Numerical Modeling of Hydraulic Confinement around Crude Oil Storage Cavern in Fractured Rocks: Direct Application of DFN Concept

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ABSTRACT: Unlined rock caverns for hydrocarbon storage are mainly excavated in strong and stable rock masses with very low-permeable matrix, where hydrocarbon migration is only possible along fractures connected to the cavern boundaries and their networks. In this paper, the hydraulic confinement around a URC cavern was simulated by directly applying distinct fracture network (DFN) model. First, a computational code, so-called "FNETF", was developed to generate DFN and solving fluid flow equation along fractures. Proper internal hydraulic boundary condition of water-hydrocarbon interface at cavern boundary was defined based on the fluids properties and applied in the FNETF code. Fluid flow in fracture network was numerically simulated for different outer boundary hydraulic conditions assigned by different groundwater pressures of water curtain. Finally, the assessment achieved to expect the occurrence of hydrocarbon.

1 INTRODUCTION

The principle of hydrocarbon storage in URC, called hydraulic confinement, is based on the applying the groundwater pressure of the surrounding rock to contain the stored product inside the cavern (Froise, 1987; Lindblom, 1989; Hamberger, 1991). The technique of hydraulic confinement is to establish water continuously flowing toward the cavern from outside rock to prevent hydrocarbon migration into the rock mass (Bérest, 1990). To reach the hydraulic confinement, the actual groundwater pressure acting at all points on the cavern periphery should be exceeded the pressure of the hydrocarbon compounds by a certain amount. The necessitate groundwater pressure can be achieved by locating the caverns far enough below the water table or, in most of the cases, artificially supplied by installing so-called "water curtain" outside the cavern periphery, which is arrays of boreholes drilled above the cavern and fed with water with desire pressure. With the hydraulic confinement and water curtain, the water hydraulic pressure in the rock mass around the cavern should be higher than the vapor pressure of the hydrocarbon and should be strong enough to prevent any leakage. Using such water curtain poses the key questions (Liang and Lindblom, 1994; Lindblom, U., 1989; Chung et al., 2003; Bérest, 1990; Heath et al., 1998); How large of pressure difference between groundwater and stored hydrocarbon in the cavern should be maintained to prevent outward leakage of hydrocarbon compounds from the cavern?

The exact criterion for preventing hydrocarbon leakage from the unlined cavern has been a matter of researches for several years. During the past decades, several gas-containment, no gas leakage, criteria have been proposed based on groundwater gradient or pressure (Åberg, 1977; Goodall et al., 1988; Kjørholt and Broch, 1992; Liang and Lindbiom, 1994; Lindblom, 1997). The gas-containment criterion suggested by Åberg (1977) is commonly used in the design of unlined cavern storage which is demonstrated that a vertical hydraulic gradient greater than 1.0 should be maintained through the rock fractures surrounding a storage cavern during operations. Goodall et al. (1988) proposed a simple criterion for practical design of hydraulic confinement around URCs, based on the simple law that no gas must leak as long as the water pressure increases along all possible gas leakage paths away from the cavern. This is a generalization of Åberg's recommendation and constitutes a simple and promising design criterion for gas-containment in unlined rock caverns without leakage. Although these hydraulic criteria are theoretically a priori, their practical application in the design process of unlined storage is not compatible with inherently heterogeneous nature of rock mass, especially in numerical modeling efforts.

Natural fractures in rock mass have a complicated geometry with different degrees of connectivity, orientation, size, and spatial distribution that cause heterogeneous and spatially nonlinear system. In such situation, discontinuous representations of fractured rock or discrete fracture methods, such as discrete fracture network (DFN) concept, appear much more adapted for fluid flow analysis in the rock mass surrounding the storage caverns. 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 storage caverns via direct utilization of DFN application. Although the above researches improved our understanding about circumstances related to fluid flow around cavern storages, few studies have been implemented on the numerical modeling of hydrocarbon migration from the unlined storage caverns via direct utilization of DFN concept that is the main contribution of this paper.

In this paper, the hydrocarbon migration from storage cavern is studied via direct utilization of DFN concept. To reach this goal, first, a special algorithm, so-called "migration tracing" is developed based on the applying the migration cessation criterion through a pathways analysis in the DFN model. The migration cessation criterion was applied based on the forces acting on the movement of hydrocarbon bubble in the water-filled fractures. A computational code, so-called "FNETF", was developed to generate DFN, solving fluid flow equation along fractures, and migration tracing of hydrocarbon. Finally, hydrocarbon migration in fractured rock mass surrounding a storage cavern was simulated for different kind of boundary conditions.

2 DEVELOPMENT OF NUMERICAL MODEL

2.1 *Migration cessation criterion*

The typical safety concern in the design of unlined storage caverns is based on the precautions to prevent hydrocarbon leakage. The hydrocarbon leakage phenomenon can be divided into two different physical processes, hydrocarbon entry and hydrocarbon migration (Åberg, 1977). The hydrocarbon entry is very complicated physical process and very sensitive to high uncertain factors. Therefore, the most practical design approach for unlined storage caverns was to prevent hydrocarbon migration not entry (Söder, 1995), as implemented in this paper.

With the hydraulic confinement, water continuously flow toward the cavern from outside rock to prevent hydrocarbon migration. The water hydraulic pressure along fractures should be strong enough to prevent any migration, where slowly moving water towards the storage was not sufficient to prevent migration. In fact, 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 forces acting on the movement of a bubble in water-filled fracture is shown in Fig. 1. These forces are weight of the bubble, F_G, capillary force, F_C, and hydraulic pressure , p_w. The necessary condition to prevent hydrocarbon migration along fractures (for two-dimensional case) can be expressed by

$$ap_{w1} + F_{C1} + F_G \cos(\theta) \geq ap_{w2} + F_{C2}\,, \tag{1}$$

where a is the aperture of the idealized parallel smooth fracture. The bubble weight (F_G) can be calculated as

$$F_G = \rho_h g L a\,, \tag{2}$$

Where ρ_h is the hydrocarbon density, g is the gravity, and L is the bubble length. By introducing Eq. (1) into Eq. (2), the rearranged form of migration cessation criterion can be written as,

$$(p_{w1} - ap_{w2}) + \frac{(F_{C1} - F_{C2})}{a} \geq -\rho_h g L \cos(\theta)\,. \tag{3}$$

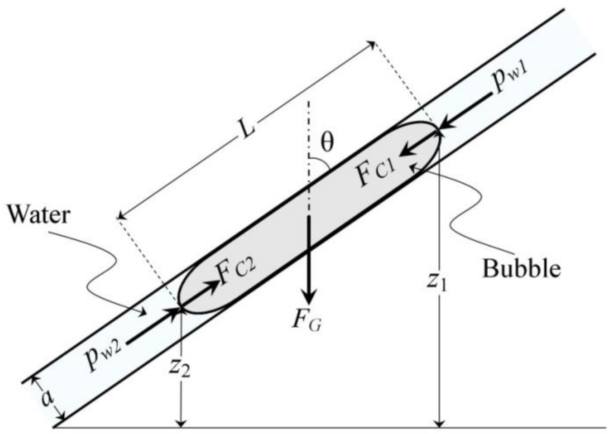

Figure 1. A schematic view of forces acting on the movement of a bubble in water-filled fracture.

At any arbitrary point along the flow streamline, the total head or energy head (H) is described by

$$H = z + \frac{p}{\rho g} + \frac{v^2}{2g} . \quad (4)$$

where z is the elevation of the point above a reference plane in the direction opposite to the gravitational acceleration, p is the pressure at the chosen point, ρ is the fluid density, and v is the fluid velocity. The decrease of total head, ΔH , between the points (1) and (2) in the Fig. 1 can be written as

$$\Delta H = H_1 - H_2 = (z_1 - z_2) + (\frac{p_{w1} - p_{w2}}{\rho_w g}) + (\frac{v_1^2 - v_2^2}{2g}) , \quad (5)$$

Where ρ_w is the density of water. By introducing Eq. (5) into Eq. (3), the migration cessation criterion can be formulated as,

$$\Delta H \geq (z_1 - z_2) - \frac{\rho_h}{\rho_w} L\cos(\theta) + (\frac{v_1^2 - v_2^2}{2g}) - (\frac{F_{C1} - F_{C2}}{a \rho_w g}) . \quad (6)$$

By neglecting the terms related to velocity and capillary force, the Eq. (6) can be reduced to,

$$\Delta H \geq \left[1 - \frac{\rho_h}{\rho_w} \right] (z_1 - z_2) , \quad (7\text{-a})$$

$$\Delta H \geq \left[1 - \frac{\rho_h}{\rho_w} \right] L\cos(\theta) . \quad (7\text{-b})$$

2.2 *DFN Generation*

The DFN concept, in which the rock is considered as a network of individual interconnected fractures, is an interesting discontinum representation of fractured rock, because of the detailed geometrical description of the fracture network geometry. The usual practice in DFN modeling is to assume that most of the geometrical parameters of each fracture set can be statistically distributed. The numerical model developed for this study, so-called "FNETF", uses a Monte Carlo approach to generate two-dimensional DFN models based on the statistical characterization of the fracture geometry. Fractures are represented as linear features defined with their geometric parameters in terms of location in the generation region, orientation with respect to the coordinate axes, length, and aperture. The individual fractures in the generation region are created one set at a time, and the number of fractures in each set is controlled by the areal density (number of fractures per unit area). A center point position for each fracture is determined by randomly selecting in the generation region. Fracture trace lengths are assigned with the cumulative probability density function of the trace length. The orientations of fractures are calculated using following respective cumulative probability density function.

After all fractures for all sets are generated, a flow domain is selected for fluid flow analysis. The flow domain lies entirely within the generation region and is usually centered in the generation region. All the fractures crossing the boundaries of the flow domain are truncated at the boundaries and out of flow domain fractures are deleted. In the next step, the underground excavation boundaries are generated through flow domain. Similarly, fractures crossing the excavation boundaries are truncated at the boundaries and inside excavation fractures are deleted. Because the generated fractures are finite, a relatively large number of fractures in the network may not be perfectly connected and some of them are not contribute in flow process. These hydraulically inactive fractures should be removed from the domain. Moreover, the "dead-ends" of the interconnected fractures are deleted and the network will be regularized. After this regularization, the DFN model becomes complete percolating graphs.

2.3 *Fluid Flow Analysis*

The regularized DFN model is a percolating graph consisting of nodes and elements that are fracture intersections and fracture segments between nodes, respectively. For this representation of the fracture network, the hydraulic head at each node and flow rate in each element are calculated using a flow network technique. To reach this goal, it is usually assumed that the cubic law governs the laminar fluid flow through fracture segments and the mass continuity equations are then established at the fracture intersections for steady state fluid flow between intersections.

Here a convention is used which indicates that flow to the node is positive and flow out is negative and the continuity equation can be represented by the matrix equation as (Rouleau and Gale, 1987; Prist, 1993):

$$HC = 0, \quad (8)$$

where C is the symmetric node conductance matrix and H is the total pressure head vector. The *i*-th diagonal component of the conductance matrix is the sum of the conductance of all the elements meeting at node *i*, and the off-diagonal component in position *i,j* either is minus the conductance of the element joining nodes i and j or is zero if they are not connected. The conductance of the fracture segment (c) is defined by

$$c = \frac{w\rho_w g a^3}{12L\mu_w}, \quad (9)$$

where μ_w is the water viscosity, L is the fracture length, and w is the fracture width in the perpendicular to the pressure gradient. The matrix and vector in Eq. (8) can be discretized according to the freedom degree of nodes and the resulting matrix equation takes the form (Rouleau and Gale, 1987):

$$\begin{bmatrix} C_{ff} & C_{fc} \\ C_{cf} & C_{cc} \end{bmatrix} \begin{Bmatrix} H_f \\ H_c \end{Bmatrix} = \begin{Bmatrix} Q_f \\ Q_c \end{Bmatrix}, \quad (10)$$

where *c* and *f* subscripts refer to free (unknown head) and constrained (fixed head) nodes, respectively, and Q is the flow rate vector. The value of the *i*-th component in the flow rate vector is non-zero for the fixed head boundary nodes and zero for the free internal nodes. Based on the statues of the nodes, the matrix and vectors in Eq. (10) are partitioned to the submatrix equation as,

$$\left[C_{ff}\right]\left\{H_f\right\} + \left[C_{fc}\right]\left\{H_c\right\} = \left\{Q_f\right\}, \quad (11)$$

The only unknown term in Eq. (11) is the internal node total pressure head vector $\left\{H_f\right\}$, which can be calculated through a numerical scheme with respect to the appropriate boundary conditions of fluid domain.

2.4 *Analysis of Hydrocarbon Migration*

Solving Eq. (11) leads the total pressure head of all fracture nodes in the flow domain. The occurrence of hydrocarbon migration through fractures in the flow domain can be calculated by using the total pressure head of fracture nodes in the flow domain. To reach this goal, a special algorithm, so-called “migration tracing” is developed that is based on the applying the migration cessation criterion (Eq. 7) through a pathways analysis in the flow domain. To apply this algorithm, first, it is necessary to define the main or initial migration source points. The main migration source points are defined as the intersection of fractures with storage cavern walls (the nodes on the cavern boundary) if there is special flow conditions. In fact, all the fractures directly connected to storage cavern are not the migration source points. Three different “kinematic states” can be considered for the nodes on the cavern boundary based on the flow direction and geometrical conditions of fractures (Fig. 2):

(I) The outward flow from inside cavern to the surrounding rock
(II) The simultaneous inward (from rock into the cavern) and downward (from the highest to lowest node) flow
(III) The simultaneous inward and upward (from the lowest to highest node) flow

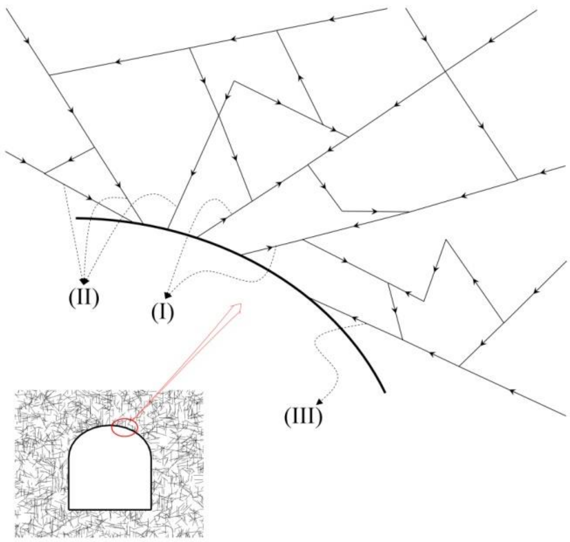

Figure 2. Kinematic states of fractures directly connected to the cavern boundary.

From the above conditions, the intersection node of all the fractures with state (I) are the main migration source points. The hydrocarbon inside cavern certainly migrates from this kind of fractures. For the fractures with state (II), the hydrocarbon migration occurs only if the migration cessation criterion (Eq. 7) is not satisfied. Such nodes also appear as the main migration source points. The hydrocarbon migration is not expected for the fractures with state (III). In fact, the fractures with inward but upward flow direction are not the source point of hydrocarbon migration. After all the main source points of migration are identified, the pathway analysis will be executed.

For each main source point, a pathway network is defined as the cluster of interconnected fractures that are directly or indirectly linked to the main source point. A library of migration fractures is formed for each main source point. All the fractures of pathway cluster that hydrocarbon migrates through them are stored in this library. The first member of this library is the fracture channel starting from the main source point. The second node on the channel starting from the main source point is considered as the interior source point. For all the channels connected to the interior source point (except the channels stored in the migration library), the kinematic states will be checked as same as described for the nodes on the cavern boundary. These channels are added to the migration library if the kinematic state indicates the migration occurrences. Similarly, the second node of these channels (added to the library) is considered as the new interior source point and the above pathway analysis will be repeated. This process will be continued until there is no new interior source point.

3 EXAMPLE APPLICATION

In order to present the applicability of developed computational code “FNETF” and “migration tracing algorithm”, hydrocarbon migration in fractured rock mass surrounding a storage cavern was simulated for different kind of boundary conditions. The simulation was performed for crude oil storage with gas pressure of 2 bar. Caverns for crude oil storage are usually pressurized to vary between 0.5 and 2.5 bar abs (Froise, 1987).

The geometrical statistics (such as orientation, trace length, and density) used for fractures generation through DFN model are summarized in Table 1. For this study, it is assumed that the rock mass around the cavern is characterized by three main fracture sets (named FS1, FS2, and FS3) and a class of randomly oriented fractures (FNS4). A constant hydraulic aperture of 500 µm was set for all the fractures in the flow domain.

A flow domain of 60 m width and 65 m height was used for fluid flow simulation and analysis of hydrocarbon migration (Fig. 3). A cavern with width of 20 m and height of 27.5 m was located in the middle of the flow domain in such a way that there was a 20 m distance between vertical walls of the cavern and vertical boundaries of the domain and also a 20 m distance between bottom of the cavern and lower boundary of the domain. The minimum distance between cavern roof and upper boundary of the flow domain is 22.5 m. The water curtain is considered to be located on the upper boundary of the flow domain.

The boundary conditions for internal boundaries (cavern walls) and external boundaries (flow domain) are set by given water head values. The fluid flow simulations were performed for seven different water heads on the external boundaries (water curtain pressure heads) including 0.0, 2.5, 5, 7.5, 10, 12.5, and 15 m. For these water heads, the corresponding pressure difference between water curtain and storage are 2.5, 5, 7.5, 10, 12.5, 15, and 17.5 m. It should be noted that the vertical distance of water curtain (upper boundary) and cavern roof is 22.5 and the gas pressure in the cavern is near 2 bar (20 m of water head). The fluid flow simulations were performed for three different oil heights in the cavern as 37.5, 40, and 42.5 m (from bottom of flow domain).

Table 1. Geometrical statistics used for fractures generation through DFN model

Parameter	Fracture class			
	FS1	FS2	FS3	FNS4
Relative frequency	37.8	23.6	11.8	26.7
Fisher constant	12.34	2.64	16.3	----*
Dip/Dip direction	57/016	63/315	57/198	----*
Fracture density (m-2)	0.242	0.150	0.074	0.168
Mean trace length (m)	2.82	2.86	3.06	3.07
Max. trace length (m)	25.0	11.5	12.2	13.0
Min. trace length (m)	0.75	0.90	1.00	0.75
Trace length Std.	0.44	0.46	0.42	0.42

* For non-systematic class FNS4, orientation is assumed to be a stationary random function.

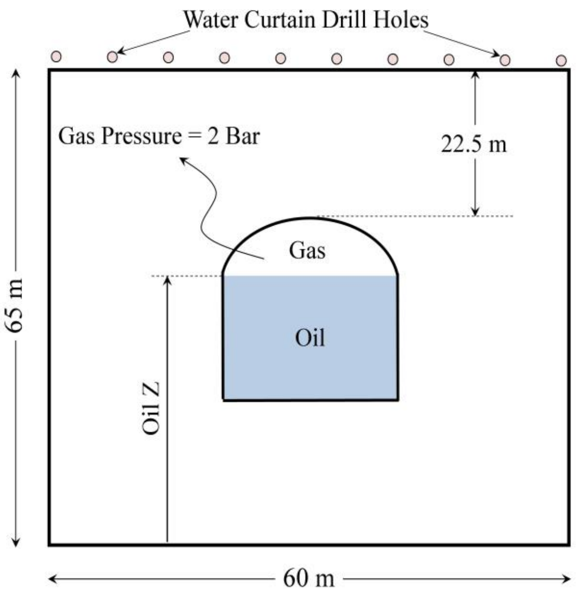

Figure 3. Geometry of flow domain for fluid flow and hydrocarbon migration analysis.

According to the stochastic nature of fractures geometry, the DFN realizations should be examined before launching the simulation procedure of water flow around cavern. Therefore, large number of DFN realizations, usually more than 500 realizations, shall be generated to ensure that the results are not dependent on specific fracture geometry arrangement and to produce more representative of stochastic behavior of the fractured media. Here, the results of two different DFN realizations are presented. Fluid flow simulations and analysis of hydrocarbon migration in fractured rock mass surrounding the cavern were performed for different arrangement of boundary conditions respect to the water head on the external boundaries and oil height in the cavern. The results of these analysis are shown in Figs. 4 and 5.

In the Figs. 4 and 5, the water pressure on the upper boundary of flow domain or water curtain pressure is shown by “WCHP” increasing from top to down. Moreover, the height of oil in the cavern (from the bottom of the domain) is shown by “Oil Z” that increases from left to right side of the figures. The hydrocarbon migration tracing was performed for both oil and gas migration that are shown with blue and red colors, respectively, in the Figs. 4 and 5.

In the first DFN realization (Fig. 4), the hydrocarbon migration is very sensitive to the hydraulic boundary conditions. In the case of zero and 2.5 m of WCHP, the gas migrates in long distances from the cavern. For these cases, also the migration distance from the cavern is sensitive to the height of oil in the cavern. The migration distances decrease effectively by increasing the WCHP to 5 m (where the pressure head difference between water curtain and storage is 7.5 m). However, by increasing the WCHP from 5 to 15, less decreasing in the migration distances of hydrocarbon was indicated in the results. For such WCHPs, the height of oil in the cavern has not much effect on the migration distance. For this DFN realization, the most of the hydrocarbon migration was for the gas and the oil migration was occurred only for the cases that have WCHP less than 2.5 m.

The results of hydrocarbon migration for the second DFN realization (Fig. 5), are not very sensitive to the hydraulic boundary conditions. For this realization, the migration distance from the cavern has not changed much effectively by increasing the WCHP. However, for all the cases with 42.5 m of “Oil Z”, the oil migrates from the cavern.

4 CONCLUSION

This paper links the hydraulic and migration of hydrocarbon in unlined storage caverns to spatially heterogeneous nature of rock mass by directly applying DFN model. To reach this goal, first, a special algorithm, so-called “migration tracing” was developed based on the pathway analysis in the DFN model and applying the migration cessation criterion. A computational code, so-called “FNETF”, was developed to generate DFN, solving fluid flow equation along fractures, and migration tracing of hydrocarbon. Fluid flow in fracture network was numerically simulated for different outer boundary hydraulic conditions assigned by different groundwater pressures of water curtain and height of oil in the storage cavern. After fluid flow simulation, the hydrocarbon migration through fractures around storage cavern was traced based on the developed algorithm. Finally, the assessment achieved to expect the occurrence of hydrocarbon migration with detail hydraulic conditions characterized by numerical simulation of fluid flow in constructed hydro-geological DFN models. Based on the presented results, the following conclusions were obtained:

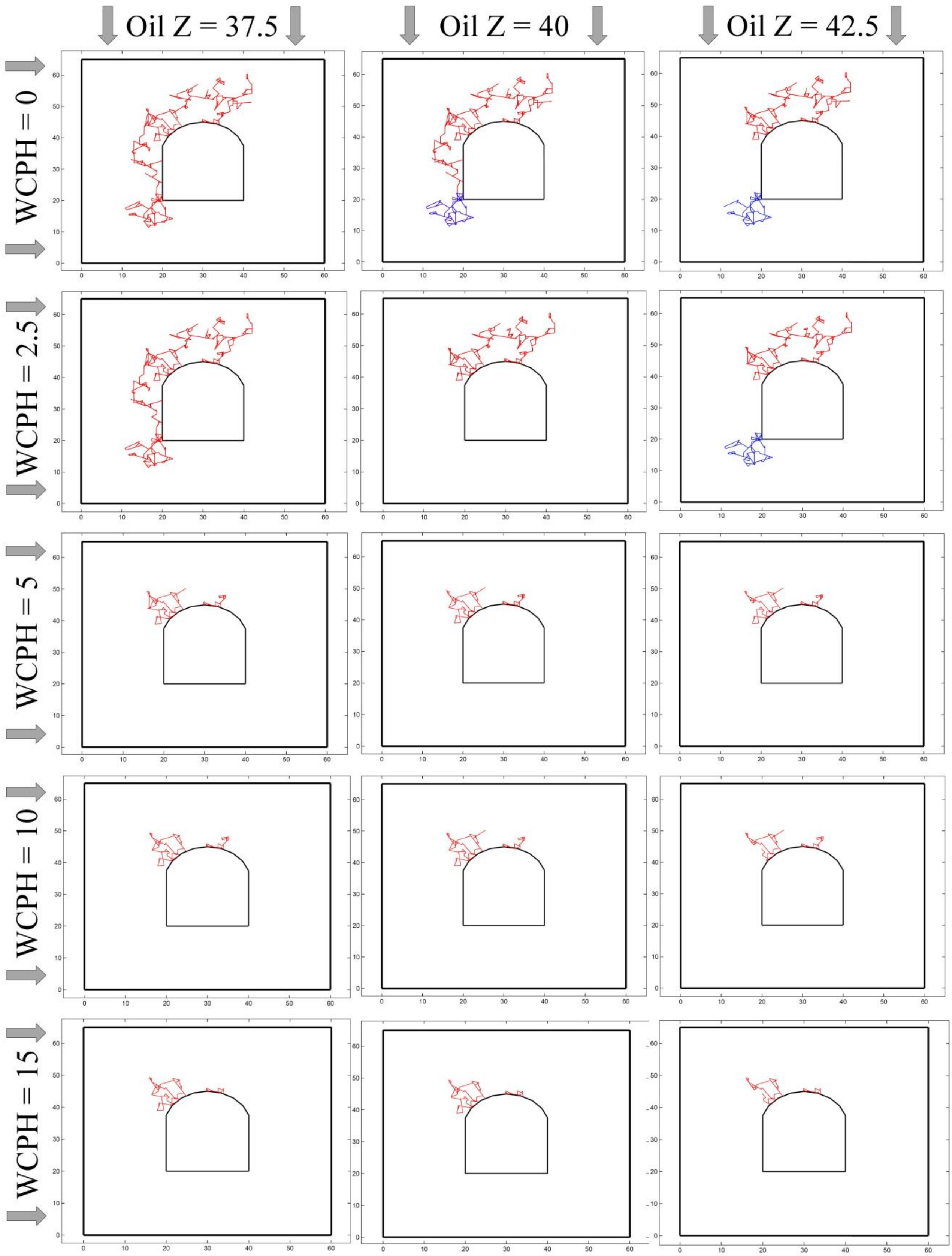

Figure 4. Results of hydrocarbon migration from cavern to fractures around the cavern (for the first DFN realization). Blue and red lines show the oil and gas migration through fractures, respectively. The water curtain pressure (WCHP) increases from top to down and the height of oil in the cavern (Oil Z) increases from left to right side.

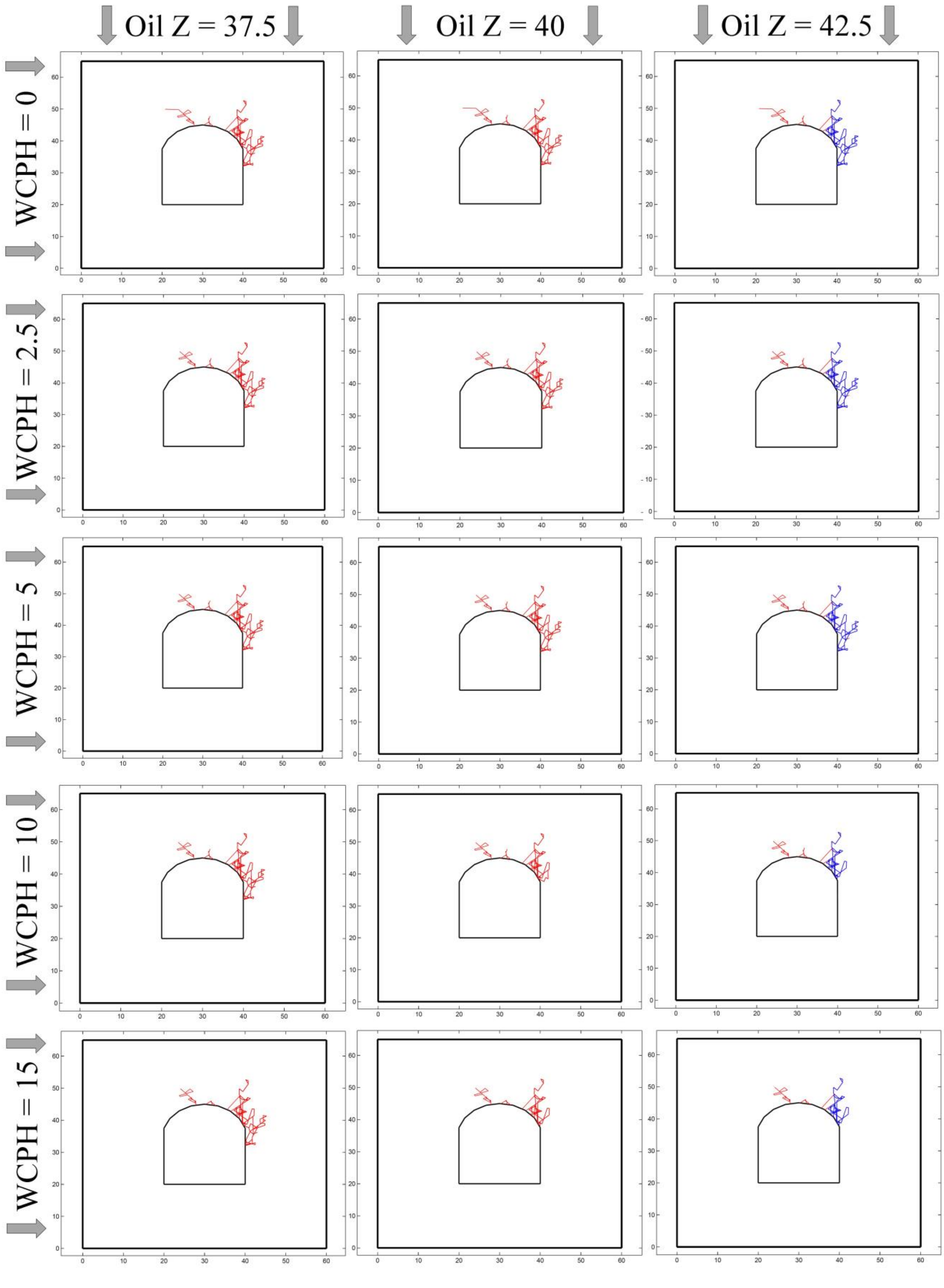

Figure 5. Results of hydrocarbon migration from cavern to fractures around the cavern (for the second DFN realization). Blue and red lines show the oil and gas migration through fractures, respectively. The water curtain pressure (WCHP) increases from top to down and the height of oil in the cavern (Oil Z) increases from left to right side.

The host rock masses for unlined hydrocarbon storage are usually hard, massive with few discontinuities where the influence of fractures on groundwater flow and hydrocarbon migration cannot be negligible. In such situation, most of hydrocarbon migration occurs through the intricately connected fracture network. Therefore, the hydrocarbon migration can be prevented by ensuring a specific water pressure in the fracture system and special hydraulic conditions. However, the hydrocarbon migration is found to be very sensitive to details of fracture geometry and as a consequence, local migration paths may develop around storage cavern through the intricately connected fracture network, despite the presence of a water curtain. In this case, the design of a unlined storage cavern under the assumption of homogeneous rock mass and with the condition that the absolute pressure in every point around the caverns must be higher than inside the caverns is not enough sufficient. It is recommended that practical design of URCs be based on the some margin of safety against uncertainty of fracture geometry and fluctuations in the pressure head of water curtain and the stored hydrocarbon. With sufficient information of fracture geometry and hydraulic condition, the developed methodology can be applied to model fluid flow and hydrocarbon migration through the interconnected fractures around storage caverns. Through this application, a better understanding can be reached on the processes and the phenomena that take place in the complex domain of natural fractures.

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