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Stochastic discontinuum analysis of hydrocarbon migration probability around an unlined rock cavern based on the discrete fracture networks

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ABSTRACT

This paper presents a framework for application of stochastic discontinuum method for evaluating the uncertainty of hydrocarbon migration around an unlined rock cavern (URC) in water-bearing rock formations. The occurrence of hydrocarbon migration in fractures around the URC was calculated by using a numerical technique based on the migration tracing algorithm and pathway analysis through discrete fracture network (DFN) realizations. The numerical modeling of hydrocarbon migration and uncertainty analysis of fluid flow processes were performed for different arrangement of hydraulic boundary conditions with respect to water curtain pressure head (WCPH) and height of oil in the cavern. The results of numerical simulations demonstrate that the uncertainty and spatial distribution of hydrocarbon migration around URC are very sensitive to the hydraulic boundary conditions, and the geometrical configuration of fractures. The migration probability of both gas and oil decreases non-linearly by increasing the WCPH; however, the rates of decrement for oil and gas are completely different. The maximum migration probability of gas and oil occurred in the case of minimum and maximum height of oil in the cavern, respectively. For most of the hydraulic boundary conditions, the distance and probability of migration for gas are much higher than those for oil. The zones prone to gas and oil migration are mainly concentrated in the neighboring area of the cavern roof and vertical walls, respectively. However, due to the heterogeneous flow system and irregular interconnected fracture networks, the gas and oil migration are possible in the regions below the oil level and below the water bed, respectively. Moreover, the mean and standard deviation of total length and number of migrated fractures around the URC decrease by increasing the WCPH. In addition, both the number of gas migrated fractures and gas escape probability decrease by increasing the height of oil in the cavern. These findings might prove useful for taking optimal decisions in an uncertain framework and for a better design analysis of unlined rock cavern.

1. Introduction

Underground storage of hydrocarbon in unlined rock caverns (URCs) is a widespread method, which has the advantages of safety and economy compared to conventional above-ground surface tanks. Utilization of URCs for hydrocarbon storage calls for stringent precautions of hydrocarbon migration and environmental protection. Prediction of environmental impacts and the efficiency of hydrocarbon storage in URCs requires realistic and robust predictive model based on the physical processes that govern the hydraulic interactions between water-saturated rock mass and hydrocarbon.

The typical safety concern in URCs is to prevent hydrocarbon migration from the cavern to the surrounding rock mass. The principle behind prevention of hydrocarbon migration in URCs, called hydraulic confinement, is to establish continuous groundwater flow toward the cavern from outside rock to confine the stored hydrocarbon inside the caverns (Froise, 1987). To achieve the hydraulic confinement, the actual groundwater pressure acting on the cavern periphery should exceed the vapor pressure of the hydrocarbon by a certain amount. The pressure difference between groundwater and vapor (or gas) in the cavern is generally determined by gas-containment criteria, which have been theoretically proposed based on groundwater gradient or pressure (Åberg, 1977; Goodall et al., 1988; Liang and Lindblom, 1994; Lindblom, 1997). These hydraulic criteria have been mostly applied in numerical modeling efforts to indirectly evaluate the efficiency of gas-containment around the storage cavern.

In many cases, gas-tightness evaluation and hydraulic modeling of URC hydrocarbon storages have been performed by using deterministic

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equivalent continuum approach (Shimada et al., 1980; Thunvik and Braester, 1981; Tal and Dagan, 1983, 1984; Liang and Lindblom, 1994; Lee and Chang, 1995; Sun and Zhao, 2010). The deterministic continuum approach relies on the assumption of homogeneous hydraulic properties of rock mass surrounding the storage caverns. However, most of the geological formations show random variations, spatial nonuniformity, and considerable uncertainty in the hydrogeological parameters (Freeze, 1975; Renard, 2007). A large part of such uncertainties can be eliminated by means of stochastic hydrogeology (Dagan, 2002, 2004; Hu et al., 2004; Neuman, 2004; Renard, 2007; Winter, 2004) that deals with stochastic methods to describe and analyze the hydraulic processes. Therefore, in recent studies the hydraulic modeling of unlined cavern storages have been performed by the implementation of stochastic continuum models that consider heterogeneity and spatial variability of hydraulic conductivity (Chung et al., 1999, 2003; Kim et al., 2007; Maejima et al., 2007; Aoki et al., 2010). However, the continuum-based models for fluid flow analysis in fractured rocks are valid only for special conditions of geological structure (Niemi et al. 2000; Lin and Lee 2009; Scesi and Gattinoni, 2009) and scale of dominant physical processes (Hsieh and Neuman, 1985; Schwartz and Smith, 1988; Bear et al., 1993). These conditions are infrequently held for rock mass surrounding the URC hydrocarbon storages; therefore, the continuum-based modeling of hydraulic processes around URCs will be associated with poor cognitive performance and impoverished reliability in the analysis, especially for hydrocarbon migration processes.

Most of the URCs are constructed in good quality and hard rocks (Froise, 1987; Zhao, 1996; Lee and Song, 2003), where fractures are the main flow paths and control the hydrocarbon migration phenomenon. Physically speaking, hydrocarbon migration from the URCs is only possible along the rock fractures (Yoshida et al., 2013, Goel et al., 2012); therefore, more realistic fluid flow analysis can be achieved through discontinuum representation of fractured rock mass surrounding the URCs. The discrete fracture network (DFN) concept is a robust alternative to the discontinuum representation of fractured rock and appears much more adaptable for fluid flow analysis (Bear et al., 1993; Min et al., 2004; Javadi et al., 2016a), especially for hydrocarbon migration processes. However, most of the discontinuum hydrogeological modeling efforts (Ra and Sung, 1999; Lee and Song, 2003; Li et al., 2014) are limited to evaluation of groundwater head distribution or water inflow into the URCs and a few studies focused on the migration analysis (Javadi et al., 2016b). On the other hand, natural fractures in rock mass have a complicated geometry with different degrees of connectivity, orientation, size, and spatial distribution (Caine et al., 1996; Cruden, 1977; Piggot, 1997; Bonnet et al., 2001; La Pointe, 2002; Wu et al., 2011) that cause spatially non-uniform and heterogeneous hydrogeological system with considerable amount of uncertainties. However, few studies have dealt with stochastic discontinuum method to describe and analyze the hydrocarbon migration around URCs, especially via direct utilization of DFN concept. The main contribution of this paper is to provide a framework for direct utilization of DFN concept for stochastic discontinuum modeling of the hydraulic interactions between stored hydrocarbon and water-bearing fractured rock mass surrounding an unlined cavern with emphasis on characterization of hydrocarbon migration uncertainty.

This paper presents the heterogeneity effects of fractures on the uncertainty of hydrocarbon migration around a storage cavern by using the stochastic discontinuum method. The analysis of hydrocarbon migration is performed based on the numerical technique that was recently developed and verified by Javadi et al. (2016b). The uncertainty analysis of fluid flow processes in terms of hydrocarbon migration is implemented for different arrangement of hydraulic boundary conditions with respect to the pressure of water curtain and height of oil in the cavern. Finally, an assessment is made to describe the uncertainty of hydrocarbon migration with detailed statistical attributes characterized by stochastic discontinuum numerical analysis.

2. Methods and background

2.1. Stochastic discontinuum method

The stochastic discontinuum method is a combination of discontinuum numerical modeling of fluid flow in fractured rock mass with stochastic hydrogeology. The main purpose of this method is to estimate the most likely range of spatial likelihood and uncertainty of hydrocarbon migration around URCs. From an engineering standpoint, the quantification of such uncertainties is extremely important not only because it allows estimating risk but mostly because it allows taking optimal decisions in an uncertain framework. Moreover, this method can be used to understand the impact of heterogeneity of hydrogeological attributes on the physical processes that govern flow in rock mass and to evaluate lack of information on design and management.

The discontinuum numerical modeling of fluid flow refers to a computational procedure including three main steps: (1) DFN generation and regularization; (2) discretizing and solving fluid flow equations; and (3) hydrocarbon migration tracing. This procedure is repeated for different sequence of random variables in computational domain (here different DFN realizations surrounding the URC) until a sufficient amount of output result is gathered. The main output result of stochastic discontinuum analysis is the statistical and spatial distribution of migrated fractures that shows the most likely range of spatial likelihood and uncertainty of hydrocarbon migration around the URC.

In order to apply the stochastic discontinuum method, the following assumptions are made in this study: (1) the URC is located in a fully saturated fractured rock mass, (2) the groundwater flow and hydrocarbon migration occur only through fractures (impermeable matrix); (3) the fluid flow through fractures is linear and governed by cubic law; (4) the fluid flow is in the steady state condition; (5) the density variation of fluids in each fracture (between fracture end points) is negligible; (6) the local-scale heterogeneity of geometrical and hydraulic properties of fractures can be represented by stochastic process, characterized by statistical parameters of probability distribution; (7) the fracture networks are statistically homogeneous at the field scale with statistically stable distribution of geometrical and hydraulic properties; and (8) the numerical simulations are performed for two-dimensional laminar flow, where the width of flow domain (third dimension perpendicular to flow domain plane) is assumed to be 1 unit.

2.2. Computational procedure and background

2.2.1. DFN generation and regularization

The stochastic discontinuum analysis in this study is performed by “FNETF” computational code, previously developed and verified for DFN generation, DFN regularization, fluid flow analysis, and hydrocarbon migration tracing (Javadi and Sharifzadeh, 2014; Javadi et al., 2016a,b). Different steps of hydrocarbon migration analysis through a DFN realization around a URC is shown in Fig. 1.

The first step of stochastic discontinuum analysis includes DFN generation and regularization. The two-dimensional DFN realizations are generated based on the Monte Carlo approach and statistical parameters of geometrical properties of fractures. The two-dimensional fracture network is created in an area called the generation region (Fig. 1-a). Fractures are represented as linear features defined with their geometrical properties in terms of location in the generation region (mainly based on the Poisson process), orientation with respect to the coordinate axes, and length that is assigned with the cumulative probability density function of the geometrical properties. After generating all fractures, a flow domain (or external hydraulic boundary) is selected for fluid flow analysis that lies entirely within the generation region. In the next step, the underground excavation boundaries are generated through the flow domain. The fractures crossing the flow domain and excavation boundaries are truncated. Then, hydraulically inactive fractures are deleted (Fig. 1-e) and the “dead-ends” of the