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Hydro-geomechanical modelling of seal behaviour in overpressured basins using discontinuous deformation analysis

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Abstract

A coupled hydro-geomechanical modelling environment, developed to evaluate the coupled responses of fluid flow in deforming discontinuous media, is described. A staggered computational framework is presented, where the two simulations tools, HYDRO and DDA, communicate via the mapping of an equivalent porosity (and related permeabilities) from the rock system to the fluid phase and an inverse mapping of the pressure field. Several algorithmic and modelling issues are discussed, in particular the computational procedure to map the current geometry of the discontinuous rock blocks assembly into an equivalent porosity (and permeability) field. A generic, geometrically simple, overpressured reservoir/seal system is analysed for illustration. Further examples investigate discontinuous, fractured configurations in flexure causing a degree of spatial variability in the induced stresses. Model predictions show that the combination of hydraulic and mechanical loads causes a dilational opening of some pre-existing fractures and closure of others, with strong localisation of the modified flow pattern along wider fracture openings.

Keywords: Discontinuous deformation analysis; Porous media; Hydro-geomechanical modelling; Overpressured basins; Seal failure

1. Introduction

The existence of overpressure in hydrocarbon reservoirs is a major reservoir management concern from both a safety and an economic perspective. Hydrocarbons are generated in the deep organic-rich mudrocks and tend to migrate to porous and permeable reservoir rocks. In locations where low permeability sealing rocks overlie the reservoir rocks a hydrocarbon trap is created (see Fig. 1). In most cases the sealing layer actually acts as a leaky seal with some flux of hydrocarbons out of the reservoir (Couples, 1999). This sealing layer is often characterised by some matrix permeability and small-aperture fractures and, when overpressures are created in the reservoir, has a higher fluid pressure below the seal than above it: this is the scenario investigated here. Such a leaky seal system operates at considerable depths and pressures, with small, but complex, block interactions, and is quite impractical for reproduction in a testing laboratory. This paper describes a numerical method of investigating the behaviour of such systems, illustrating the use of this approach in some very simple reservoir-seal scenarios.

On the computational front, continuum approaches have been used successfully for many subsurface geo-

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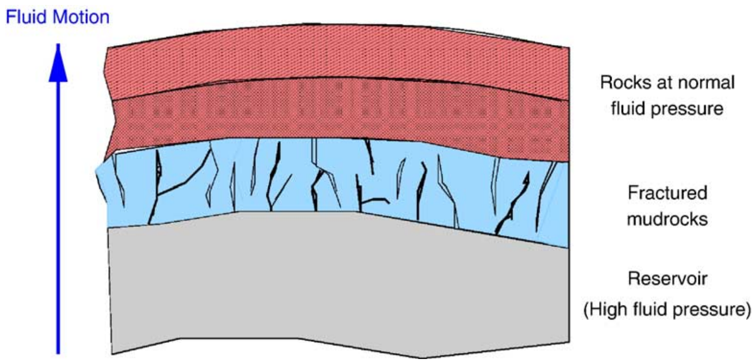

Fig. 1. Schematic vertical diagram through the top of a reservoir, highlighting the overpressured reservoir and fractured mudrocks (the seal).

logical and hydrogeological problems, but the use of continuum approaches to model saturated materials with discrete discontinuities has met with only limited success. A number of discontinuum-based, or discontinuum-incorporating simulators have been developed in the disciplines of geomechanics, petroleum, and environmental engineering (e.g., Lee et al., 2000; Gurpinar and Cossack, 2000). Typically, most of these tools focus on only a few components of the complete multi-physics problem, or greatly simplify the interactions between these components. For example a finite element stress analysis crudely coupled with a finite difference flow program can be used for predicting surface subsidence. Other studies (e.g., Aifantis, 1980; Barenblatt et al., 1960; Elsworth and Bai, 1992; Smart et al., 2001; Lewis and Ghafouri, 1997; Koutsebeloulis et al., 1994) use the double porosity approach — where one porosity represents the fracture network and the other a continuum porous medium. This approach treats matrix and fracture systems as essentially independent of one another, communicating through a leakage, or transfer, term, but still demonstrates a strong coupling between fluid flow and solid deformability.

In this paper a framework for modelling deformable discontinuous media is coupled with a continuum formulation for flow through fractured media. In such a system there is considerable flexibility in defining initial block and fracture geometries. Furthermore, solid deformability and fracture/matrix fluid flow are represented in such a way that fracture apertures reflect both the deformation of solids and changes in the fluid pressure. Fractures are represented deterministically. The discontinuous medium is represented by the Discontinuous Deformation Analysis DDA method (Shi, 1988) and the fluid flow system by a continuum finite element steady-state flow model HYDRO. The fluid system is assumed to obey Darcy's law which employs a fixed finite element mesh and responds to pressure (potential energy) boundary conditions (e.g. Garven and Freeze, 1985). The DDA method represents the blocky, dry, discontinuous deformable solid phase responding to force or displacement boundary conditions and to the initial state of stress. Block contact constraints are imposed through an implicit augmented Lagrangian format. These two linked frameworks, denoted here as HYDRO–DDA, communicate via mapping of an equivalent porosity field from the solid to the fluid phase and an inverse mapping of the calculated pressure field (Rouainia et al., 2001). This linkage allows us to investigate the interaction between the pore-fluid and mechanical loads. HYDRO–DDA is currently realised as a two dimensional simulator.

2. The HYDRO–DDA components

HYDRO–DDA is the product of a staggered coupling of the two modelling environments HYDRO and DDA. The principle of the interface is illustrated schematically in Fig. 2, where HYDRO calculates the fluid pressures and flow rates in a 2-D model containing a number of different materials with specific permeabilities. Fluid pressures are then passed to the DDA environment. The pressure field is interpolated to the current positions of the DDA block vertices, which furnishes the equivalent forces used in the calculation of the further deformation of the loaded assembly of blocks. These equivalent forces – which represent effective stress behaviour – produce, in general, a change in the configuration of the solid block assembly — i.e. they induce block rotations, translations and/or straining. These changes in block geometry are returned to HYDRO as changes in porosity and permeability. The new fluid flow solution is found for the current level of permeabilities, which leads to