to show that they can capture the evolution of behaviour as conditions change
- Continuous, ongoing improvements in current operations are needed. Field measurements should not only target the vulnerabilities that the SAE and hazard appreciation processed identify, they should target SAE tool verification and improvement.
- In green-fields operations, local calibration is of course not possible, so SAE tools for these environments should make the fewest possible assumptions, and the testing of the assumptions should become a scheduled aspect of the implementation process. The SAE tools become a part of the verification process, with continuous testing, review and updates of results used to adjust the design as information becomes available.

3.2 Information sharing: collaborative, 3d workspaces

Another important aspect of SAE is information sharing and data transparency. The computational tools may allow rapid turn-around to facilitate the consideration of more information, but this is no use if the data is not available or the results are not understood by the members of the team who will use them. Proper data collection, storage, sharing and maintenance is actually an enabling step for SAE.

In SAE, ideally, the outputs of forecasts would be shared in a 3-dimensional, collaborative work-space that is fully integrated with the mines measurements and production systems. In effect, a visual forecasting and measurement database with information spatially, temporally and content cross-referenced.

The intent of the collaborative workspace is that individual members of the team are 'situationally aware' of the problems and considerations of their team members and that as revelations are made and decision points are approaching, there would be appreciation across the team of the inputs that are required and the constraints and freedoms for the rest of the project that are evolving. The information flow should be seamless. In this environment, rapid examination of likely long term performance of designs becomes more valuable. Most importantly, more of the team are 'situationally aware', more of the time.

An example of a prototype collaborative workspace is shown in Figure 2. This figure shows a combination measured and modelled data: measured seismicity and rock mass changes viewed in open holes, compared to model forecasts of stress, cave back locations and tunnel conditions. In this example, anything which the mine measures, and anything which its engineering tools forecasts, and any design or schedule that the planning team proposes can theoretically be seen in one place.

Ideally, CAD should also take place in the same tool and virtual reality interfaces also become a potentially valuable option as more data streams are integrated with the system.

There are certain requirements to facilitate a collaborative workspace in a meaningful way for SAE:

- Data needs to be in an accessible format.
- The data needs to be owned by members of the team who will maintain the data in their area of responsibility.
- The data needs to be of a quality that it can be shared with an end-user.
- Mines should consider giving all data a 'use-by' date. If the date is passed, its use will need to be re-authorised by the data owner.
- There needs to be a system by which the usefulness of a data-stream is regularly reviewed. If the data is not being used, either it is unnecessary and should be culled or else the process improved.

- SAE data needs to meet the sufficiency requirements, if results information is to be openly shared without fear of misinterpretation or misuse.

  In the area of geotechnical modelling, the highest fidelity, highest similitude analysis is generally implied by the need to provide results in a format anyone in the team can understand. Displacements and damage are more easily understood than stress for example, and can be directly measured against field measurements, but few models replicate these accurately.

  Notwithstanding that the difficulty some models face matching field measurements actually invalidates them for general use, the high standard for SAE outputs especially makes some conventional, more simple analysis not useable for this purpose. Such simple analysis may be qualitatively useful and has an important place in mine design, but sharing such data in raw form across a larger team would cause problems because it is too hard to interpret and understand.

  Though best of industry practice is probably sufficient for most SAE for mining, it is very likely that a step change in modelling standards would be needed in most mines. The main issue is modeling that does not properly capture the interaction between stress, strain, strength and structure to produce outcomes that can be directly compared to field measurements.
- The results of forecasts must have defined precision and resolution. End-users have to be able to understand the limitations.
- There should be regular sessions where the whole team are briefed on major updates and changes to the data, for example, rock mechanics should regularly present the changes to the results database, outlining the key developments.
- The workspace needs to incorporate an alert system for highlighting data changes.

4 BENEFITS OF SAE FOR MINING

The benefits of SAE are numerous. In concept development:

- Rapid simulation can be used to test designs, to verify the resilience of the concepts of to identify where modifications are needed. Successive iterations can occur rapidly to develop a resilient concept.
- The general principal is to identify the likely response to any potential problem as early as possible, to have the eventual solution 'on the shelf'. This assists not only in prompt response, but also in ensuring that opportunities to manage future issues are not sterilized by design decisions
- As in the example of Figure 1, a series of vulnerabilities not necessarily foreseeable at the outset can be eliminated through an iterative process to achieve a resilient mine plan.
- Although calibration is not possible, the key is that the governing physics of the problem is captured. If this is the case, it is only the variables and the particular circumstances of the environment that are unknown and a reasonable range of outcomes should be able to be established.
- Uncertainties in material properties or equipment performance can be dealt with as a range or by expressing outcomes as a probability distribution. It may be that the underlying probability of failure could exclude certain courses of action, or else, the SAE tools may help identify the particular unknowns on which the decision will eventually depend. These can be targeted in a timely manner by considering the last safe moment to make a decision and the resources available to gain the necessary information

- The plan that is developed will need to retain sufficient flexibility to deal with the possible range of circumstances that could develop, and SAE tools can be used to test these hypothetical courses of action, to be implemented should certain triggers be measured.
- In some cases, a major flaw, or potential flaw may not be able to be excluded to the satisfaction of decision makers. This is still a successful outcome as it means that the design is not meeting all of the constraints - in this case it would be violating the risk profile adopted by management.

In operations:

- Because the SAE results are produced in simple measures such as displacement or tunnel damage, they are conceptually accessible; all members of the team can directly appraise them. This
- This results in transparency. If the results are not matching observations, this becomes immediately apparent. All team members have the opportunity to identify model-field incongruities which is important, as no single member of a planning team can observe the entire mine at once, and certainly not through the eyes of the collective experience of the entire team.
- In the case of a mismatch between the model and field measurements, either a scenario is playing out in real life that was not forecast and action is needed (plan modification or a hazard reduction strategy), or the SAE tools need adjustment, and the observed incongruity becomes a data point for calibration.
- Whatever the cause of the incongruity, the forecasts can be updated using the updated SAE tools or the environmental model and the mine plan adjusted if possible. If the updates tool identifies a critical vulnerability or hazard, it can be addressed.
- Over time, as data is won and the tools are refined, the resolution and precision of the forecasts will improve.

Training and skills development:

- There is an added, often unforeseen benefit: as planners, production engineers, geologists and non-geotechnical personnel receive information from other specialties in a format that they can understand, as a background to their normal tasks, and as they become immersed, or at least peripherally exposed to it, their intuitive understanding of the couplings between different aspects of a problem will improve. Non-rock engineering professionals much more quickly come to appreciate the interactions between stress, strain, strength, structure, water and their design decisions.
- The improvements may even be inadvertent, but the learning process is surely accelerated. This does not occur to the same extent in planning environments where simulation results occur out of sequence with the design process.

  In rock mechanics, stress is an abstract, often ambiguous concept out of context, but strains and displacements layered on real world measurements of the same things are easily understood.

5 CONCLUSIONS

Rapid, high similitude, multi-scale, simulation is possible in rock mechanics, production simulation and geological modelling. More data may be needed to achieve true SAE in these fields, but given data and an efficient workflow, many SAE tools and concepts , when implemented properly should be part of everyday planning.

SAE concepts do not require step changes in the body of mining science but they do require skills that may not currently exist at most mine sites. High similitude rock mechanics modelling for instance is an emerging field and is not currently mainstream, everyday practice, but is off-the-shelf as far as accessibility to off-site tools is concerned. The hurdle to implementing SAE in this and other areas is thus one of training, acceptance and commitment.

If these hurdles can be overcome, the SAE concept can be achieved quickly for immediate benefit. The benefits of better mine reliability outweigh the training and implementation costs by a large margin.

6 REFERENCES

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