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Verification of capillary pressure functions and relative permeability equations for gas production

Submitted by:
Jaewon Jang

Jaewon Jang

Wayne State University
DUNS #: 001962224
5050 Anthony Wayne Dr.
Detroit, MI 48202
e-mail: jaewon.jang@wayne.edu
Phone number: (313) 577-3854

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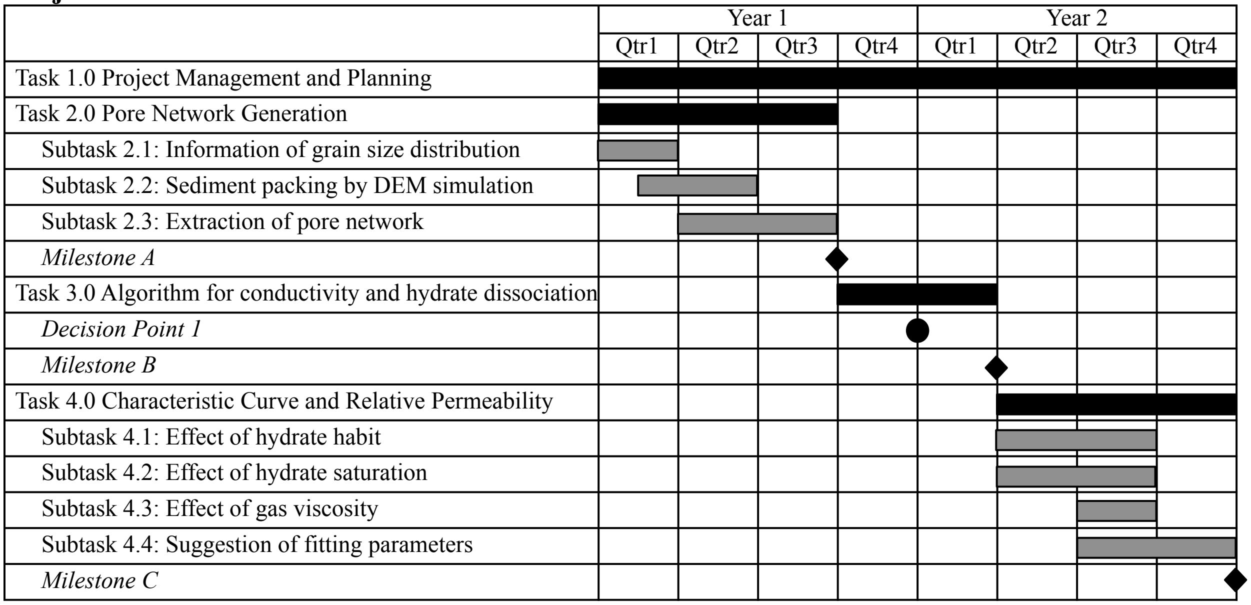
SUMMARY

Task 1.0	Project Management and Planning <u>Done</u>
Task 2.0	Pore Network Generation <u>In progress</u>
Subtask 2.1	Information of relevant information of in-situ hydrate-bearing sediments <u>Done</u>
Subtask 2.2	Generation of sediment packing using Discrete Element Model (DEM) <u>Done</u>
Subtask 2.3	Extraction of pore-network from sediment packing <u>Done</u>
Task 3.0	Algorithm for conductivity and hydrate dissociation <u>In progress</u>

Project timeline



	Year 1				Year 2			
	Qtr1	Qtr2	Qtr3	Qtr4	Qtr1	Qtr2	Qtr3	Qtr4
Task 1.0 Project Management and Planning	■	■	■	■	■	■	■	■
Task 2.0 Pore Network Generation	■	■	■					
Subtask 2.1: Information of grain size distribution	▨							
Subtask 2.2: Sediment packing by DEM simulation	▨	▨						
Subtask 2.3: Extraction of pore network		▨	▨					
Milestone A			◆					
Task 3.0 Algorithm for conductivity and hydrate dissociation				■	■			
Decision Point 1				●				
Milestone B					◆			
Task 4.0 Characteristic Curve and Relative Permeability						■	■	■
Subtask 4.1: Effect of hydrate habit						▨	▨	
Subtask 4.2: Effect of hydrate saturation						▨	▨	
Subtask 4.3: Effect of gas viscosity							▨	
Subtask 4.4: Suggestion of fitting parameters							▨	▨
Milestone C								◆

Verification of capillary functions and relative permeability equations for gas production from hydrate bearing sediments

Summary

There are several studies of numerical simulation on predicting long-term behavior of hydrate-bearing sediments during gas production. Numerical simulators explore coupled processes that require numerous equations and parameters. Important equations for the estimation of gas production from hydrate-bearing sediments are soil-water characteristic curves and relative permeability equations. These equations require empirical parameters, laboratory and in-situ experiments which are very difficult and expensive. In this research, pore-network model simulation is performed to obtain the fitting parameters for capillary pressure functions and relative permeability equations. First, several sediment packings similar to in-situ sediment are generated by discrete element method. Then, the pore-network model is extracted from the pore space of sediment packing as a system of pores connected at throats. Numerical algorithm to simulate gas hydrate dissociation and gas expansion, and calculate gas and water relative permeability at every saturation is developed for the pore-network model. The assessment of water pore connectivity and the identification of gas clusters are performed using Hoshen-Kopelman algorithm. Finally, reliable fitting parameters for capillary pressure functions and relative permeability equations during gas production will be suggested for further use.

1. Introduction

Gas and water permeability control the gas recovery efficiency and determine the economic development of hydrate bearing sediments [Johnson et al., 2011; Minagawa et al., 2004; Minagawa et al., 2007; Gupta, 2007; Kleinberg et al., 2003]. While it would appear that gas and water permeability during hydrate dissociation should depend on initial hydrate distribution, laboratory data or numerical simulation results are not available to guide the selection of adequate parameters for reservoir simulations. Expressions for capillary pressure Pc and permeability k_r as a function of the degree of water saturation S_w have been proposed in the field of unsaturated soil behavior [Corey, 1954; Brooks and Corey, 1964; Stone, 1970; van Genuchten, 1980]. These expressions are used to simulate similar conditions in resource recovery such as oil production and the injection of liquid CO_2 into water-saturated sediments. The air-vapor fluid invades the medium from a boundary and remains as a continuous phase in unsaturated soils. However, gas comes out of solution and bubbles grow within the sediment during methane production from hydrate-bearing sediments; this situation also takes place during depressurization of gas-saturated liquids, such as gassy flow in oil production. These two cases are referred to as "external gas drive process" for gas invasion and "internal gas drive process" for the cases of nucleation and gas liberation during depressurization [Yortsos and Parlar, 1989; Poulsen et al., 2001; Nyre et al., 2008].

The objective of this research is to obtain reliable parameters for capillary pressure functions and relative permeability equations applicable to hydrate dissociation and gas production. In order to achieve this goal we will perform the following tasks; (1) compile the information of grain size distribution of hydrate-bearing sediments worldwide, (2) obtain spatial and statistical pore size distribution from particle packing generated from discrete element method is obtain, (3) extract the network model from the generated pore geometry is extracted, (4) develop the algorithm for gas hydrate dissociation, gas expansion, and relative permeability calculation, (5) obtain the parameters for capillary pressure function and relative permeability equation by simulating hydrate dissociation, and (6) modify existing equations or suggest a new form of equation.

2. Previous Studies – Literature Reviews

Numerical simulation is used to estimate and predict long-term behavior of hydrate-bearing sediments during gas production [Kurihara et al., 2008; Moridis et al., 2009; Moridis et al., 2005; Moridis and Regan, 2007a; Moridis and Regan, 2007b; Anderson et al., 2011, Myshakin et al., 2011; Myshakin et al., 2012]. Numerical simulators for gas hydrate are very complicated programs that include many equations and parameters. Important equations among many others embedded into numerical simulators are capillary pressure function and relative permeability equation. Permeability is the most important characteristic to predict gas production rate during gas hydrate development [Johnson et al., 2011; Minagawa et al., 2004; Mingawaga et al., 2007; Kleinberg et al., 2003]. Permeability governs the production rate of water as well. Therefore, it is very important to determine proper parameters for a capillary pressure function and a relative permeability equation to enhance the ability of hydrate simulators to predict gas and water production rate.

The soil-water characteristic curve captures the causal link between water saturation and capillary pressure [Leong and Rahardjo, 1997; Fredlund, 2002; ASTM D6836-02]. Pore throat size distribution, connectivity and spatial correlation, soil fabric, contact angle, and interfacial tension determine the characteristic curve [Chan and Govindaraju, 2004; Francisca and Arduino, 2007]. There is hysteresis in wetting and drying; most studies are conducted in drying to minimize experimental difficulties [Hillel, 1980], and involve controlled air-water pressure difference or drying the soil specimen under controlled relative humidity.

Analytical expressions have been proposed to capture the soil-water characteristic curve in terms of capillary pressure *Pc* as a function of relative water saturation $S = (S_w - S_r)/(1 - S_r)$, where S_w is the water saturation and S_{rw} is the residual water saturation [Corey, 1954; Brooks and Corey1964; van Genuchten, 1980; Fredlund and Xing 1994]. Two frequently used equations are:

$$P_c = P_0 \left(\frac{S_w - S_r}{1 - S_r}\right)^{\lambda} \qquad \text{Books-Corey (1964)} \qquad (1)$$

$$P_c = P_0 \left[\left(\frac{S_w - S_r}{1 - S_r}\right)^{\frac{1}{m}} - 1\right]^{1-m} \qquad \text{van Genuchten (1980)} \qquad (2)$$

Where P_0 is the pressure when gas enters the sediment. Compiled *m*-values range from *m*=0.07 for very fine soils, to *m*=0.34 for coarse soils [Wösten et al., 1999 for 5521 samples]. The effect of different parameters on the soil water characteristic curve is explained in Figure 1. Parameters used in published hydrate-bearing reservoir simulations are compiled in Table 1 and 2. Note that *m*-values used for hydrate simulations vary from *m*=0.386 to *m*=0.77.

The relative gas or water permeability *k* is the hydraulic conductivity normalized by the corresponding phase conductivity at 100% saturation. The conductivity at irreducible phase saturation may be used as a reference value instead [Jaiswal, 2004]. Relative permeability varies as a function of saturation, and predictive models are intimately related to the soil water characteristic curve models [Brooks and Corey, 1964; Stone, 1970; van Genuchten, 1980]. Model predictions and the effect of different parameters on relative permeability are shown in Figure 1. The relative permeability equations and fitting parameters used in hydrate-bearing reservoir simulations are summarized in Table 2.

Capillary pressure functions and relative permeability equations originate from unsaturated soil mechanics [Corey 1954; Brooks and Corey, 1964; Stone, 1970; van Genuchten, 1980]. These equations inherently need the empirical parameters; the capillary pressure parameter λ and m in Equation 1 and 2, the relative permeability equation parameter n_g and n_w in Table 2, the irreducible (residual) water S_{rw} and gas saturation S_{rg} to calculate the relative saturation (Table1 and 2) should be determined. There are several studies dedicated to determine these parameters by laboratory experiments [Wösten et al., 1999].

However, in all experiments performed in those conventional studies, water and gas were injected from one boundary to the other boundary of the specimen. The gas injection from one boundary is totally different gas generation mechanism compared to the gas generation mechanism during hydrate dissociation. When gas hydrate dissociates, gas nucleates from several pores inside sediments. In order words, gas is generated inside sediments instead of being pushed from outside. This different gas generation mechanism may result in totally different gas permeabilities during gas invasion and gas nucleation.

3. Numerical Method

Sediment Packing Generation. Based on the grain size distribution and effective stress of in-situ hydrate bearing sediments, three-dimensional sediment packing is generated using discrete element modeling (PFC 3D). Figure 2 shows the complied information of grain size distribution of in-situ hydrate-bearing reservoirs. As a boundary condition, pressure-controlled wall is used to apply in-situ effective stress on particle packing. Once the particle packing is obtained, the pore space of the packing is extracted by generating a network of voxels in the packing and determining whether each voxel is a pore or particle. For any grain and voxel, with centers O_1 and O_2, the voxel is pore (denoted by 1) if distance $(O_1, O_2) <$ grain radius. A simplified for the digitization of a pore space is shown in Figure 3.

Pore Network Extraction. Several numerical algorithms have been developed to simulate the pore network model from pore space images. The algorithm used in this research is the maximall ball algorithm originally proposed by Silin et al. (2003) and developed futher by A.S Al-Kharusi, M.J. Blunt (2007).

Three-dimensional image of pore space that consists of particle voxels (denoted by 1) and pore voxels (denoted by 0) used as the input of maximal ball algorithm. The algorithm includes several subroutines to generate maximal balls, clusters and throats. The final pore network model of pore space consists of a network of pore balls connected by tubes. The procedure of generating the pore network model from sediment pack simulation is shown in Figure 4.

Gas Expansion and relative permeability. Hydrates dissociate into methane gas and water by depressurization or thermal stimulation. The dissociated methane is a function of pressure-temperature conditions. The modified Peng-Robinson equation of state (PRSV) is used to compute volume of methane gas during depressurization:

$$P_g = \frac{RT_g}{V_g - b} - \frac{a}{V_g(V_g + b) + b(V_g - b)} \tag{3}$$

where R is the universal gas constant and the values of *a* and *b* are parameters of methane gas which are summarized in Ttable 3 [Stryjek and Vera, 1986]. Differential pressure between gas and water in a porous medium is the capillary pressure that is a function of surface tension Γ, contact angle θ and pore throat radius R:

$$P_c = P_g - P_w = \frac{2\Gamma\cos(\theta)}{R} \tag{4}$$

The procedure of gas expansion starts by gradually decreasing the water pressure at the boundaries of pore network model. The pore network model has been modified to apply periodic boundary condition to effectively represent a large hydrate-bearing reservoir using a relatively small size pore network. Gas expands to the neighboring water pores if the gas pressure is higher than the sum of water pressure and the capillary pressure at the connection between gas pore and water pore:

$$P_g > P_w + P_c \tag{5}$$

Gas expands to water pores that have the minimum value of capillary pressure plus water pressure (P_c+P_w). The pressure drop in the tubes of pore network model is determined using Poiseuille equation either in gas or water phase:

$$\Delta P = \frac{8\mu Q.\Delta L}{\pi r^4} \tag{6}$$

Where ΔP is the pressure drop, Q is the flow rate, ΔL is the length of tube, r is the radius of pore and μ is the dynamic viscosity. Hoshen-Kopelman algorithm is used for clustering either water and gas pores during each step of depressurization [Hoshen and Kopelman, 1976; Al-Futaisi and Patzek, 2003].

The fluid expansion factor is defined as a ratio of gas and water (V_g and V_w) to the initial hydrate volume (V_h) to determine the rate of expansion process in every step:

$$\beta = \frac{V_g + V_w}{V_s} \tag{7}$$

Gas expands with increasing the expansion factor β to the neighboring water clusters unless one of the following situations happens:

- As soon as a path of gas percolation occurs. In this case gas clusters cannot expand to the neighboring water clusters and gas production starts through the gas percolation path.
- When gas pores surround an isolated water cluster. The cluster doesn't have access to a water percolation path.
- Some of gas clusters cannot overcome the condition of $P_g > P_w + P_c$.
- As soon as water percolation path disappears.

All the mentioned steps are defined in a Matlab code that the flowchart is shown in Figure 5.

Table 1. Capillary pressure in hydrate bearing sediments as a function of water saturation.

Equation		Factors used in hydrate bearing sediment study					References
		Relative saturation $\bar{S}$	S_{mxw}	S_{rw}	P_0	m or λ	
van Genuchten (1980)	$P_c = P_0\left[\bar{S}^{-\frac{1}{m}} - 1\right]^{1-m}$	$\bar{S} = \frac{S_w - S_{rw}}{S_{mxw} - S_{rw}}$	1	0.14	nr	0.46	Gamwo and Liu (2010)
			nr	nr	0.1MPa	0.45	Moridis and Reagan (2007^a) Moridis and Reagan (2007^b)
			nr	0.19	2kPa	0.45	Moridis and Sloan (2007)
			nr	nr	0.1MPa	0.45	Moridis et al. (2009)
			nr	nr	5kPa	0.77	Moridis et al. (2010) Reagan et al. (2010)
			nr	0.19	2kPa	0.45	Reagan and Moridis (2008)
			1	nr	2kPa	0.45	Rutqvist and Moridis (2007)
		$\bar{S} = \frac{S_w - S_{rw}}{1 - S_{rg} - S_{rw}}$	S_{rg}=0.5	0.3 0.2	1kPa	0.45	Hong and Pooladi-Darvish (2003) Uddin et al. (2008)
Corey (1954)	$P_c = P_0\bar{S}^{\lambda}$	$\bar{S} = \frac{S_w - S_{rw}}{1 - S_{rw}}$	nr	nr	nr	- 0.5	Corey (1954)
			nr	nr	nr	- 0.65	Liang et al. (2010)
		$\bar{S} = \frac{S_w - S_{rw}}{1 - S_{rg} - S_{rw}}$	S_{rg}=0.1	0.1	5kPa	- 0.25	Konno et al. (2010)

Note: (1) $Smxw$: maximum water content, Srw: residual water saturation, $P0$: air entry value, m: van Genuchten equation's fitting parameter, and λ: pore size distribution index. (2) Factors depend on soil type: the finer the soil is, the higher $P0$ is. (3) nr: not reported.

Table 2. Relative permeability equations – Parameters used in gas hydrate simulation studies.

Equation		Factors used in published hydrate bearing sediment studies				References
		$\bar{S}$	S_{rw}	S_{rg}	m	
van Genuchten (1980)	$k_{rw}=\bar{S}^{0.5}\left[1-\left(1-\bar{S}^{1/m}\right)^{m}\right]^{2}$ $k_{rg}=\sqrt{1-\bar{S}}\left(1-\bar{S}^{1/m}\right)^{2m}$	$\frac{S_w-S_{rw}}{1-S_{rw}}$	0.3	0.05	0.45	Hong and Pooladi-Davish (2003)
			0.2	0.05	0.45	Uddin et al. (2008)
			0.1	-	0.45	Moridis (1998)
					0.386	Hong and Pooladi-Darvish (2005)
Corey (1954)	$k_{rw}=\bar{S}^{4}$ $k_{rg}=\left(1-\bar{S}\right)^{2}\left(1-\bar{S}^{2}\right)$	$\bar{S}=\frac{S_w-S_{rw}}{1-S_{rw}-S_{rg}}$				Nazridoust and Ahmadi (2007)
	$k_{rw}={S'_{l,g}}^{4}$ $k_{rg}={S'_{g}}^{2}\left(1-\left(1-S'_{g}\right)^{2}\right)$	$S'_{l,g}=\frac{S_{l,g}}{1-S_{h}}$				Tonnet and Herri (2009)
(modified) Stone (1970)	$k_{rw}=\left(\frac{S_w-S_{rw}}{1-S_{rw}}\right)^{n_w}$ $k_{rg}=\left(\frac{S_g-S_{rg}}{1-S_{rg}}\right)^{n_g}$ or $k_{rg}=\left(\frac{S_g-S_{rg}}{1-S_{rw}}\right)^{n_g}$	n_w	n_g	S_{rw}	S_{rg}	
		3.0	3.0	0.15	0.05	Gamwo and Liu (2010)
		4.0	4.0	0.20	0.02	Reagan and Moridis (2008)
		3.0	3.0	0.25	0.02	Moridis and Kowalsky (2005) Moridis et al. (2007)
		3.6	3.6	0.25	0.02	Moridis and Reagan (2007[a])
		3.6	3.6	0.25	0.02	Moridis and Reagan (2007[b])
		4.0	4.0	0.20	0.02	Moridis and Sloan (2007)
		4.0 3.6	4.0 3.6	0.20 0.25	0.02 0.02	Rutqvist and Moridis (2007)
		4.0	4.0	0.20	0.02	Reagan and Moridis (2008) Rutqvist and Moridis (2009)
		3.6	3.6	0.25	0.02	Moridis et al. (2009)
		4.5	3.2	0.24	0	Anderson et al. (2011) Kurihara et al. (2010)
		4.5 -	- 3.2	0.25 0	- 0	Kurihara et al. (2010)
	$k_{rw}=\left(\frac{S_w-S_{rw}}{1-S_{rg}-S_{rw}}\right)^{n_w}$ $k_{rg}=\left(\frac{S_g-S_{rg}}{1-S_{rg}-S_{rw}}\right)^{n_g}$	-	3.0 or 4.0	0.12	-	Gupta (2007)
		3.0	2.0	0.10	0.10	Konno et al. (2010)
		0.2	0.4	-	-	Liang et al. (2010)

Table 3. Parameters Used in the Equation of State[a]

Parameter	Symbol	Value
Universal gas constant	R	83.15 [bar ··cm^3/mol·K]
Attraction term parameter	a	$(0.457235R^2T_c^2/P_c)\alpha$
Repulsion term parameter	b	$0.077796RT_c/P_c$
	α	$[1 + \kappa(1 - T_r^{0.5})]^2$
Adjustable parameter	κ	$\kappa_0 + \kappa_1(1 + T_r^{0.5})(0.7 - T_r)$
Adjustable parameter	κ_0	$0.378893 + 1.4897153\omega - 0.17131848\omega^2 + 0.0196544\omega^3$
Adjustable parameter	κ_1	−0.00159 for methane
Acentric factor	ω	0.01045 for methane
Critical pressure	P_c	4.595 MPa for methane
Critical temperature	T_c	190.555 K for methane
Reduced temperature	T_r	T/T_c

[a] *Stryjek and Vera* [1986].

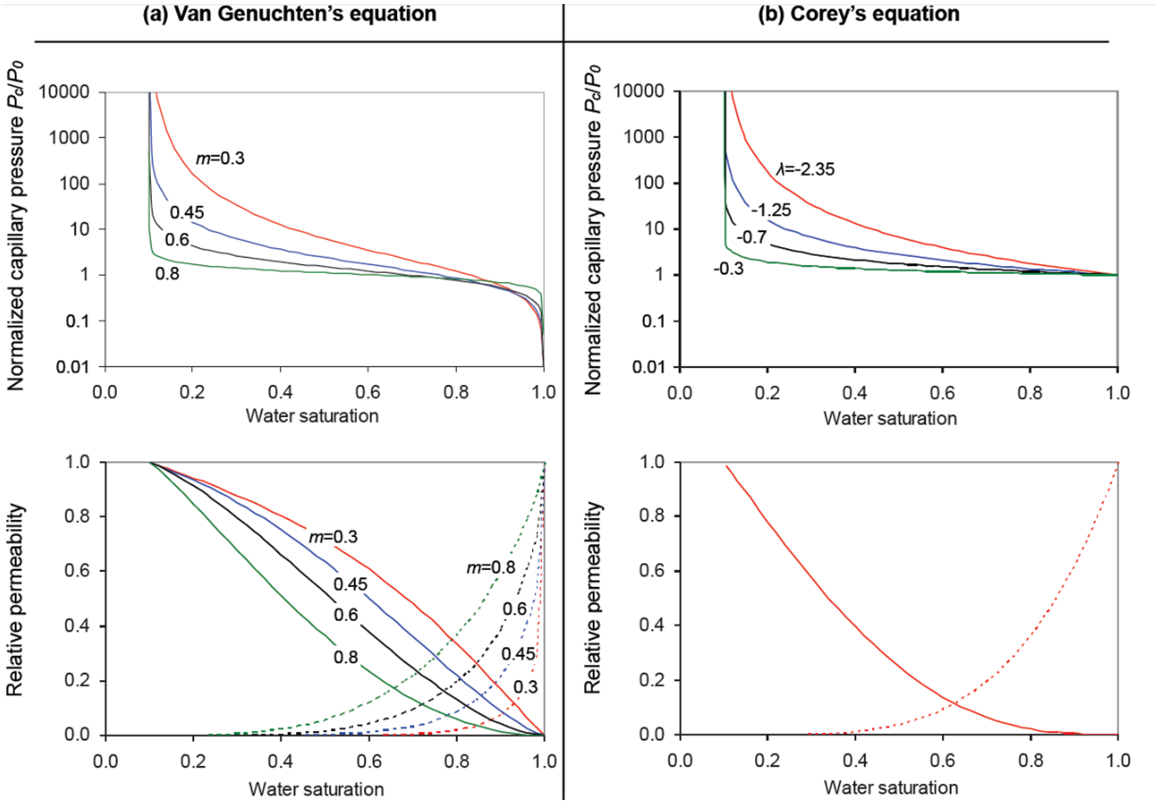


Figure 1. Normalized capillary pressure Pc/P0 and relative permeability kr as a function of water saturation Sw. (a) van Genuchten's model. (b) Corey's model. Selected m and λ values shown for each trends, equations in Table 1 and 2.

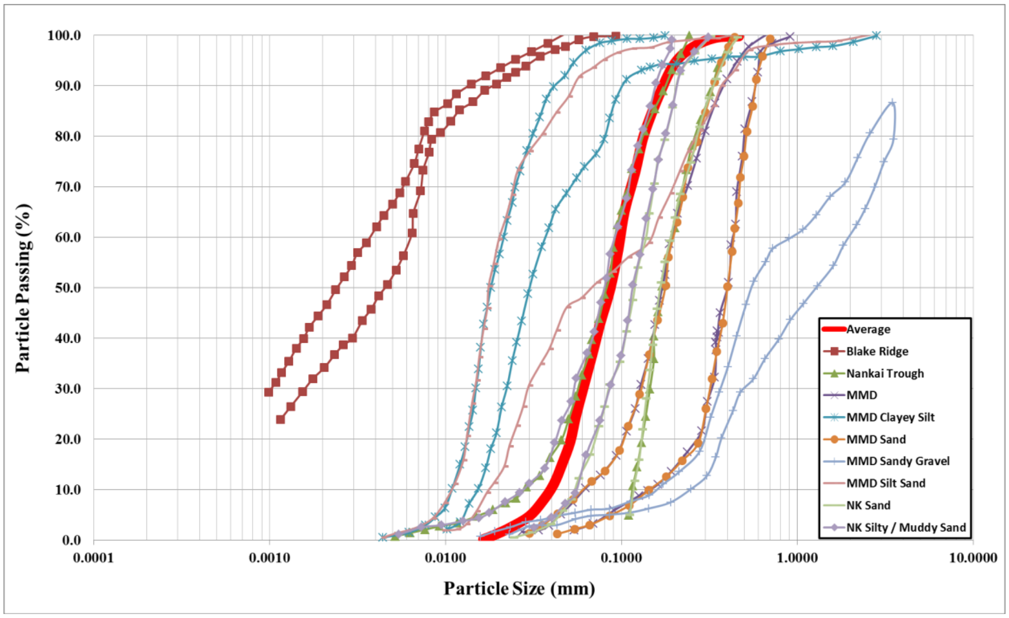
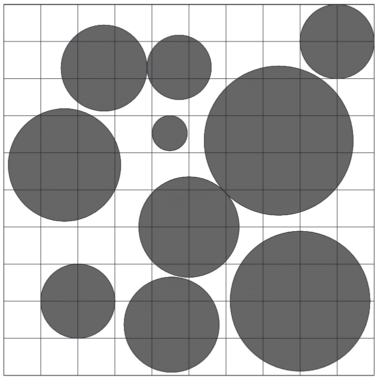


Figure 2. Particle size distribution [Graphs from Soga et al., 2007]. (a) Nankai Trough [Masui et al., 2006], Mallik 5L-38 [Jenner et al., 1999], Blake Ridge [Paull et al., 2000], and Hydrate Ridge [Tan, 2004]. (b) Nankai Trough [Masui et al., 2006] and Mallik-Mackenzie Delta [Jenner et al., 1999].



0	0	0	0	0	0	0	0	1	1
0	0	1	1	1	1	0	0	1	1
0	0	1	1	1	0	1	1	1	0
1	1	1	0	1	1	1	1	1	0
1	1	1	0	0	0	1	1	1	0
0	1	1	0	1	1	0	1	0	0
0	0	0	0	1	1	0	1	1	0
0	1	1	0	1	0	1	1	1	1
0	1	1	1	1	1	1	1	1	1
0	0	0	0	1	0	0	1	1	0

Figure 3. Digitization of sediment packing using 1 and 0.

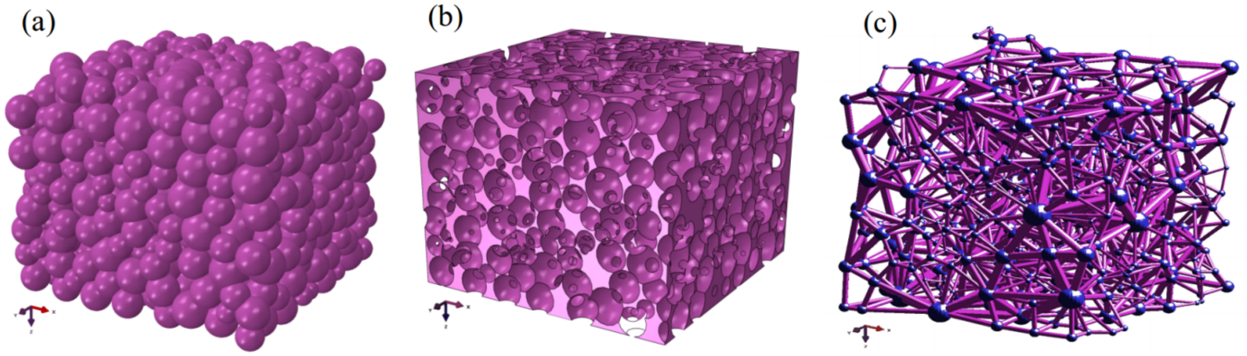


Figure 4. Pore-network model extracted from simulated sediment packing. (a) Sediment packing generated by discrete element model (PFC 3D) using in-situ data of grain size distribution and effective stress. (b) Pore space of the sediment packing. (c) Pore network model extracted from pore space by using maximum ball theory.

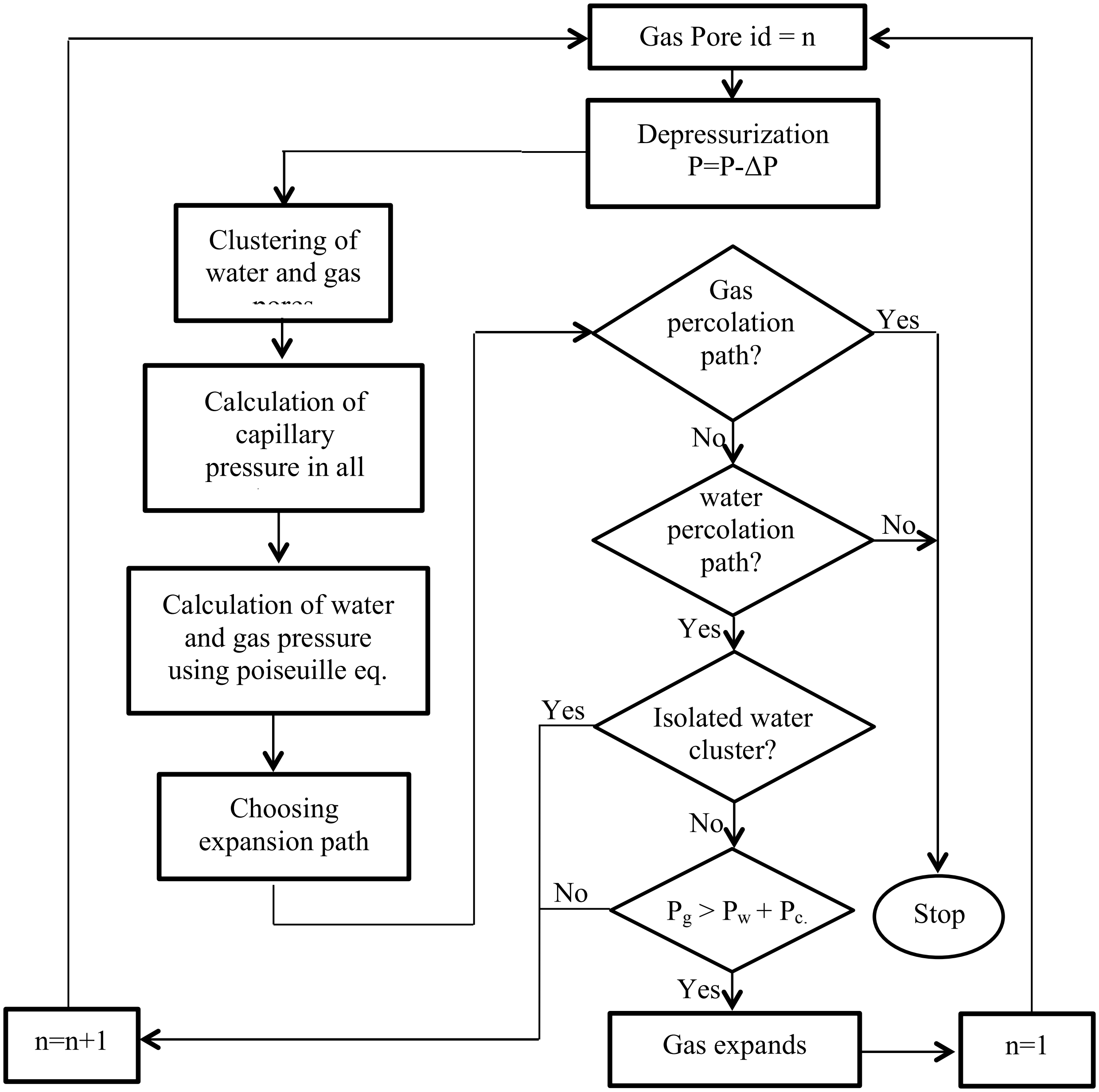


Figure 5. Flowchart of the pore network model simulation (depressurization-gas expansion-permeability calculation).

National Energy Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880

13131 Dairy Ashford Road, Suite 225
Sugar Land, TX 77478

1450 Queen Avenue SW
Albany, OR 97321-2198

Arctic Energy Office
420 L Street, Suite 305
Anchorage, AK 99501

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