The importance of simulation in geotechnical and mining applications

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Abstract: Simulation tools can play a significant role in meeting design challenges within the mining and resources sector. Potential applications range from the analysis of design and placing for individual key infrastructure potentially affected by surface or underground deformation (i.e. shafts), to the review of safety and stability of all excavations (i.e. pillar and wall stability) in a single model. The success of the analysis is linked to the ability to replicate realistic behavior in complex three-dimensional problems. Increased confidence in the results and improved accessibility promotes collaboration for interpretation and informed decision making throughout a multidisciplinary team. However, applications in mining, petroleum and civil engineering and earth science require a different development focus than classical mechanical or aerospace applications. A discussion of current developments and market needs will show where some of these industries are headed and give an insight into the future of simulation in disciplines that traditionally were driving research and innovation in the methods used today in geotechnics. Abaqus has a leading role as a robust solver for these applications and new features in the latest releases enable realistic simulation and multiphysics applications for a number of geotechnical problems including in-elastic soil and rock mechanics, pore pressure and flow.

1. Introduction

Assessment of geotechnical data and the mechanical / fluid response of geotechnical domains is an important consideration for risk and operational management in many mining, civil, resource, energy and environmental sectors. Examples of such geotechnical data interpretation is categorized below.

1.1 Mining

- Open pit
    - Pit wall stability
    - Surface subsidence
- Underground
    - Access, Shafts, Portals and Declines
    - Pillar Stability
    - Surface subsidence
    - Ground support integrity

1.2 Civil Engineering

- Infrastructure
    - Consolidation
- Tunneling
    - Tunnel excavation
    - Tunnel stability
    - Ground support integrity
    - Surface subsidence

1.3 Oil & Gas, Energy and Environment

- Reservoir mechanics and geothermal power
    - Pore fluid distribution
    - Phase and flow characteristics
    - Well production and stability
    - Injection pressure
    - Surface subsidence

In many of these disciplines empirical, experimental or observatory techniques have been adopted. Numerical simulation capabilities such as finite element analysis are a more recent alternative that have been rapidly gaining acceptance. Abaqus currently offers a powerful suite of capabilities that can provide tailored solutions to these problems.

The aim of this article is to briefly outline current capabilities and simultaneously highlight potential enhancements to further the application of Abaqus in these areas of interest. The capabilities and markets discussed herein represent those identified and serviced by the Numerical Modeling Group in Coffey Mining.

2. Simulation in geotechnical and mining applications

The success of numerical simulation in a geotechnical environment, as with other engineering disciplines, can be directly linked with the capacity of the simulation to accurately represent realistic behavior. In geotechnical applications, this means the simulation must:

1. Provide an accurate three dimensional description of the interested continuum or dis-continuum environment. This may include:
    a. An accurate depiction of surface topology when considering open pit excavations or near surface underground excavations, particularly in mountainous terrain.
    b. An accurate depiction of open pit excavation geometry and/or underground excavation geometry.
    c. An accurate representation of geological regions to define both mechanical and fluid response where necessary.

    d. An accurate representation of initial in-situ stress fields, pore fluid flow and pore fluid pressure.

2. Utilize appropriate non-linear, strain softening, dilatant constitutive behavior for regions of interest, such as:
    a. Mohr-Coloumb material plasticity.
    b. Drucker-Prager material plasticity.
    c. Hoek-Brown material plasticity.
    d. Pore pressure and fluid flow (effective stress).
3. Incorporate levels of scale necessary for the problem of interest. For example:
    a. An assessment of global open pit wall stability would only require model resolution of inter ramp scale.
    b. An assessment of local open pit wall stability would require model resolution at a bench and/or berm scale.
    c. An assessment of surface subsidence due to underground mining operations would require a global mine scale model that captures interaction with the underground extraction and fractured/caving zones.
    d. An assessment of drive deformation or pillar stability in an underground operation would require explicit representation of drive and/or pillar geometry, representing the mine plan more accurately. This could also involve:
        i. The use of sub modeling capabilities to apply global mine scale deformation.
        ii. Consider the effect of ground support and reinforcements.
        iii. Iteratively couple with a global model to achieve greater simulation confidence.
4. Resolve instances of structure (i.e. faults, shears or joints) that are deemed important. This may include:
    a. Incorporation of faults/shears that have the potential to mobilize when exposed to open pit and/or underground mining excavations.
    b. Incorporation of faults/shears that have the potential to transmit pore fluid to open pit and/or underground mining excavations.
    c. Incorporation of interconnecting faults between fluid bearing layers
5. Be capable of incorporating sequence or model change over time, accounting for excavation advance and refill where necessary.

Examples where Abaqus has been successfully applied under this framework include analysis of open pits as Figure 1, "(Arndt, 2007; Beck, 2007; Beck, 2010a)", underground operations "(Arndt,2009; Beck,2006; Reusch, 2008)" and ground support conditions "(Beck, 2010b)".

The methods employed in these analyses are:

1. In most cases a quasi static Abaqus/Explicit simulation was performed, with the advantages of both its capacity to efficiently run simulations with of tens of millions of degrees of freedom (DOF) and the robustness of the explicit solver regarding highly non-linear (strain-softening) material behaviour.
2. Model creation and mesh generation often used third party software though Abaqus/CAE has proven suitable for models containing thousands of internal geometrical cells.
3. Faults and joints were incorporated using frictional contact or cohesive elements to achieve a large displacement discontinuous mechanical response. Wedge elements were used in case of pore fluid transport, and element deletion where appropriate including general contact in this case.
4. Material properties adopted a user material constitutive behavior that included element removal and refill options, a strain softening dilatant material response for continuum regions and a traction-separation response to model dislocation, dilation and degradation in case of cohesive element based discretisaton of discontinua .

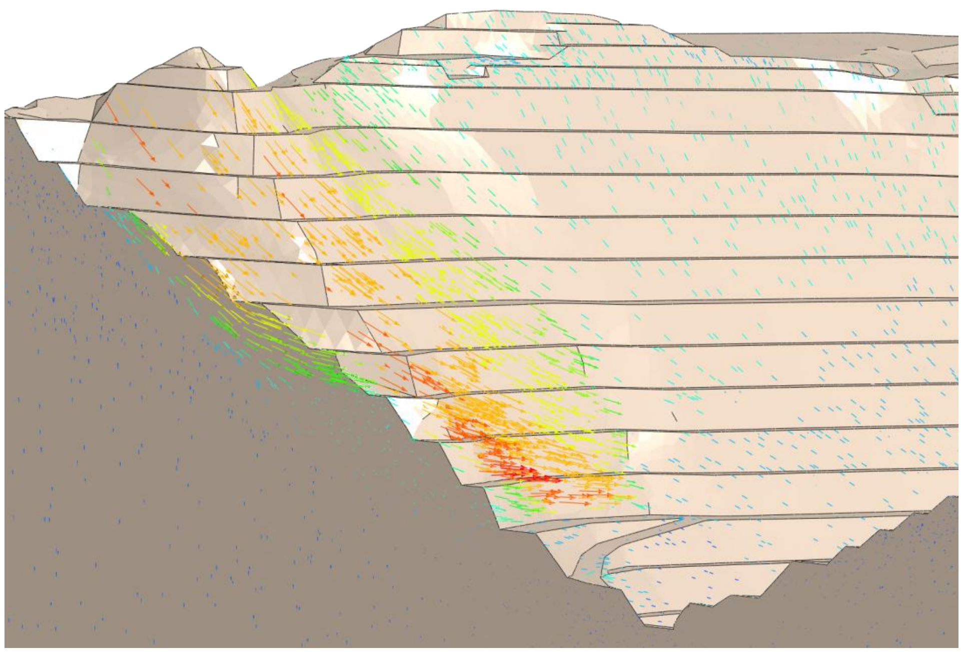

Figure 1. Analysis of a failure mechanism in a large open pit using Abaqus.

Markets where utilization of Abaqus simulations could significantly grow include:

1. Resources sectors, in particular assessment of hydrocarbon reservoir dynamics, subsidence and well bore stability / integrity as a result of hydrocarbon production in continuum or dis-continuum environments.
2. Environmental sectors, for example, simulation of ground water flow for aquifer production and recharge in either continuum or dis-continuum environments.
3. Energy sector, for example, simulation of hydrothermal energy
4. Civil sector, for example, analysis of slope stability or tunneling operations with or without consideration of ground water influence in continuum or dis-continuum environment.

However, it is to be realized that the commercial application of Abaqus in these markets, including the mining sector, is small when compared to the automotive or aeronautical industry. It is a common perception that Abaqus is either not suitable or is too complex for utilization at say a mine site level, and a reluctance to use or accept the use of Abaqus ensues. Thus, whilst Abaqus has been shown to exhibit the capacity to be applied in a rapidly expanding economic market, it is currently of secondary consideration behind other analysis suites that offer a simplified approach, often at the expense of simulation accuracy or flexibility. Strategic areas of potential enhancement to Abaqus have been identified to increase what is best described as `user friendliness`, and can be directly linked to the marketability of Abaqus for future geotechnical applications. These items are discussed below

3. Enhancing Abaqus for simulation in geotechnical and mining applications

Many advances developed to enhance simulation in traditional markets such as automotive and aeronautical industries are equally beneficial for geotechnical markets, such as advances in model creation and meshing tools, solution parallelization and development of robust contact behavior. The following are potential enhancements that if implemented, could improve the acceptance of Abaqus in the field of mining and geotechnical simulation.

3.1 Enhancing Abaqus for simulation in mining / civil applications

Simulation in mining applications presents multiple challenges including:

1. The necessity to represent multiple levels of scale ranging from a kilometer scale to cover the full extent of the mine to a meter scale for drives / extraction geometry.
2. Complex strain softening, dilatant material behavior.
3. The presence of discontinua (i.e. faults).
4. Complex 3D geometry.
5. Detailed sequence or model change conditions such as extraction and refill. Several hundred steps are typically necessary to simulate the stress path accurately.
6. The need to couple the effect of pore water in large scale models.

A necessity for multiple levels of scale in conjunction with an occurrence of complex 3D geometry often manifests in terms of very large mesh sizes with millions of higher order elements, which often preludes the use of ABAQUS/Standard and necessitates the use of quasi static Abaqus/Explicit analysis. Unfortunately, there are several inherent restrictions for an `out of the box` user that can limit `usability`. For example:

1. Abaqus/Explicit does not enable element deletion or activation via functionality similar to that exhibited by *MODEL CHANGE, REMOVE. Excavation and refill options must be incorporation via amplitude curves using field variables and material property dependencies or implemented with of user subroutines (i.e. VUMAT and VUSDFLD).
2. Abaqus/Explicit does not incorporate a geostatic stress option to initiate in-situ geostatic stress without introduction of strain, or damage. The equivalent option is available in Abaqus/Standard (*GEOSTATIC).
3. Incorporation of cohesive elements along intersecting discontinuities such as faults can be difficult using Abaqus/CAE.
4. The absence of a pore fluid simulation capabilities in Abaqus/Explicit

Based on the above observations the following enhancements can be suggested to improve the functionality of ABAQUS regarding mining applications:

1. Introduce `out-of-the-box` model change capability to model element deletion/removal and refill in Abaqus/Explicit. This method must be able to support several hundred instances of model change and large meshes in excess of tens of millions of DOF.
2. Introduce the geostatic step in Abaqus/Explicit for strain free ramping of in-situ geostatic stress.
3. Introduce pore fluid modeling capabilities to Abaqus/Explicit.
4. Introduce framework for modeling intersecting faults / slides using cohesive elements. Particularly important if pore fluid transport in such faults / slides is to be examined. A more detailed discussion on this topic is presented below.

3.2 Enhancing Abaqus for simulation in reservoir applications

Abaqus/Standard currently supports the analysis of continuum reservoir environments that contain a single phase pore fluid. Potential application of ABAQUS to key markets including hydrocarbon production, ground water modeling and geothermal energy production will require the capability to incorporate:

1. Multi-phase pore fluid flow capability in Abaqus/Standard and Abaqus/Explicit.
2. Flow along intersecting discontinua such as faults.
3. Efficient representation of appropriate near well bore dynamics.

The latter two points need further explanation.

Consider the inclusion of discontinua such as faults into a large scale reservoir model. As with applications in mining, reservoir models are likely to be expansive whilst also requiring inclusion of small scale features such as the geological thickness of fluid bearing layers or stratigraphy in reservoir geology. Inclusion of discontinua such as faults using a continuum approach will therefore be detrimental to mesh size and a `structural` approach is required. At the present stateof-the-art, Abaqus/Standard incorporates a similar cohesive gap element functionality, though this approach is not easily adapted to model pore flow as opposed to its intended gap flow, an interconnected fault network or critical changes in permeability (resistance to flow) that may arise due to progressive damage. Furthermore, the expectant size of such reservoir models may necessitate the need to adopt an explicit solution approach. It is suggested advantageous to investigate inclusion of pore fluid flow capabilities to an explicit solution scheme and investigate the inclusion of a cohesive element through which pore fluid flow in fault networks can be incorporate via material constitutive properties such as porosity, permeability etc. How this may impact application of mass scaling will also need consideration.

The topic of efficient representation of near well bore dynamics is derived from an observance that an explicit cylindrical representation of a well or wells in a large full scale reservoir model will potentially introduce a very large model size that make simulation on a global scale unfeasible. An alternative approach would be to develop an element enrichment protocol for pore fluid pressure / flow similar to X-FEM capabilities developed for structural assessment of cracked bodies. In this case, enriched elements are used on / adjacent to a line or stringer that defines the well trajectory and associated near well bore dynamics. Significant savings in model size are expected.

4. Conclusions

Simulation in mining and geotechnical applications is a growing market, one in which Abaqus is well positioned. This article describes current Abaqus analysis capabilities in the field of geotechnical simulation and poses potential Abaqus enhancements to enable Abaqus to become a market lead in the fields of mining and reservoir engineering. The capabilities and markets discussed herein represent those identified and serviced by Coffey Mining.

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