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Fully coupled poroelastic peridynamic formulation for fluid-filled fractures

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ABSTRACT

A new fully coupled poroelastic peridynamic formulation is presented and its application to fluid-filled fractures is demonstrated. This approach is capable of predicting porous flow and deformation fields and their effects on each other. Moreover, it captures the fracture initiation and propagation in a natural way without resorting to an external failure criterion. The peridynamic predictions are verified by considering two benchmark problems including one- and two-dimensional consolidation problems. Moreover, the growth of a pre-existing hydraulically pressurized crack case is presented. Based on these results, it is concluded that the current peridynamic formulation has a potential to be used for the analysis of more sophisticated poroelastic problems including fluid-filled rock fractures as in hydraulic fracturing.

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1. Introduction

The coupling between changes in stress and changes in fluid pressure forms the foundation of the subject of poroelasticity (Wang, 2000). The theory of poroelasticity has important applications in geomechanics including oil exploration, gas-hydrate detection, seismic monitoring of CO_2 storage, hydrogeology, etc. (Carcione et al., 2010). Poroelasticity has been studied for the last one hundred fifty years. The increase of exploitation of groundwater and hydrocarbon resources during early 20th century gave impetus to poroelastic research (Wang, 2000). Original formulation of poroelasticity was developed by Terzaghi (1925) based on his one-dimensional laboratory experiments and is known as Terzaghi's consolidation theory. This formulation was extended to a general three-dimensional formulation by Biot (1941). Numerical approaches have been widely used in the solution of poroelastic equations. Amongst these numerical techniques, finite-difference, psuedospectral, low-order finite element and spectral-finite element methods can be cited.

A recent popular application of poroelasticity is the analysis of hydraulic fracturing. The hydraulic fracturing process creates and propagates cracks in a porous medium by injecting fluid pressure. It has gained significant attention as a result of its use in oil and gas extraction from unconventional shale resources. In this particular application, a mixture of hydraulic fluid, sand, and chemicals is pumped into a well to create cracks in low-permeable shale, and keep them open after the removal of the fluid. Once the process is complete, the permeability of the shale increases significantly; thus, oil and/or gas starts to flow through the well. Another application of hydraulic fracturing concerns heat extraction from geothermal resources. Similar to the technique used in oil and gas extraction, the permeability of hot rocks is enhanced by pumping cold water into the rock. Cold water can be pumped from one well (injection well), and hot water can be extracted from the other well (production well). This technique, known as Hot Dry Rock (HDR), is used in the production of electricity.

It is difficult to model the hydraulic fracturing process due to the presence of multiple physical mechanisms; it involves fluid flow in a porous medium, mechanical deformation as a result of fluid pressure, and crack initiation and propagation. Various numerical models exist for the simulation of hydraulic fracturing. They are based on the Finite Element Method (FEM), Cohesive Zone Elements (CZE), eXtended FEM (XFEM), and, most recently, peridynamics. Hunsweck et al. (2013) developed a FEA-based algorithm, and captured the nonlinear coupling between the fluid pressure and crack opening. They included the fluid lag (the gap between the fluid front and the crack tip), which can be important for small toughness, and used the Griffith criterion for crack propagation. In another study, Ouyang et al. (1997) performed FEA for coupled hydraulic fluid transport and fracture analysis. They used an automatic and domain-adaptive remeshing technique for crack propagation.

Remeshing can be numerically difficult for certain problems; thus, CZE can be used to model hydraulic fracturing. Chen (2012) used a CZE to simulate the propagation of a viscosity-dominated hydraulic fracture in an infinite and impermeable elastic medium. Two different meshing schemes were utilized. The first scheme employed much finer cohesive elements than those of the neighboring elements. The second scheme employed the cohesive elements comparable in size with those of neighboring regular elements. The top and bottom faces

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of the cohesive elements were tied to the surrounding regular elements by imposing a surface-based tie constraint. As expected, the first scheme was computationally more expensive than the second scheme. It was reported that the accuracy did not depend on the size of the cohesive element.

This situation may cause a numerical problem in modeling the pressure distribution near the injection point and the crack tip for a viscosity-dominated hydraulic fracture because the fluid pressure changes rapidly at these locations. Although cohesive zone elements are easy to use for crack propagation, the method leads to a mesh dependency problem since the crack must follow the regular element boundaries. In order to overcome this problem, an extended finite element method (XFEM) was introduced and also used for hydraulic fracturing simulations. Lecampion (2009) utilized XFEM by introducing special tip functions to capture the crack tip asymptotic accurately. Both toughness-dominated and viscosity-dominated conditions were investigated; a difficulty was encountered in simulating large toughness and small viscosity conditions when the fracture was driven by a very small pressure gradient. In addition to FEM based approaches, meshless techniques are also developed for fluid-driven fracture such as immersed particle method (Rabczuk et al., 2010a). In this technique, structure and fluid particles are coupled by using a master-slave scheme and fluid is allowed to flow through openings between crack surfaces.

As opposed to the aforementioned studies that are mainly based on classical continuum mechanics, the hydraulic fracturing phenomenon can also be analyzed by using peridynamics (Silling, 2000), which is a non-local continuum mechanics approach. Peridynamics removes the difficulties that were observed in earlier studies, such as mesh dependency, unphysical singularities, and selection of a suitable failure criterion. Moreover, the inherent characteristic of peridynamics permits crack propagation in a natural way. Hence, Turner (2013) extended the original form of peridynamics by including the fluid pore pressure. However, the pore pressure was calculated by using a local approach a priori. On the other hand, this study presents a fully coupled bond based peridynamics approach to simultaneously simulate both deformation and porous flow fields. The current peridynamic formulation has a potential to be used for the analysis of more sophisticated poroelastic problems including fluid-filled rock fractures as in hydraulic fracturing and presented in Zhou and Burbey (2014), Li et al. (2014) and Helmons et al. (2016). Moreover, the formulation can be extended to be applicable for more complex material behavior by following a similar procedure explained in Oterkus and Madenci (2014).

2. Peridynamics

A non-local continuum theory, peridynamics, introduced by Silling (2000) overcomes the aforementioned difficulties arising due to the existence of discontinuities in the structure. As opposed to classical continuum mechanics, a material point inside the body can interact with other material points within its domain of influence called the “horizon,” H with radius δ as shown in Fig. 1. The interaction (bond) between two material points $\mathbf{x}$ and $\mathbf{x}'$ is expressed by using a response function, $\mathbf{f}$. The response function contains all the constitutive information related to the material point. It is assumed that the interactions beyond the horizon vanish. Although the original application of peridynamics concerns the equation of motion and cracking in an elastic medium, it is also applicable to other field equations (Gerstle et al., 2008; Oterkus and Madenci, 2011, 2013, 2014; Oterkus et al., 2013, 2014a,b,c; Oterkus, 2015; Han et al., 2015, 2016; Kilic and Madenci, 2010; De Meo et al., 2016; Bobaru and Duangpanya, 2010, 2012; Chen and Bobaru, 2015). The detailed derivation of peridynamics and its applications are given in a book by Madenci and Oterkus (2014).

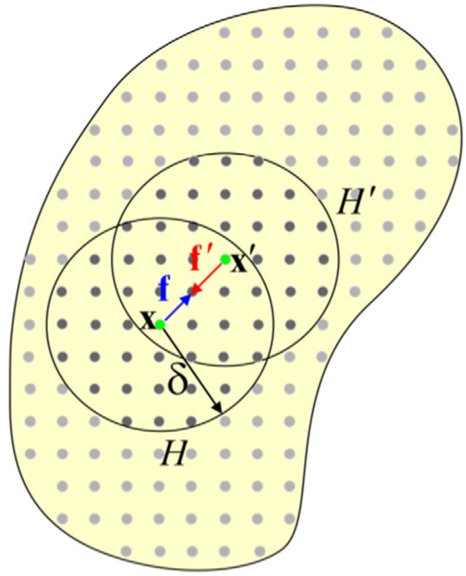

Fig. 1. Interaction of a material point with its neighboring points.

2.1. Peridynamic equation of motion

As opposed to the classical continuum mechanics, displacement derivatives do not appear in peridynamic (PD) equations, allowing the peridynamic formulation to hold everywhere whether or not displacement discontinuities are present. As derived by Silling (2000), the peridynamic equation of motion at a reference position of $\mathbf{x}$ and time t is given as

$$\rho(\mathbf{x})\,\ddot{\mathbf{u}}(\mathbf{x},t)=\int_H \mathbf{f}(\mathbf{x}'-\mathbf{x},\mathbf{u}'-\mathbf{u})\,dV+\mathbf{b}(\mathbf{x},t) \tag{1}$$

in which $\mathbf{u}$ is the displacement vector field, $\mathbf{b}$ is a prescribed body-force density field, and ρ is mass density in the reference configuration. The response function, $\mathbf{f}$, that defines the force between two material points is written as

$$\mathbf{f}=cs\frac{\mathbf{y}'-\mathbf{y}}{|\mathbf{y}'-\mathbf{y}|} \tag{2}$$

in which $\mathbf{y}$ represents the position of the material point, $\mathbf{x}$ in the deformed configuration. Also, the stretch, s, between the material points is defined as

$$s=\frac{|\mathbf{y}'-\mathbf{y}|-|\mathbf{x}'-\mathbf{x}|}{|\mathbf{x}'-\mathbf{x}|} \tag{3}$$

As derived by Silling and Askari (2005), the material parameter (bond constant), c, for an isotropic material can be expressed as

$$c=\frac{2E}{A\delta^2}\ \text{(1-D)} \tag{4a}$$

$$c=\frac{9E}{\pi h\delta^3}\ \text{(2-D)} \tag{4b}$$

$$c=\frac{12E}{\pi\delta^4}\ \text{(3-D)} \tag{4c}$$

in which E represents the Young's modulus of the solid skeleton, and A and h are the cross-sectional area and thickness, respectively.

2.1.1. Mechanical deformation due to fluid flow

There exists a complete analogy between poroelasticity and thermoelasticity (Wang, 2000). Therefore, in the presence of a fluid pressure, the peridynamic equation of motion of a material point at $\mathbf{x}$

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