Borehole stability in the brittle and ductile regime

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Introduction

Borehole stability and its prediction is an important part of the production from reservoirs. The failure takes place in the form of breakouts, whose geometry depends on the properties of the rock and the stress state. When not leading to failure, the geometry of breakouts can serve for the determination of the stress state. In the present work, two methods are presented for the simulation of borehole breakouts in the ductile and in the brittle regime, respectively. In the first case, the challenge is posed by the localization of the deformation in narrow zones, that renders the solution mesh-dependent. A non-local model is introduced to resolve the dependence on the mesh refinement. The model is calibrated on experimental results and its capacity to capture the different types of breakouts is illustrated. For brittle failure, continuum models are not suitable, as continuity is lost once fragments separate themselves from the wall of the borehole. A numerical technique based on conformal mapping is introduced to resolve the issue. This method is semi-analytical, in the sense that the evaluation of the solution itself is analytical, while the mapping between the reference and the final domain is numerical. The procedure is relatively straightforward and very efficient. This model is calibrated on the same experimental results and its effectiveness is illustrated. Finally, the results of the two models are compared and conclusions are drawn.

Ductile borehole failure

For the description ductile failure, a cap yield surface with strain softening was used, calibrated on gasbeton (Gerolymatou 2017). A nonlocal model was implemented in the commercial code Abaqus, to resolve the mesh dependence resulting from softening. The simulations were performed under plane strain conditions with about 200’000 elements each and a duration of about two days on 4 cpus. Examples under different initial stress conditions are given in figure 1. The boreholes were assumed vertical, so that the vertical stress, σ_v, is the out of plane stress component. σ_h is acting in the horizontal direction, as the figures are viewed. The legend gives the degree of damage. The initial stress states for the first three figures from left to right are given in Table 1.

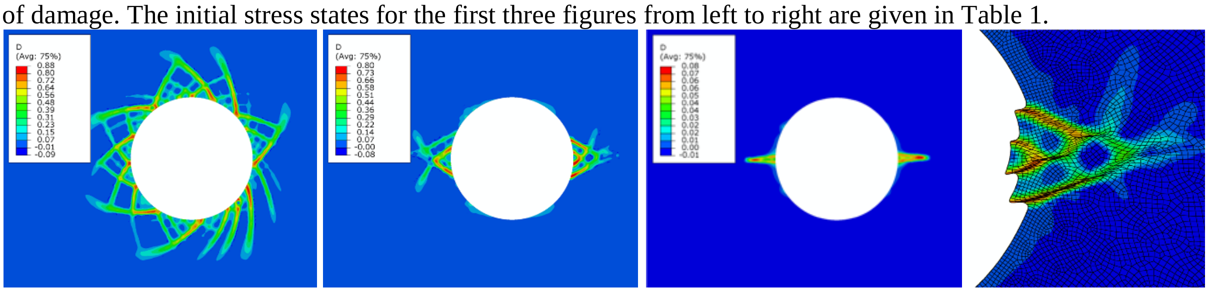

Fig. 1: Examples of evaluated borehole breakouts under different initial stresses (1-3 from left to right) and verification of mesh independence

Table 1: Initial stress states in MPa for the results depicted in figure 1

Component	σ_h	σ_H	σ_v
1	2.5	2.5	2.5
2	2.0	2.5	2.2
3	3.5	3.8	3.5

The stresses were selected to yield the different breakout patterns observed in the literature, for example in (Meier et al. 2013, Haimson and Kovacich 2003, Ewy and Cook 1990). The figures were plotted in the initial, i.e. in the undeformed, configuration. The fourth subfigure of figure 1 is a magnification of a detail of the second subfigure in the deformed configuration. As may be observed, the zone of localized deformation has a width of several elements. Moreover, the simulation converges in spite of the strongly deformed mesh.

Brittle borehole failure

In the case of boreholes in brittle material, finite element methods are not applicable, as continuity is lost. A semi-analytical method based on conformal mapping is suggested here. Using conformal mapping, the problem of an opening of arbitrary shape in the actual space can be transformed to that of a circular opening in a reference space. The mapping needs to be evaluated, as well as the boundary conditions in the reference domain. The solution can then be evaluated analytically, though a numerical approach is selected here, due to the large number of calculations involved. The interested reader may find more details on the method in (Muskhelishvili 1977).

A variation of the method of simultaneous equations, introduced by (Kantorovich 1933), is used here to evaluate the conformal map. This method can be applied when the function of the boundary in the reference space is known, which is generally not the case. To circumvent the problem, a procedure similar to the one suggested by (Fornberg 1980) is introduced. When the stress field is evaluated, the areas that fail are removed and the procedure is repeated for the new geometry.

Two examples of results are shown in figure 2. A Mohr-Coulomb failure criterion was used with friction angle and cohesion equal to 40º and 2 MPa, respectively. The minimum in plane primary stress was equal to 2.0 MPa in both cases, while the maximum was equal to 4.0 and 5.5 MPa for the subfigure on the left and on the right, respectively. The minimum stress acts in the horizontal direction with respect to the view, while the axes represent spatial coordinates. The different lines correspond to different iterations. The duration of the simulation was in both cases about 6 min on a personal computer with two cpus for 1’000’000 points.

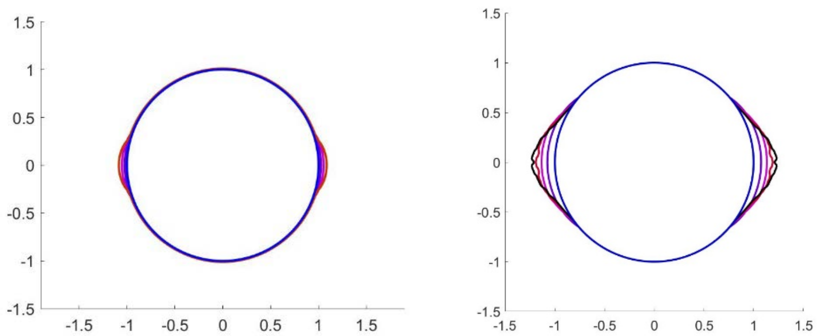

Fig. 2: Breakouts for different initial states.

Comparison and conclusions

Both methods presented here can reproduce experimental and in situ results. The numerical cost of the first method is significantly larger than that of the second one. On the other hand, due to the consideration of the internal length, the first approach can reproduce scale effects, whereas the second cannot. It is expected that the second method will predict larger breakouts, as yielding material is immediately removed and residual strength is not taken into account. At the same time, its calibration is much easier, as the post failure branch of the material response is not required. It may thus be concluded, that the first method is more suitable where high precision is of importance and the material behavior is well documented. The second method on the other hand is at an advantage, when uncertainties are present, information is scarce or parametrical analyses should be performed.

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