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FLUID DRIVEN FRACTURE ANALYSIS WITH ZERO-THICKNESS INTERFACE ELEMENTS

Josep M. Segura* **and Ignacio Carol***

* Civil Engineering School of Barcelona (ETSECCPB)
Technical University of Catalonia (UPC)
Campus Nord UPC – Build.D2; E-08034 Barcelona, Spain
e-mail: josep.maria.segura@upc.edu – ignacio.carol@upc.edu

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Summary. *This paper deals with the hydro-mechanical coupled analysis of cracks and discontinuities. The formulation of the problem is based on the discrete crack approach, in which each discontinuity is explicitly discretized by means of interface elements of zero-thickness and with double nodes, which are equipped with the appropriate mechanical and diffusive constitutive laws. The use of the same interface element to describe the mechanical and the hydraulic behavior of the discontinuity is very advantageous, especially in the context of the staggered procedure that has been used to solve a fluid driven fracture problem in an initially intact porous medium (i.e. hydraulic fracture).*

1 INTRODUCTION

In geomechanical or geotechnical problems, the mechanical and hydraulic behavior often appear combined and influenced reciprocally, leading to the so-called hydromechanical (HM) coupled problems. The creation and progressive opening of discontinuities due to the action of a pressurized fluid is a key aspect that will represent an additional coupling factor.

Although extensive literature is available on the mechanical analysis of fractures and the HM coupled formulation of porous media, HM models for fractured porous medium are not so common[1], and even less common are the formulations for fluid driven fractures –hydraulic fracture– in porous media[2].

This article proposes a FEM formulation for the HM coupled problem in cracks and discontinuities provided the use of zero-thickness interface elements with double nodes. Its use for mechanical analyses has been well established since some time already[3], whereas for hydraulic problems it has been recently proved to give reasonable results in standard diffusion problems[4] and also introducing the influence of a transversal transmissivity. The use of the same joint element for both flow and mechanical problems is numerically convenient. As a previous step to the development of a fully coupled formulation, a staggered strategy is followed and its scheme is briefly introduced. An application example that deals with the classical hydraulic fracture phenomenon is presented.

2 HM COUPLED FORMULATION

The HM coupled problem can be tackled according to three different approaches[5]: a fully coupled formulation, a one-directional formulation and a staggered formulation.

In the *fully coupled formulation*, the HM behavior of the system is described by means of a single group of equations that incorporates all the physics and couplings relevant to the problem. Analogously to the case of saturated porous media, the HM behavior of a joint can be described through the FEM based "u-p formulation", which results in a system of equations of the following type:

$$\begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{E} \end{bmatrix} \begin{bmatrix} \mathbf{u} \\ \mathbf{p} \end{bmatrix} + \begin{bmatrix} \mathbf{K} & \mathbf{L}^T \\ \mathbf{L} & \mathbf{S} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{u}} \\ \dot{\mathbf{p}} \end{bmatrix} = \begin{bmatrix} \dot{\mathbf{F}} \\ \mathbf{Q} \end{bmatrix} \tag{1}$$

This system is usually highly non-linear, since its components can strongly depend on the solution of the system (u-displacements, p-fluid pressures), and proper advanced numerical techniques must be used.

The sometimes called *uni-directional coupling formulation* solves both hydraulic and mechanical problems separately by two independent codes. However, the results of one of the analyses are periodically used by the other one to capture the coupling effects. The information exchange is always in the same direction and it is not considered at every time-step (in the case of transient analyses).

In the iterative coupled or *staggered formulation*, the hydraulic and the mechanical equations are solved separately too, but the coupling loops iteratively transfer the information between the two codes until convergence is reached. It is important to note that in this case the information exchange is always in the two directions and for each time step.

In the work presented, the staggered methodology starts with the solution of the hydraulic problem, which gives the nodal pressure distribution. This fluid pressure distribution is used by the mechanical problem to perform the analysis in terms of effective stresses. Resolution of the mechanical problem allows us to calculate the joint aperture, which in fact will influence the joint hydraulic conductivity value and its space to store fluid (i.e. capacity term). Resolution of the hydraulic problem with the new aperture influence results in a new nodal pressure distribution, so that an iterative procedure is established until a tolerance is satisfied.

2.1 Mechanical constitutive model

Interface mechanical behavior is reproduced by means of a work-softening elasto-plastic constitutive law, formulated in terms of the stresses on the interface plane, normal and shears, and the corresponding normal and tangential relative displacements. This constitutive model is described and analyzed in detail in Carol et al.[6], and used in many other analyses[7,8] involving 2D and 3D crack opening and propagation.

2.2 Hydraulic constitutive model

A recently proposed diffusion interface formulation described in detail in Segura and Carol[4] is used for the open or potential discontinuities. It reproduces longitudinal and transversal diffusion processes to the discontinuity through a double-nodded zero-thickness interface element, resulting in an improvement of previous proposals. The use of the same interface element with two nodes allows us to use the same mesh in the staggered procedure.

3 HM COUPLED ANALYSIS: HYDRAULIC FRACTURE

The considered problem[2] consists of injecting fluid along an incipient crack located at the lower left corner of the domain (Figure 1). This produces the propagation of a fracture along the lower boundary, where the zero-thickness interface elements have been inserted. The problem is analyzed in steady-state, i.e. studying the long term behavior of the system and analyzing which would be the ultimate length of a fracture for a given flow injection. This influx is progressively increased. Interface elements are inserted along the crack path (lower boundary). Fluid flow along the opening discontinuity is supposed to follow the cubic law[9].

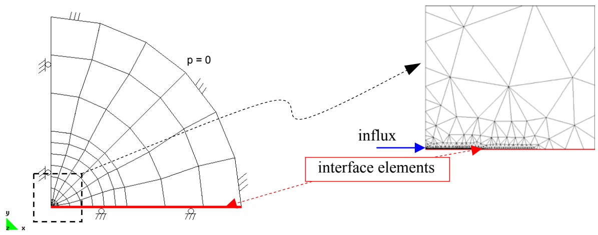

Figure 1: Scheme of the hydraulic fracture problem.

Figure 2(a) depicts the development of the crack as the value of the fluid flow entering the system is increased. This preliminary results show how the fracture effectively propagates, although it has to be noted that the convergence of the method needs considerable iterations in advanced stages of the analysis. Therefore, a fully coupled formulation of the problem would seem desirable and remains an objective in the immediate future. Figure 2(b) shows how, once the fracture has reached a sufficient development, the pressure profiles at the injection zone change and the flow enters the porous medium from the fracture. At the same time, and in connection to that, the fluid potential drop along the fracture is very low.

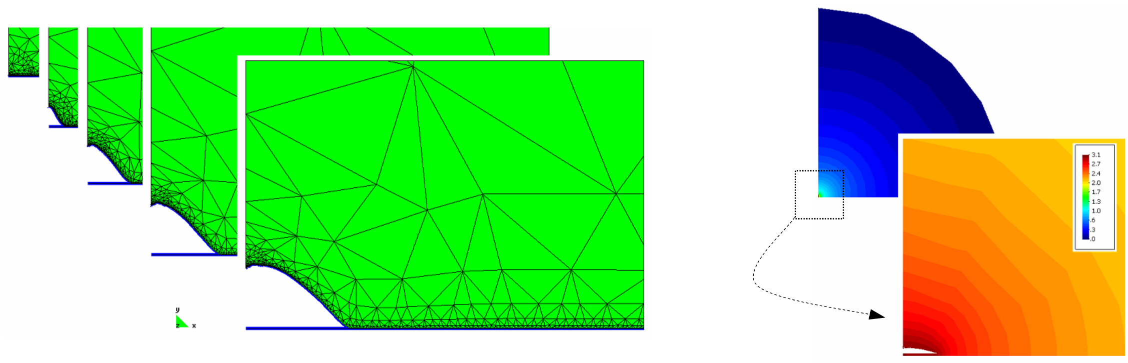

Figure 2: (a) Fracture propagation (b) Hydraulic head profile.

4 CONCLUDING REMARKS

- A new formulation based on the FEM using zero-thickness interface elements and staggered strategy is being developed to solve numerically the coupled hydro-mechanical problem, with application to hydraulic fracture and other processes with mechanical-diffusion coupling through interfaces.
- The formulation is based on a double-node interface element for both mechanical and diffusion analysis, and it incorporates a transversal potential drop trough the discontinuity. The same finite element mesh may be used for mechanical and flow analysis, with the subsequent advantages in numerical implementation.
- Preliminary results on fluid-driven fracture have been obtained, which satisfactorily reflect the physics of the process. On going work is devoted to a fully coupled procedure in order to improve the numerical efficiency.

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