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하이드레이트 함유 퇴적물의 역학적 성질 및 지구물리 물성

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Mechanical and Electrical Properties of Hydrate-bearing Sediments

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Abstract : Using an oedometer cell instrumented to measure the evolution of electromagnetic properties, small strain stiffness, and temperature, we conducted consolidation tests on four types of sediments. The tested specimens include sediments with different gas hydrate saturation at four stages of loading. The test results show that the electromagnetic and mechanical properties of hydrate-bearing marine sediments are governed by the vertical effective stress, stress history, porosity, hydrate saturation, fabric, ionic concentration of the pore fluid, and temperature. The results also show that permittivity and electrical conductivity data can be combined to estimate hydrate volume fraction in laboratory sediments, methodology that might eventually be extended for estimation of hydrate concentrations in field settings.

1. Introduction

In any geologic setting, complete characterization of the natural gas hydrate system requires an overlapping approach that includes acquisition and analysis of remote sensing data (e.g., geophysical site surveys), downhole logs, and coincident seafloor samples. Seafloor samples, while the most difficult to obtain, are also the most critical. Such samples can be used to calibrate indirect measurements and to provide physical and chemical data at higher spatial resolution than most geophysical techniques.

Ultimately, scientists aspire to rely more heavily on indirect techniques such as downhole logs and multichannel seismic data to characterize natural gas hydrate reservoirs. Unfortunately, the inherent complexity and heterogeneity of natural systems can render the interpretation of such data difficult. Laboratory studies measure the properties of hydrate-bearing sediments having known grain characteristics and gas hydrate concentration. Such laboratory efforts lead not only to new effective media and mixture models that can be extended to interpret natural sediments, but also to a better mechanistic description of the interaction between hydrate and sediment grains.

2. Experimental Study

To contribute to a better understanding of the complex natural system, we conducted an exhaustive series of

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laboratory experiments to measure the electrical and mechanical (high-strain and low-strain) properties of fully saturated, homogeneous sediments containing synthesized THF hydrate. These experiments measure a large array of parameters using consistent instrumentation, effective confining pressures of up to 2 MPa, sediment properties that span most of the range represented in natural marine sediments (grain sizes of 1 to 100 μm), and gas hydrate concentrations of 0% to 100% in pore space. The laboratory experiments have produced data that constrain many key parameters, including electrical resistivity, and real permittivity in the 200 MHz to 1.3 GHz range; such low-strain mechanical properties as P- and S-wave velocities, dynamic bulk modulus, and volume change during phase transformation. We have also conducted destructive testing to demonstrate the homogeneity of gas hydrate distribution in the sediments and the locus of gas hydrate formation. Finally, the laboratory program has included a significant number of experiments to track the change in basic properties (e.g., P- and S-wave velocities, electrical conductivity) during pressure or temperature variations that lead to cycles of hydrate formation and dissociation in sediments. Experiments were conducted with an oedometer and a newly constructed high pressure cell. To the greastest extent possible, measurements were automated and recorded digitally, and care was taken to demonstrate reproducibility of the results, to calibrate equipment, and to maintain close temperature control on specimens.

We used four distinct homogeneous sediments for this study: Ottawa sand, precipitated silica flour, crushed silica flour (silt), and kaolinite (clay). The sediments were chosen to represent an ordered progression from grain sizes of 120 μm (sand) to ~1 μm (clay) and specific surface ranging from ~10^{-4} m^2/g (sand) to ~35 m^2/g (clay). Unexpectedly, precipitated silica flour, which met the ~20 μm grain size criterion we required for silt, proved to have much higher specific surface than a nominal silt due to the tendency of the silica flour particles to clump together. Particularly in mechanical tests, we observed that the high specific surface of the precipitated silica flour caused it to behave like clay. We have therefore repeated a significant number of the tests with crushed silica flour, which possesses both grain size and specific surface characteristics more typical of a true silt.

3. Experimental Results

This presentation highlights some of our key results and observations, which include:

- Hydrate formation leading to the overall stiffening of sediments, whether measured in the high or low strain regimes
- Non-recoverable deformation of the sediment matrix associated with formation and dissociation of hydrate and loading/unloading cycles
- A clear evolution of S-wave velocities from cementation controlled at lower effective vertical stress values to stress controlled at higher vertical stress for hydrate-bearing sediments
- For all sediments, dramatic lowering of the effective electrical conductivity following formation of gas hydrate

4. Conclusions

Our first analysis of this exhaustive new data set reveals that sediments containing hydrate tend to behave mechanically like other cemented sediments. The data set has important implications for the calibration and interpretation of geophysical measurements and downhole logs collected in gas hydrate provinces, providing particular insight for the interpretation of P- and S-wave data and resistivity logs. In addition, the extensive new constraints on various elastic moduli (static and/or dynamic) lead to a revised consideration seafloor/slope stability issues in areas with hydrate-bearing sediments.

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