Modeling of inelastic failure leading to borehole breakout

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Abstract

Inelastic deformation is an irreversible process that is not adequately described with linear elastic-brittle approach. The classical linear elastic-brittle approach systematically overestimates the stress concentrations on the borehole wall, because inelastic deformation is underestimated. A continuum damage mechanics (CDM) concept is implemented in a finite element software Abaqus to model the complex fracturing process and inelastic deformation in the development of the borehole breakout. The proposed approach explicitly models dissipative behavior of the material due to cracking and its evolution which leads to an inhomogeneous redistribution of material properties and stresses in the vicinity of the borehole wall. We are able to represent several characteristics of the failure processes during the breakout development as observed in experimental results, e.g. localized cracks distribution in the vicinity of borehole wall, damage evolution which shows a widening process in the beginning followed by subsequent growth in depth, shear-fracturing-dominated breakout in sandstone. Furthermore, a good agreement between the geometry of the breakout resulted from our numerical simulations and the laboratory experiments is achieved.

Introduction

Continuum damage mechanics (CDM) was developed since the work of Kachanov [1] and Rabotnov [2], who considered the creep of metal. The key concept of this method is that distributed defects in the material and structure not only lead to crack initiation and coalesce to fractures, but also induce progressive material damage. The theoretical framework was not developed further until the work of Chaboche [3] who use the general framework of thermodynamics of irreversible processes. The CDM approach does not prescribe the microcracks that causes the damage, rather it uses a damage parameter to define the effect of damage on the free energy of the system [4].

Modeling the expected degree of damage of a rock mass around cavities is required in many subsurface geotechnical problems such as for boreholes and tunnels. The importance of the material properties on the borehole breakout development have been highlighted in some studies, e.g. Zheng et al. [5], Sahara et al. [6] among many others. Several modelling attempts that take into account the changes of the material properties of the rock have been conducted in order to model the damage propagation around boreholes.

Here we study the development of borehole breakouts in a plastic homogeneous material using the CDM approach. The plastic law obtained by Busetti et al. [7] is used as a basis for the plastic deformation involved in the simulation. Some micromechanical analyses of borehole breakouts available in the literature, e.g. Ewy [8], Haimson and Lee [9], Haimson [10], are used to better interpret and compare the results obtained in this study. As we model the transient process of damage propagation, we aim for a better understanding of the failure processes that lead to the final breakout shape observed in the laboratory and the field.

Method

A continuum damage mechanics concept (CDM) is used in this study to handle the complex fracture network and inelastic deformation that could not be explained by the elastic approach. It is a concept of deformation simulation in material, based on the damage evolution due to microcrack development, which might better represent the in-situ rock behavior. Unlike the insertion of cohesive or shielding zones, damage propagation is localized within weakening zones that are determined by the material constitutive behavior. Yielding is characterized by nonlinear inelasticity associated with stress-induced damage accumulation [11]]. This approach has several advantage points. First, field and experimental studies display complex networks of fractures that cannot be explained by elastic analysis. Second, damage mechanics does not require any special assumption, such as initial perturbations or nonrealistic high stresses. Third, damage fracturing does not suffer from the present computational limitations of local element enrichment formulations (e.g., the extended finite element method [XFEM]).

Table 1. Model parameters for the breakout simulation

Density (kg/m^3)	2100
Young's modulus (GPa)	23.2
Poisson's ratio	0.17
Dilation angle (°)	15
Eccentricity	0.1
Ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress	1.16
Stress intensity factor	0.66

The CDM approach is implemented by using the concrete damage plasticity capability of the finite element suite Abaqus [12]. The Busetti [7] plastic law is taken as basis for the CDM model. We apply the initial stress at the mesh to model the stressed rock in the underground. Displacement boundary conditions are chosen, i.e. the outer nodes are fixed and the inner nodes of the wellbore wall are free. At the beginning of the simulation the nodes at the wellbore wall are fixed to simulate the undisturbed rock. Drilling of the well is simulated by instantaneous release of this boundary condition. The effect of the weight of the mud, which usually is used to stabilize the wellbore, can be added by applying a radial pressure to the borehole wall. The parameters used in this simulation are listed in Table 1.

Results

The code is run for a synthetic plastic medium with a modified plastic law from Busetti et al [7]. A borehole with radius of 10 cm is modeled. This model is pre-stressed with a far field effective stress with a magnitude of 25 MPa and 60 MPa for the minimum (Shmin) and the maximum horizontal stress (SHmax), respectively, and 40 MPa for the vertical stress (Sv). This model is built to represent the production borehole in the typical reservoir at depth of around 2.5 km.

Figure 1 shows the development of the damage area with time. The elements within the boundary shown in this figure are highly damaged, which means that they would be easily washed off by the circulation of the drilling mud. It can be seen that the damage area propagation is governed by the high stress distribution at the damage front. Inserting the invariant stresses magnitude at each time step into yield surface equation [8], it is found that the stress magnitude at time t=0.01 s and t=0.04 s are bigger than the yield strength, hence the damage area continuously expanse at this time period. At the end of the simulation, time t=0.1 s, von Mises stress concentration at the damage front is very high, however the radial stress is also high. The radial stress act like normal stress in Mohr-Coulomb criterion. The increase of the magnitude of this stress make the stress concentration at the damage front is lower that the yield surface. Hence it can be concluded that model has reached the stable condition. At the end of the simulation, a wide and deep damaged area is formed. Under high values of compressive stress, tensile splitting is suppressed and shear failure takes place, hence, only compressional damage is formed in this simulation.

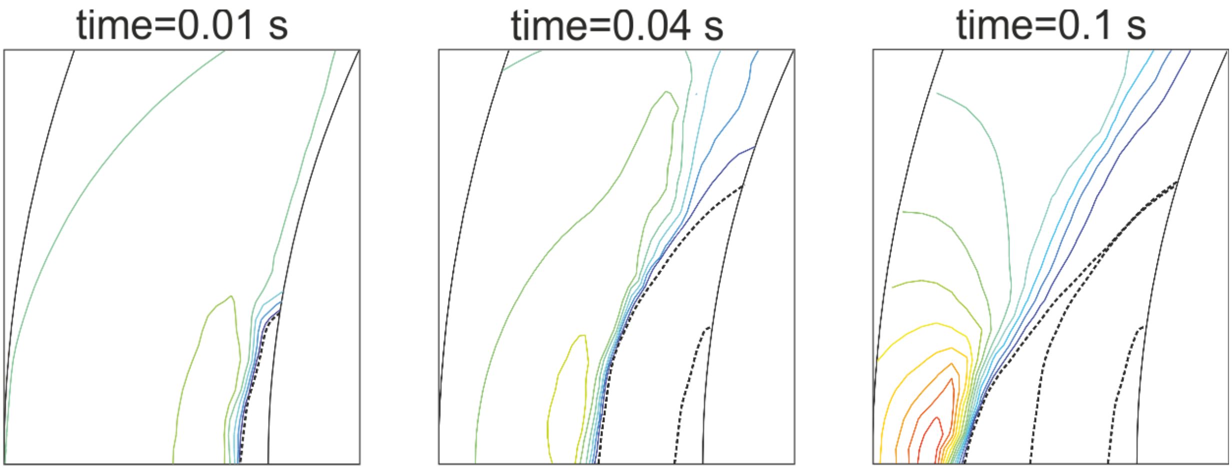

Figure 1. The development of the breakout area (dashed line) and the von Mises stress distribution (solid line) as a function of time. Breakout is interpreted as the area of damaged elements. Colors indicate the von Mises stress magnitude.

Discussion and conclusion

One issue that commonly occurs in simulations that involve softening processes is mesh dependency. Several models with element sizes at the wellbore wall ranging from 1.5 mm to 3 mm are used to check the consistency of the results. The outer shape of the damage area is picked as a proxy for the outer boundary of the breakout. It is found that the shape of the damage area resulted in this simulation is consistent for five model used in this test. The variation of the breakout size is entirely within the element size used. Hence it can be concluded that the geometry of the damaged area is mesh independent. Although the element size does not influence the inferred size and shape of breakouts, the internal structure obtained in this numerical simulation is mesh dependent. Hence we do not interpret this internal structure. A more sophisticated mesh scheme is required in order to model those locally failure processes, e.g. Cosserat continuum [13].

Based on the numerical modeling results, it can be concluded that the very first stage of breakout development is the development of the small plastic strain area very close to the borehole wall in the minimum horizontal stress direction. This is similar with the initiation of small intergranular cracks at the highest stress-strength ratio area at a low applied stress observed in the laboratory experiments e.g. Haimson [10], Ewy and Cook [14]. The damage area could not penetrate deeper because the overstressed area in the vicinity of the borehole wall does not extend very deep into the rock, due to the strengthening effect of radial stress.

It is interesting as the breakout develop wider and deeper at the beginning and, after time t=0.04 s, the damage area only develop deeper. It is in agreement with the hypothesis from the early work of Zoback et al. [15] and Zheng et al. [5] which showed that the redistribution of stress around a broken out borehole deepen the failed zone but do not widen it. The microscopic observation of borehole breakout at sandstone done by Ewy and Cook [14] also revealed that the growth of splitting cracks which oriented parallel to the tangential stress, starting with a long splitting crack very close to the hole wall and deepening with a shorter crack to the rock. Haimson [10] also showed (figure 19 of his paper) a series of the spallation zone which develop wider at the beginning before it is deepening at the later stages. Hence, it can be concluded that, at least for sandstone, CDM model able to reproduce the similar features observed in the laboratory measurement.

References

[1] Kachanov LM. Time of the rupture process under creep conditions. Izv Akad Nauk {SSR} Otd Tech Nauk. 1958;8:26-31.
[2] Rabotnov YN. Kinetics of Creep and Creep Rupture. In: Parkus H, Sedov LI, editors. Irreversible Aspects of Continuum Mechanics and Transfer of Physical Characteristics in Moving Fluids: Springer Vienna; 1968. p. 326-34.
[3] Chaboche JL. Continuum Damage Mechanics: Part II—Damage Growth, Crack Initiation, and Crack Growth. Journal of Applied Mechanics. 1988;55:65-72.
[4] Lubliner J, Oliver J, Oller S, Oñate E. A plastic-damage model for concrete. International Journal of Solids and Structures. 1989;25:299-326.
[5] Zheng Z, Kemeny K, Cook NGW. Analysis of borehole breakouts. Journal of Geophysical Research. 1989;94:7171-82.
[6] Sahara DP, Schoenball M, Kohl T, Müller BIR. Impact of fracture networks on borehole breakout heterogeneities in crystalline rock. International Journal of Rock Mechanics and Mining Sciences. 2014;71:301-9.
[7] Busetti S, Mish K, Hennings P, Reches Z. Damage and plastic deformation of reservoir rocks: Part 2. Propagation of a hydraulic fracture. AAPG Buletion. 2012;96:1711-32.
[8] Ewy RT. Yield and closure of directional and horizontal wells. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. 1993;30:1061-7.
[9] Haimson B, Lee H. Borehole breakouts and compaction bands in two high-porosity sandstones. International Journal of Rock Mechanics and Mining Sciences. 2004;41:287-301.
[10] Haimson B. Micromechanisms of borehole instability leading to breakouts in rocks. International Journal of Rock Mechanics and Mining Sciences. 2007;44:157-73.
[11] Heap MJ, Faulkner DR, Meredith PG, Vinciguerra S. Elastic moduli evolution and accompanying stress changes with increasing crack damage: implication for stress change around fault zones and volcanoes during deformation Geophysical Journal International. 2010;183:225-36.
[12] Simulia. Concrete damaged plasticity. In: Abaqus, editor. Rode Islan: Dassault Systèmes; 2015.
[13] Bazant Z, Belytschko T, Chang T. Continuum Theory for Strain-Softening. Journal of Engineering Mechanics. 1984;110:1666-92.
[14] Ewy RT, Cook NGW. Deformation and fracture around cylindrical openings in rock—II. Initiation, growth and interaction of fractures. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. 1990;27:409-27.
[15] Zoback MD, Moos D, Mastin L, Anderson RN. Wellbore breakouts and in situ stress. Journal of Geophysical Research. 1985;90:5523-30.