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Research paper

# Migration tracing and kinematic state concept embedded in discrete fracture network for modeling hydrocarbon migration around unlined rock caverns

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ABSTRACT

This paper presents a numerical method for the modeling of hydraulic confinement and hydrocarbon migration around the unlined rock caverns (URCs) by directly applying distinct fracture network (DFN) concept. A "migration tracing" algorithm for the assessment of hydrocarbon migration around URCs was developed based on the applying migration cessation criterion and pathway analysis in the DFN realizations. The veracity of the developed numerical method was explored by predicting the hydrocarbon migration in a uniform fracture network around an unlined cavern that consists with results obtained from the finite element continuum fluid flow analysis. Finally, the applicability of the proposed method was evaluated by simulation of hydrocarbon migration in the DFN realizations around a URC. The results demonstrate that the hydrocarbon migration is sensitive to the hydraulic boundary conditions, and the geometrical properties of fractures. Establishing sufficient water pressure in the fracture system controls hydrocarbon migration; however, the effect of external water pressure on the hydrocarbon migration is controlled by the fractures geometry. Consequently, local migration paths may develop around storage caverns through the intricately connected fracture network, despite the presence of high pressurized water curtain. The proposed method may prove useful for better design analysis of hydraulic confinement around URCs, or inclusions in simulators for computational demands.

## 1. Introduction

Prediction of environmental impacts and the efficiency of hydraulic confinement for hydrocarbon storage in unlined rock caverns (URCs) are the most critical issues faced by Hydrogeologists. Successful prediction of such issues requires realistic and robust predictive models based on the physical processes that govern fluid flow in rock mass.

The typical safety concern in URCs is to prevent hydrocarbon leakage from the cavern to the surrounding rock mass. The principle behind prevention of hydrocarbon leakage in URCs, called hydraulic confinement, is based on the application of groundwater pressure on the surrounding rock to confine the stored hydrocarbon inside the caverns (Froise, 1987). Appropriate application of hydraulic confinement poses a key question; (Liang and Lindblom, 1994; Chung et al., 2003); How large of pressure difference between groundwater and stored hydrocarbon in the cavern should be maintained to prevent hydrocarbon leakage?

The exact criterion for preventing hydrocarbon leakage from the URCs has been a matter of research for several years. During the past decades, different gas-containment, no gas leakage, criteria have been proposed based on groundwater gradient or pressure (Åberg, 1977; Goodall et al., 1988; Liang and Lindblom, 1994; Lindblom, 1997) that are theoretically a priority. These hydraulic criteria have been mostly applied in continuum numerical modeling efforts (Thunvik and Braester, 1981; Chung et al., 2003; Kim et al., 2007; Maejima et al., 2007; Aoki et al., 2010; Sun and Zhao, 2010). However, 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 leakage phenomenon (Goel et al., 2012; Yoshida et al., 2013). In fact, the physical processes that govern hydraulic behavior of rock mass are significantly controlled by the fractures (Indraratna et al., 1999, 2003; Javadi et al., 2010, 2014, 2015). In such situation, discontinuum representations of fractured rock,

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such as discrete fracture network (DFN) concept, appear much more adapted to physical processes. However, only a few studies (Dershowitz and Lapointe, 1995; Ra and Sung, 1999; Lee and Song, 2003) have been implemented on the fluid flow analysis in the rock mass surrounding the URCs via direct utilization of DFN. Dershowitz and Lapointe (1995) used a combination of DFN and percolation theory to evaluate the probability of gas escape (a percolation problem). Ra and Sung (1999) utilized a flow simulator in DFN to investigate the distribution of hydraulic head around a URC. The result of these studies showed that the discrete fracture model is more appropriate for the analysis of groundwater flow than the continuum model. A similar attempt was reported by Lee and Song (2003). Although the above-mentioned researches improved the general knowledge about the circumstances related to fluid flow around the URCs, a few studies have been focused on the numerical modeling of hydrocarbon migration. Moreover, few efforts have been implemented on the numerical modeling of hydrocarbon migration from the URCs to surrounding rock mass via direct utilization of DFN concept. Due to the destructive environmental consequences of hydrocarbon leakage, a more efficient and reliable model is strongly required for analysis of water-hydrocarbon interaction through the fractured rock mass surrounding the URCs that is developed and illustrated in this paper.

The purpose of this study is to develop a more realistic numerical method for modeling the hydrocarbon migration from URCs. For this purpose, an algorithm including new concepts, so-called "migration tracing" and "kinematic state", was developed based on the pathway analysis in the DFN and applying the migration cessation criterion. These procedures were integrated into the "FNETF" computational code, previously developed and validated for fluid flow analysis in fractured rocks (Javadi and Sharifzadeh, 2011a, 2011b, 2014; Sharifzadeh and Javadi, 2011; Javadi et al., 2016). The accuracy of the developed algorithm and numerical method was explored by predicting the hydrocarbon migration in a uniform fractured rock around an unlined cavern and comparing it with the results of finite element continuum fluid flow analysis. Finally, the procedure for hydrocarbon migration was numerically investigated in two different DFN realizations to evaluate the applicability of the developed numerical method for naturally fractured rock mass.

## 2. Concepts and theoretical background

### 2.1. Hydraulic confinement

The methods for limiting or eliminating hydrocarbon leakage from rock caverns can be categorized based on two main principles of permeability control, and hydraulic confinement (Kjørholt and Broch, 1992; Lu, 2010). Permeability control means that the leakage is eliminated by excavating the cavern in natural tight rocks (such as salt beds) or by using extra supplementary lining that refer to lined rock cavern. The second principle or "hydraulic confinement" is based on the application of groundwater pressure in the surrounding rock to confine the stored hydrocarbon inside the caverns. The technique of hydraulic confinement is to establish continuous groundwater flow toward the cavern from outside rock to prevent the hydrocarbon migration. 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.

Prevention of leakage by hydraulic confinement offers two alternatives: (1) natural groundwater pressure supplied by natural sources such as lake or sea; and (2) artificial water supply that is provided by installing so-called "water curtain" outside the cavern periphery. The groundwater pressure will drop if water is continuously removed from the cavern without sufficient natural replenishment (Thunvik and Braester, 1981). In most cases, the sufficient replenishment and necessary groundwater pressure can only be artificially achieved by installing water curtain. The water curtain installation consists of some infiltration galleries located above the caverns and arrays of boreholes drilled from these galleries (Fig. 1). The infiltration galleries will be filled and fed with pressurized water to supply the boreholes. The water is permanently injected to ensure full water saturation of rock in the construction and utilization phases. The water leaking into the cavern forms a layer, so-called water bed, on the cavern floor. The hydrocarbon products float freely on the water bed, because they are lighter and also insoluble in water. The leaking water is collected in a sump excavated in the cavern floor and pumped out (from sump) continuously to maintain the water bed in a constant level near the cavern floor. Pumping out the leaking water and feeding the infiltration gallery with external supply remain the system in a stable hydraulic state in the operation phase.

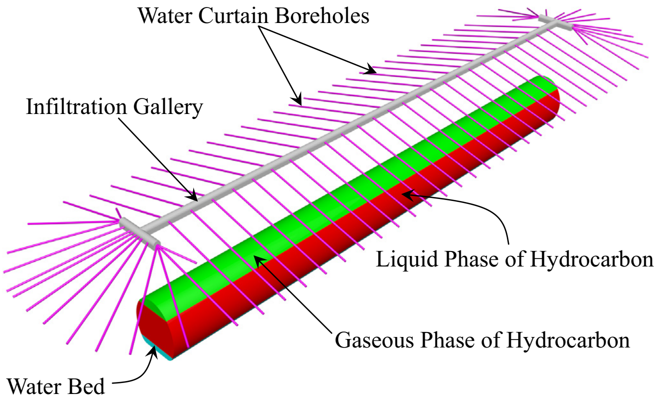

**Fig. 1.** Installation and components of water curtain around an unlined storage cavern.

### 2.2. Migration cessation criterion

Physically speaking, hydrocarbon migration from URCs is only possible along the fractures that provide declining hydrodynamic pressure away from the cavern (Goel et al., 2012). The hydrocarbon leakage phenomenon can be divided into two different physical processes. The first process is "hydrocarbon entry" from the storage into the rock fracture entrance that occurs when the hydrocarbon capillary force exceeds the pressure difference across the fracture interface within the cavern. The second process refers to the further movement of entering hydrocarbon along the fractures that called "hydrocarbon migration" (Åberg, 1977). Since the hydrocarbon entry is a very complicated physical process and very sensitive to high uncertain factors such as fracture-cavern intersection geometry, distribution of capillary force, and pressure distribution across the fracture interface, this process is rarely considered in practical design. In fact, most practical design approach for URCs is the prevention of hydrocarbon migration, not the entry (Söder, 1995). Therefore, the numerical method developed in this paper mainly focuses on the hydrocarbon migration process.

The hydrocarbon migration mostly occurs in the form of bubbles moving upward through the fracture (in the opposite direction of downward water flow). A schematic view of the forces acting on a hydrocarbon bubble in water-filled fracture (with downward water flow) is shown in Fig. 2. These forces are weight of the bubble, $F_G$, capillary force, $F_C$, and hydraulic pressure, $p_w$. The necessary condition to prevent the upward movement of hydrocarbon bubble along the fractures (for two-dimensional cases) can