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A time step criterion for the stable numerical simulation of hydraulic fracturing

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The process of propagating or widening cracks in rock formations by means of fluid flow, known as hydraulic fracturing, has been gaining attention in the last couple of decades. There is growing interest in its numerical simulation to make predictions. Due to the complexity of the processes taking place, e.g. solid deformation, fluid flow in an open channel, fluid flow in a porous medium and crack propagation, this is a challenging task.

Hydraulic fracturing has been numerically simulated for some years now [1] and new methods to take more of its processes into account (increasing accuracy) while modeling in an efficient way (lower computational effort) have been developed in recent years.

An example is the use of the Extended Finite Element Method (XFEM), whose application originated within the framework of solid mechanics, but is now seen as an effective method for the simulation of discontinuities with no need for re-meshing [2].

While more focus has been put to the correct coupling of the processes mentioned above, less attention has been paid to the stability of the model. When using a quasi-static approach for the simulation of hydraulic fracturing, choosing an adequate time step is not trivial. This is in particular true if the equations are solved in a staggered way. The difficulty lies within the inconsistency between the static behavior of the solid and the dynamic behavior of the fluid. It has been shown that too small time steps may lead to instabilities early into the simulation time [3]. While the solid reaches a stationary state instantly, the fluid is not able to achieve equilibrium with its new surrounding immediately. This is why a time step criterion has been developed to quantify the instability of the model concerning the time step.

The presented results were created with a 2D poroelastic model, using the XFEM for both the solid and the fluid phases. An embedded crack propagates following the energy release rate criteria when the fluid pressure within the crack rises. The fluid flow within the crack and in the porous medium are simulated using the mass balance for water and Darcy's law for flow. The equations for flow and deformation in the rock and that for flow in the fracture are solved in a staggered manner. The two sets of equations are coupled via Lagrange multipliers. We present a time step criterion for the stability of the scheme and illustrate this criterion with test examples of crack propagation.

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