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Mechanisms Leading to Co-Existence of Gas and Hydrate in Ocean Sediments

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MECHANISMS LEADING TO CO-EXISTENCE OF GAS AND HYDRATE IN OCEAN SEDIMENTS

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QUARTERLY PROGRESS REPORT
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Summary

Work during this quarter focused on verifying our insights from previous modeling of capillary displacements coupled with grain movement. The objective is to obtain reliable estimates of the area and location of the gas/water interface at the grain scale. A premise being tested in this project is that the gas/water interface is the site where hydrates form, and we are using the configuration of the interface to estimate hydrate growth habit in Task 7.

We previously demonstrated the first mechanistic coupling of stress/strain of a granular material with gas/water displacement through the material under the control of capillary forces. We used a commercial code (PFC) in which the pressure force exerted by pore fluids on the grains was rigorously treated. We obtained the fluid pressures and the location of the gas/water interface (and hence determined the grains on which pressure forces were imbalanced) with our research code (LSMPQS). We demonstrated this capability in 2D, and found that our earlier approximations to the fully coupled model gave useful qualitative insight into the behavior observed in the rigorous model. The extension of this coupling to 3D reported here is conceptually straightforward, as the physics are the same. Demonstrating the capability in 3D is nevertheless useful. The nature of the gas/water interface differs in 3D, and so does the existence of disconnected volumes of gas or of water. Thus comparison of model predictions with empirical observations is best done in 3D.

We also report the pore-level verification of a 3D network model of drainage/imbibition against LSMPQS simulation, which is effectively an analytical solution. This verification is valuable because the LSMPQS method becomes computationally prohibitive for large model sediments (10^3 to 10^4 grains). A pore-level verification in a realistic porous medium, in this case a packing of ca. 10^2 grains, is unprecedented; all previous network validations have been against macroscopic observations (drainage/imbibition curves), in which many pore-level events are averaged together.

Two papers were presented at the Society of Petroleum Engineers Annual Technical Conference and Exhibition (Sept. 2008): "Investigating Matrix-Fracture Transfer via a Level Set Method for Drainage and Imbibition" by Prodanovic, Bryant and Karpyn, and "Capillarity Controlled Displacements in Sediments With Movable Grains: Implications for Growth of Methane Hydrates" by Prodanovic and Bryant.

Activities in This Reporting Period

Task 7.0 - Coupled gas/water/sediment dynamics with hydrate formation

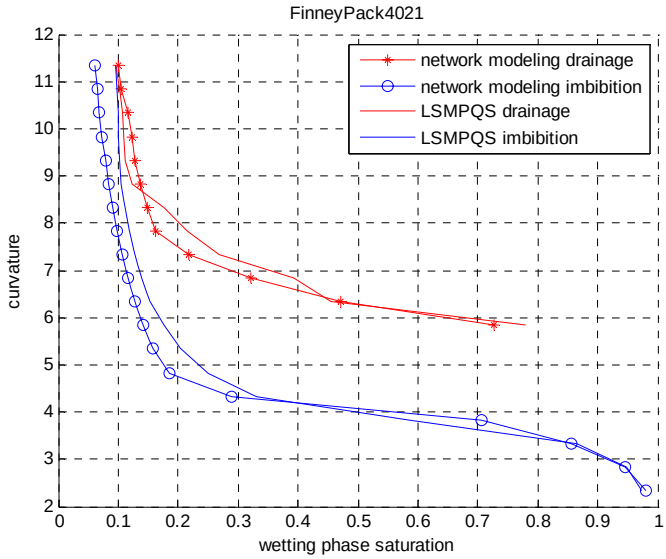
Preparatory to modeling hydrate formation from capillarity-controlled fluid configurations, we performed a careful pore-level verification of a network model of drainage and imbibition.

All network models introduce simplifying assumptions, and this appears unsatisfying when a rigorous method for computing capillarity-controlled displacements is available, namely our LSMPQS algorithm. The purpose of using a network model here is to establish a valuable upscaling capability.

Current hardware limitations restrict the application of LSMPQS to subsets of a few hundred grains of a model sediment. This is unlikely to be large enough to evaluate correctly the effect of connected and disconnected volumes of fluid (gas or water) on the growth of hydrates. Hence a tradeoff arises between accuracy of local interface movements (captured by LSMPQS) and accuracy of phase connectivity (captured by the infinite-acting networks developed in this project).

Fortunately, as shown in Fig. 1, it is possible to capture the rigorous prediction of behavior with remarkable fidelity in the network model, using the novel estimate of critical curvature for imbibition developed previously in this project. Moreover, as shown in Figs 2 through 4, drainage and imbibition events occur in very nearly the same individual pores at the same applied capillary pressure (curvature). This confirms that the network model will produce the same fluid configurations (in terms of pores and throats filled) as the more accurate LSMPQS approach. We can therefore use the network approach in much larger model sediments (several thousand spheres packed in a periodic cell) with some confidence that the resulting fluid configurations will be representative of what occurs in nature.

Fig. 1. Drainage and imbibition curves simulated in a subset of 200 equal spheres from a dense, disordered packing. The network model uses a set of critical curvatures for local events estimated from the geometry of the throats, while the LSMPQS makes no assumptions whatsoever and is effectively an analytical solution. The agreement suggests the network approximations are physically reasonable.



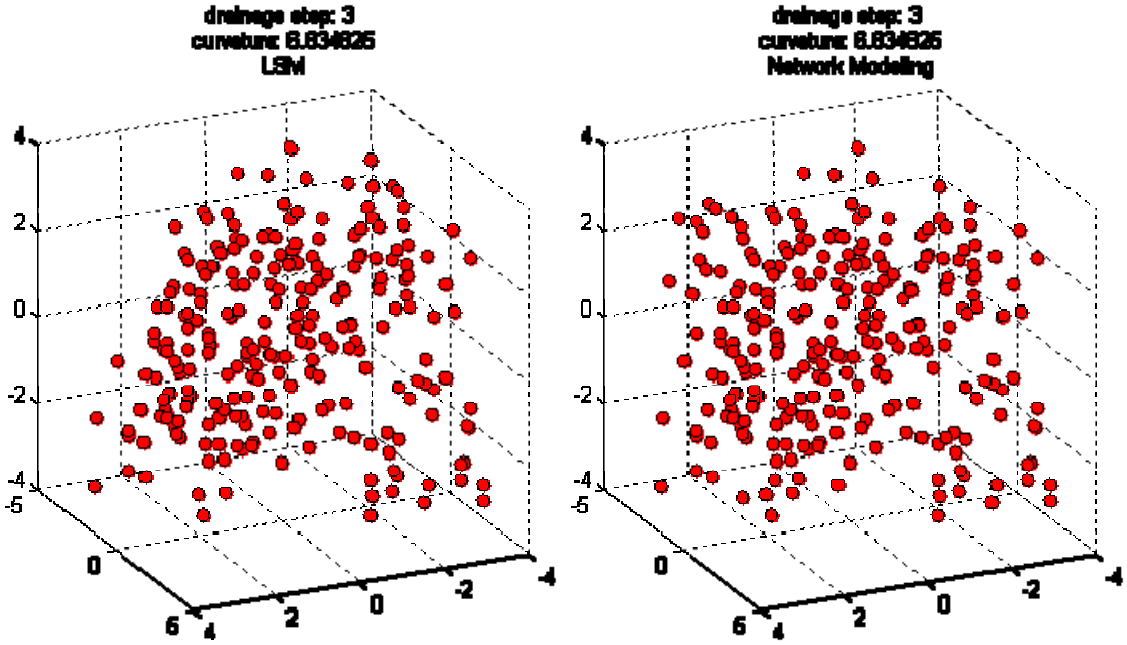


Fig. 2. Pores occupied by nonwetting phase (gas) during drainage and in a subset of 200 equal spheres from a dense, disordered packing (see capillary pressure curves in Fig. 1) . (Left): results of LSMPQS drainage simulation. (Right): results of network model drainage simulation. Ninety-three percent of the occupied pores are the same.

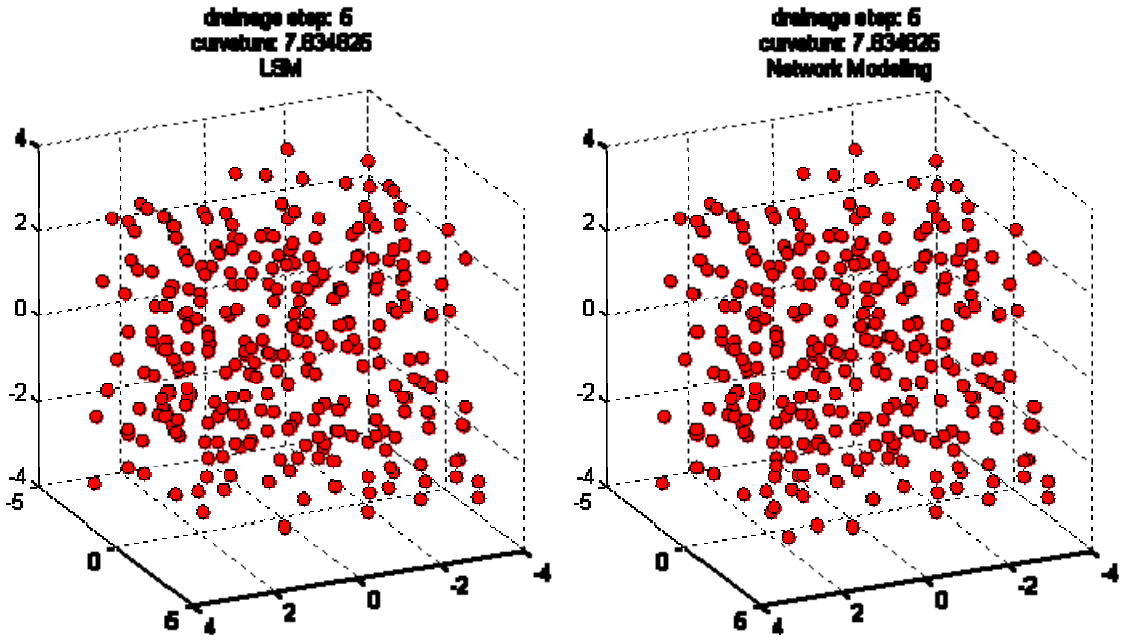


Fig. 3. Pores occupied by nonwetting phase (gas) during drainage and in a subset of 200 equal spheres from a dense, disordered packing (see capillary pressure curves in Fig. 1) . (Left): results of LSMPQS drainage simulation. (Right): results of network model drainage simulation. Ninety-five percent of the occupied pores are the same.

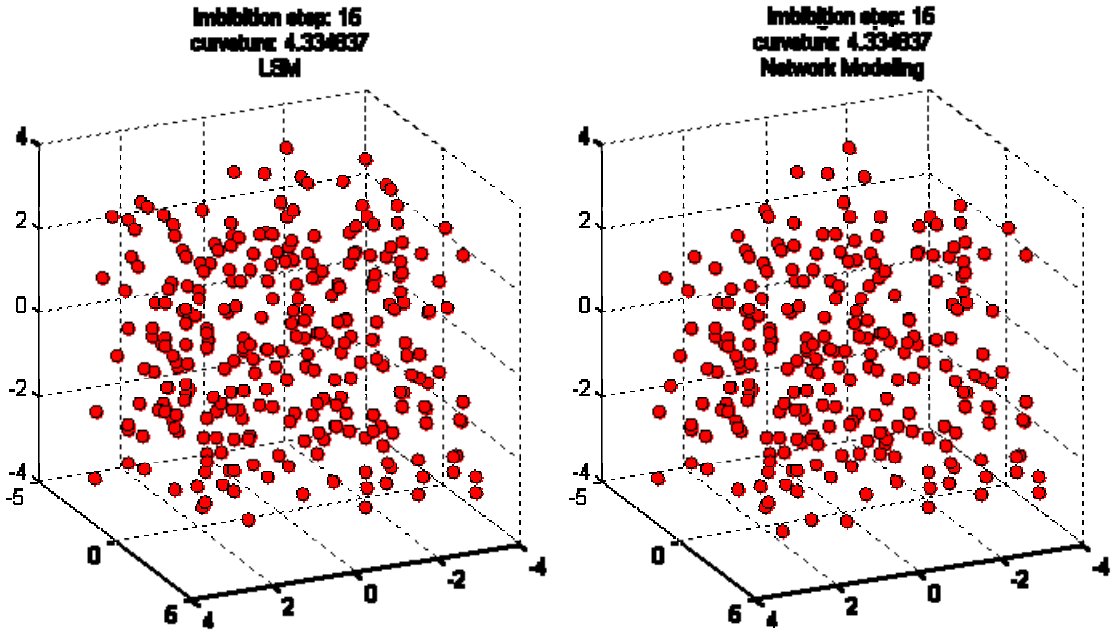


Fig. 4. Pores occupied by nonwetting phase (gas) during drainage and in a subset of 200 equal spheres from a dense, disordered packing (see capillary pressure curves in Fig. 1) . (Left): results of LSMPQS imbibition simulation. (Right): results of network model imbibition simulation. Ninety-five percent of the occupied pores are the same.

Coupled 3D grain mechanics and capillary displacement. This provides an important tool for comparing behavior in the 'intermediate' regime when neither capillary displacement nor sediment fracturing controls the invasion of gas into the hydrate stability zone. The transition occurs at a grain size of 1 micron in the example of Figure 5, reproduced from our previous reports.

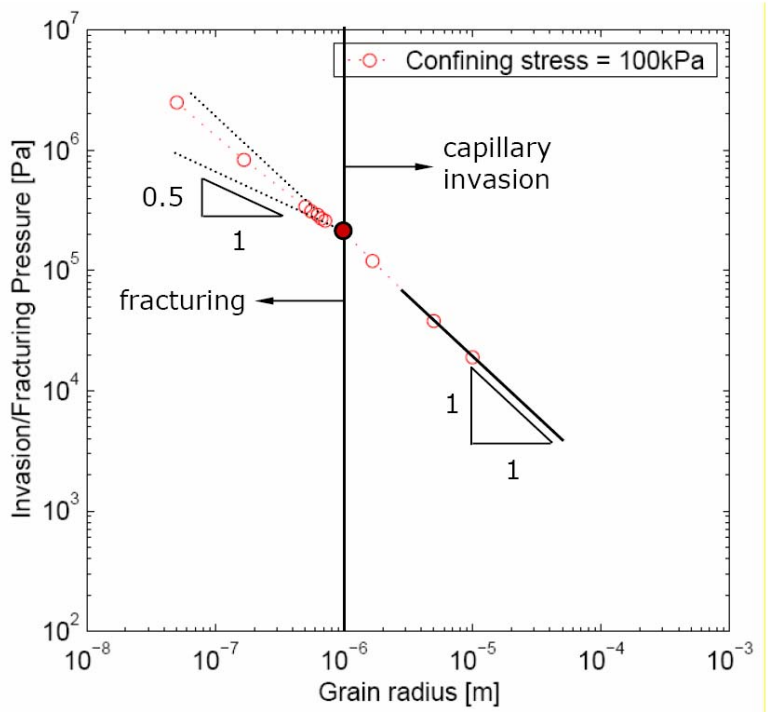


Figure 5. Simulations with PFC using new capabilities developed in this project for handling two fluids within the pores show a transition between capillary dominated behavior (classical drainage) and fracturing. As reported previously, the possibility that grains can move can also alter the capillary behavior dynamically.

To extend our previously demonstrated coupling in 2D, we closely packed 176 spheres with uniformly distributed radii in the interval [47,49] microns using PFC3D. Initial sphere center fall in a box of size 450 microns by 450 microns by 400 microns, Fig. 6. Several confining stress conditions were applied in PFD3D. The location of the fluid interfaces was computed directly within LSMPQS. The locations of the spheres were exported from PFC3D and imported into LSMPQS, discretizing the box with a spacing of dx=0.05 *R*, where *R* is the average grain radius. The capillary pressure is prescribed in LSMPQS, which then finds the equilibrium location of the menisci. The forces on grains in gas-filled pores are computed from the geometry of the configuration and capillary pressure. These forces are exported from LSMPQS and read into PFC3D, which then computes a new arrangement of grains accounting for the pore pressures. In this fashion we iterate between the two codes and observe the evolution of the gas phase configuration during drainage. Figure 7 illustrates the gas phase partway through drainage. Corresponding to the same step of the simulation as Fig.7, Figure 8 shows which spheres have been moved by gas phase pressure. This example shows the "bootstrapping" behavior that is possible when the grains can be moved during drainage by the gas phase pressure. Moving the grains causes pore throats near the gas/water interface to expand, allowing drainage to continue without increasing the capillary pressure as shown in Fig. 9.

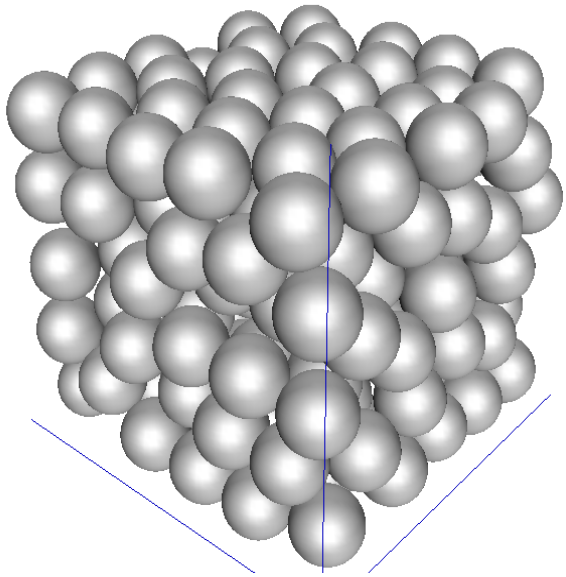


Fig. 6. Packing of spheres generated in PFC3D for demonstrating coupling of grain mechanics (rigorously calculated in PFC3D) with capillarity controlled interface movement (rigorously calculated in LSMPQS). The invading gas phase can move grains in a drained pore by virtue of the capillary pressure difference.

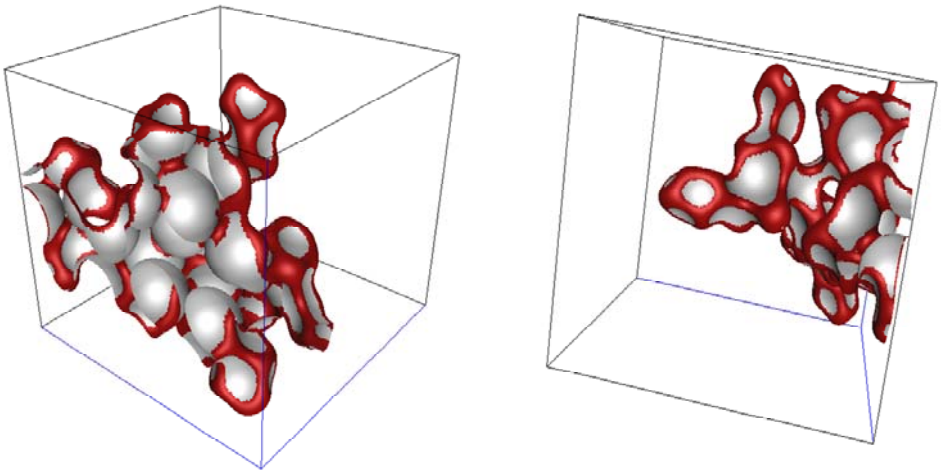


Fig. 7. Two views of the interface at step 6 during the coupled mechanics/drainage simulation. LSMPQS curvature is kept constant at the value 4.0 (normalized by average grain radius).

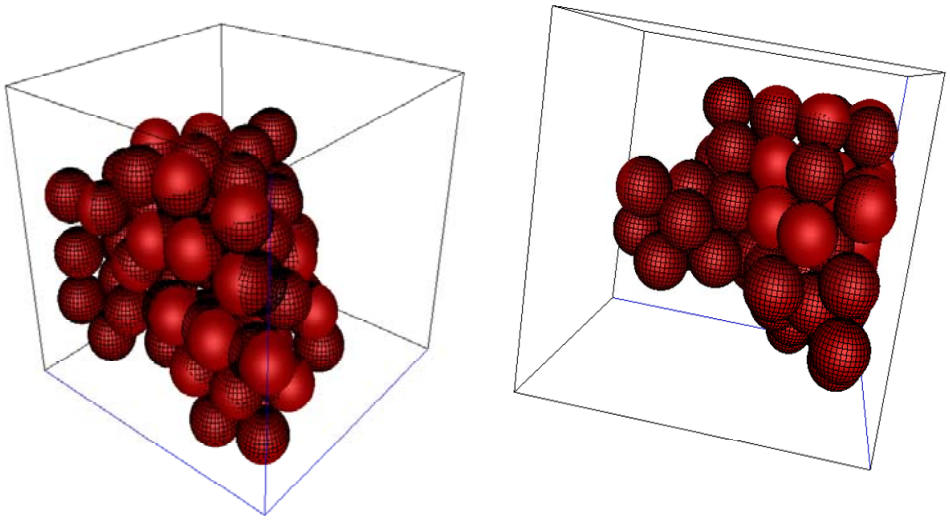


Fig. 8. Balls (in red) in contact with fluid at step 6 (see corresponding fluid interface in Fig. 7). Black mesh frames outline initial ball position. [If black mesh and red surface are in the same position, the ball has not moved].

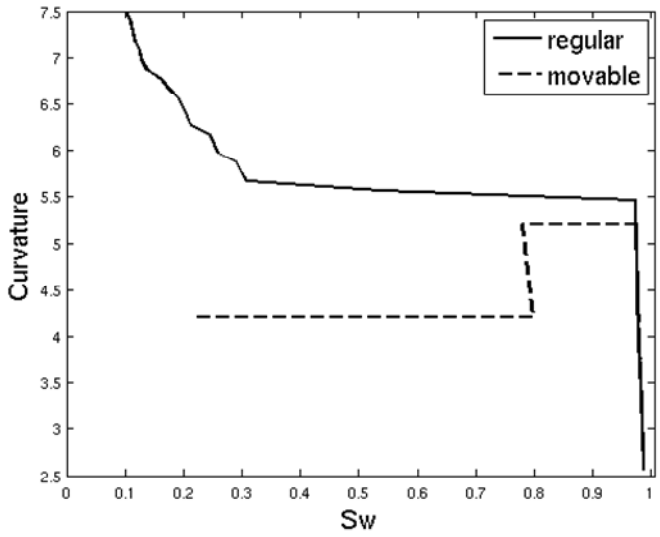


Fig. 9. Drainage curve (labeled "movable") for the simulation from which Figs. 7 and 8 were taken. The "normal" curve is the result in the same packing when the grains are held fixed. The gas phase pressure is sufficient to move grains apart, thereby increasing the diameter of some pore throats near the interface. Consequently once drainage begins, it becomes self reinforcing. In fact one can decrease the capillary pressure (in this case to 4.2 from 5.2) and drainage can continue. In terms of fluid configuration, the result is rather similar to fracturing.

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