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Model for simulating hydromechanical responses in aquifers to induced hydraulic stresses: Laboratory investigation and model validation

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ABSTRACT

The environmental consequences of the hydraulic fracturing of shale beds have raised widespread concern, especially with regard to groundwater. For example, the hydraulic pressure and permeability in an upper aquifer may be affected by a flow injection process owing to the interaction between the fluids and the deformation of porous media. To experimentally investigate the hydromechanical (HM) effect of the induced hydraulic stresses, a column device was developed. The acquired experimental data was used to develop a coupled HM numerical model, which was used to further investigate the upper aquifer properties. A multiphysics simulator was used to implement the relationship between the permeability and the volumetric strain, and the permeability of the numerical model was calibrated by an error analysis. The results of the HM model were compared with those of a single flow model, and the variations of the hydraulic pressure and permeability with the injection pressure were also analyzed. It was found that the coupled HM model was more sensitive to changes in the permeability compared to the single flow model, and that the former produced better numerical results. The hydraulic pressure in the upper aquifer was determined to decrease with increasing height and the largest change was 1.13 times the initial value. Furthermore, the largest permeability change was observed to correspond to an injection pressure of 40 kPa and was 3.33E-4 times the initial value. This maybe neglected. A higher injection pressure was further found to increase the permeability, which also generally increased with increasing height.

1. Introduction

Shale gas has attracted much attention in the global oil and gas industry as an important unconventional gas resource. Currently, shale gas production wells are either vertical or horizontal. Moreover, due to the ultra-low permeability and low porosity of shale gas reservoirs, the production wells require large-scale multistage hydraulic fracturing treatment to ensure economic production. By 2030, it is expected that half of all natural gas produced in the United States will come from unconventional sources, primarily shale formations (Rozell and Reaven, 2012). At the Marcellus production well site in American, a single well consumes 545,000 gallons (2063 m^3) of fracturing fluid, 0.5% (approximately 10 m^3) of which comprises fracturing additives (Lee et al., 2011). About 91% of the fracturing fluid used at the Pennsylvania fracking site is retained in the shale gas reservoirs or adjacent stratum structures. The effect of stranded fracturing fluid on shallow drinking water aquifers has become a matter of concern (Myers, 2012).

The above is a complex problem. Shale gas is stored under certain environmental conditions that are subjects of thermodynamics (Wu et al., 2013, 2015), hydraulics, mechanics, and chemistry, and these conditions affect the production process. Thus, the fracking process changes the environmental conditions (Flewelling and Sharma, 2014) such as the ground stress, groundwater pressure, and geothermal properties (Saiers and Barth, 2012). Therefore, correct analyses of the environmental conditions of the shale gas reservoir and the multi-field coupling characteristics are necessary for the effective production of shale gas.

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Generally, an injection process induces complex hydromechanical (HM) interactive processes. For instance, when the fracturing fluid is injected into a vertical shale gas production well, the fractures are generated under the high pressure of the injected fluid. According to Soeder (Soeder, 2010), there are mainly two stratum overburdens on the Marcellus shale gas reservoir in the Appalachian Basin in eastern United States, namely, a sandstone layer (beginning at the surface) and a siltstone layer (Fig. 1). In an accidental event, the fracturing fluid breaks through the shale gas reservoir and bursts into the overburden layer, with the high hydraulic pressure of the fluid increasing the stress in the layer and causing a little deformation. This is in accordance with the Terzaghi effective stress theory. The deformation also affects the matrix porosity and permeability, thereby altering the fluid flow through the pores as well as the groundwater table. During a HM process, the mechanical compression induces fluid pressure response, pressure storage and dissipation modify the mechanical condition through the effective stress (McKee et al., 1988; Neuzil, 2003). There is thus the need to clarify the HM mechanism of an induced hydraulic stress process.

Some theoretical and experimental studies of the behavior of low-permeability materials have been conducted to investigate the HM behavior during an induced hydraulic stress process. Investigation of the HM coupling effect on the hydraulic pressure was also recently discussed (Murdoch and Germanovich, 2006; Walsh et al., 2008; Castelletto et al., 2012; Nagel et al., 2013; Zhu et al., 2013; Vishal et al., 2015a,b). Several simulation codes are used for numerical investigation of the HM behavior. For example, OpenGeosys, which is an open-source code (Li et al., 2013), has been used to analyze the effect of heat on the HM properties of clay (Wang et al., 2014) and the coupled flow and mechanical deformation of a fractured rock (Walsh et al., 2008). The Universal Distinct Element Code (UDEC), which is a two-dimensional discrete element method (DEM) code, has also been used to investigate the effect of stress field changes due to hydraulic fracturing on the natural fracture system of shale formations (Nagel et al., 2013). The reservoir simulator COMET3 has been used to develop a 3-D numerical model that replicates the field conditions using data for Indian coal seams (Vishal et al., 2013, 2015). In addition, many researchers have used numerical methods to study the effect of an HM process on the hydraulic pressure (Lin and Lee, 2009; Wang et al., 2010; Zhou and Hou, 2013). This is relevant to several other injection processes.

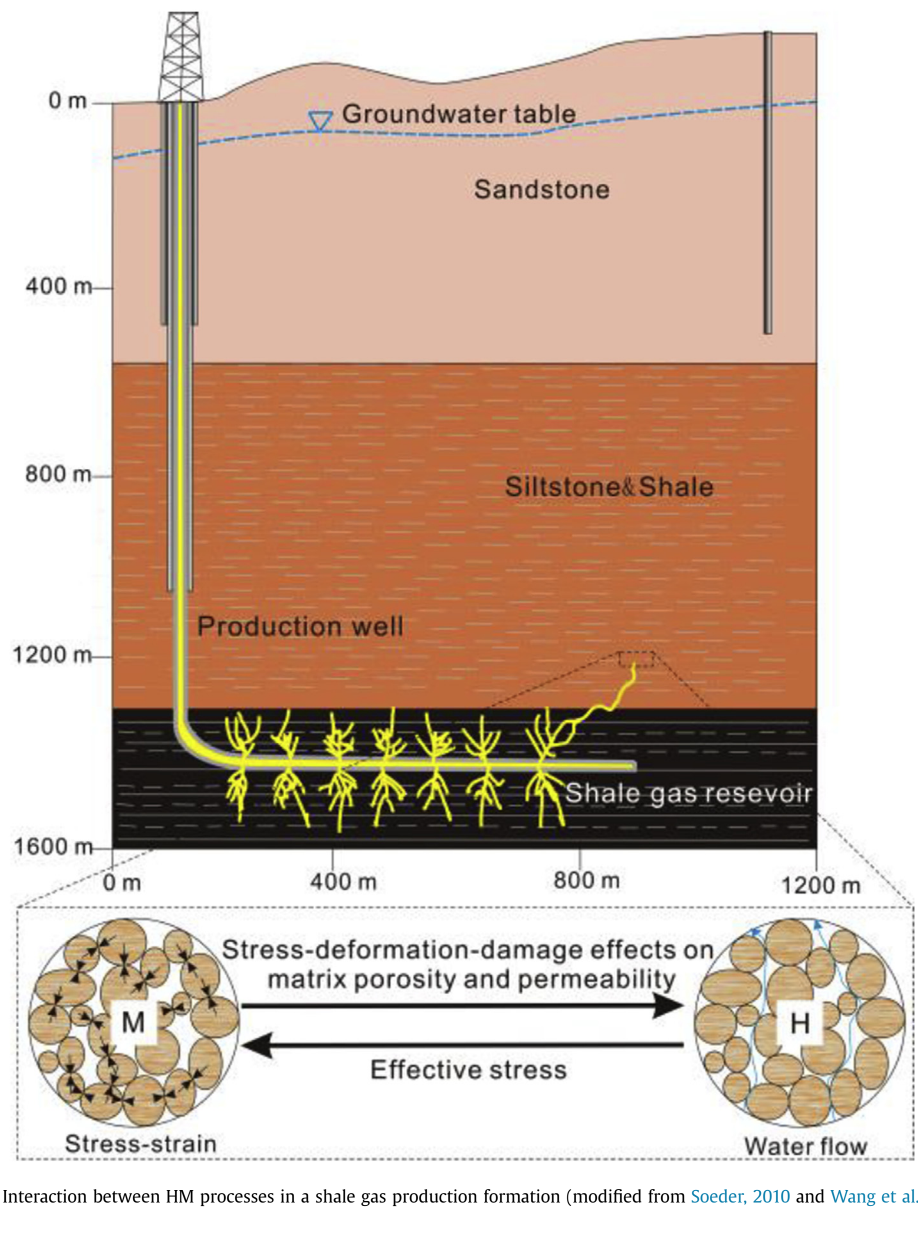

Fig. 1. Interaction between HM processes in a shale gas production formation (modified from Soeder, 2010 and Wang et al., 2014).