GEOMECHANICAL PERFORMANCE OF HYDRATE-BEARING SEDIMENTS IN OFFSHORE ENVIRONMENTS

Semi-Annual Report

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1. Executive Summary

The main objective of this research is to develop the necessary knowledge base and quantitative predictive capability for the description of geomechanical performance of hydrate-bearing sediments (hereafter referred to as HBS) in oceanic environments. The focus is on the determination of the envelope of hydrate stability under conditions typical of those related to the construction and operation of offshore platforms. To achieve this objective, we have developed a robust numerical simulator of hydrate behavior in geologic media by coupling a reservoir model with a commercial geomechanical code. To be sure our geomechanical modeling is realistic, we are also investigating the geomechanical behavior of oceanic HBS using pore-scale models (conceptual and mathematical) of fluid flow, stress analysis, and damage propagation. In Phase II of the project, we will review all published core data and generate additional core data to verify the models.

To generate data for our models, we are using data from the literature and we will be conducting laboratory studies in 2007 that generate data to (i) evaluate the conceptual pore-scale models, (ii) calibrate the mathematical models, (iii) determine dominant relations and critical parameters defining the geomechanical behavior of HBS, and (iv) establish relationships between the geomechanical status of HBS and the corresponding geophysical signature.

There are four organizations involved with this project. These four are Texas A&M University (TAMU), University of California at Berkeley (UCB), Lawrence Berkeley National Laboratory (LBNL), and Schlumberger (SLB). The milestones for Phase I of this project are given as follows:

- Literature survey on typical sediments containing gas hydrates in the ocean (TAMU)
- Recommendations on how to create typical sediments in the laboratory (TAMU)
- Demonstrate that typical sediments can be created in a repeatable manner in the laboratory and gas hydrates can be created in the pore space (TAMU)
- Develop a conceptual pore-scale model based on available data and reports (UCB)
- Test the developed pore-scale concepts on simple configurations and verify the results against known measurements and observations (UCB)
- Complete the FLAC3D routines that will be linked with the reservoir model (LBNL)
- Complete the TOUGH-Fx/HYDRATE modifications and extensions (LBNL)
- Complete the TOUGH-Fx/FLAC3D interaction interface (LBNL)
- Integrate and test the coupled geomechanical numerical model TFxH/FLAC3D (LBNL)
- Demonstrate that Petrel can be used to develop an earth model for providing data to the TOUGH-Fx/FLAC3D (SLB)

The project was awarded effective October 1, 2005. However, it took several months to get the subcontracts in place with UCB and LBNL. **UCB began work in January 2006 and LBNL began work in March 2006.** Partly because of the late start, we requested an extension to complete Phase I of the project. Below is a summary of the results during the past six months.

Summary of Pore Scale Modeling by UCB

We have developed a technique for estimating the elastic moduli of a heterogeneous grain pack by modeling mechanical interactions among the grains. Each grain is elastic, and the contact deformations are modeled using Hertz and Mindlin theories. We model the deformation of a grain pack as a sequence of static equilibrium configurations. Each configuration is sought by minimization of the potential energy of the pack. For a loose configuration, our algorithm produces a more realistic tighter pack than other methods. We capture and analyze hysteretic events, such as different loading and unloading responses or abrupt breakage of grain clusters. The computed bulk modulus estimates match experimental values reported in literature. The current progress has been presented at two conferences.

Summary of TOUGH/Fx-FLAC3D Model Development by LBNL

We coupled the TOUGH+/HYDRATE code (developed by LBNL and used for the description of system behavior in HBS) with FLAC3D (a commercial code that is widely used in soil and rock mechanics engineering, and for scientific research in academia). TOUGH+/HYDRATE allows the study of flow and transport of fluids (distributed among four phases) and heat in hydrate deposits, and accurately describes the thermodynamics of hydrates as they are distributed among fifteen possible states (i.e., phase coexistence combinations). FLAC3D has built-in constitutive mechanical models suitable for soil and rocks, including various elastoplastic models for quasi-static yield and failure analysis, and viscoplastic models for time-dependent (creep) analysis. The coupled model (hereafter referred to as the TH+/FLAC model) is the first of its kind, can be used for the joint analysis of hydraulic, thermal, flow and geomechanical behavior in HBS, and is a unique tool for the analysis of the effect of hydrate dissociation processes on the structural stability and possible displacement of HBS and of their overburdens.

Summary of Sediment Descriptions and Recommendations by TAMU

We have completed a comprehensive literature review to characterize the sediments containing hydrates that have been recovered from scientific cruises. The various regions that have been explored for gas hydrates and were reviewed in our work include Blake Ridge (Offshore South Carolina), Gulf of Mexico, Offshore Oregon (Cascadian Margin and Hydrate Ridge), Nankai Trough (Offshore Japan), Offshore Peru and various other regions explored by the Ocean Drilling Program (ODP). After analyzing all the sediments, we have recommended that three sediment mixtures that we can use for mechanical properties testing in Phase II of this project. We have included recipes to make these sediments in the laboratory. We expect that TAMU and LBNL will build these sediments for testing during Phase II so that the results of the laboratory experiments at both institutions can be used seamlessly. As we gain experience in the laboratory, it is possible the 'recipes' and procedures for building the sediments may need to be improved during Phase II of the project.

Summary of Petrel-FLAC3D Interface by Schlumberger

We have been developing a method to use Petrel as a platform for entering geologic and reservoir data into the ToughFX-FLAC3D model when it is completed. There are two requirements for using Petrel to populate FLAC3D with geological surfaces and rock properties. One is to demonstrate that FLAC3D can import surfaces and properties from Petrel. The other is to verify that Petrel can generate the geologic structures characteristic of the hydrate zone offshore. After a series of meetings between Schlumberger and ITASKA, ITASKA has told us they can import properties and surfaces from Petrel. They have demonstrated the ability to import into FLAC3D surfaces generated in Petrel. For the second part, Schlumberger is working internally to characterize geologic structure from 2D seismic lines crossing the hydrate zone in the Gulf of Mexico.

2. Introduction

Gas hydrate is a solid material resulting from the orderly assembly of gas molecules such as methane, carbon dioxide, and hydrogen sulfide, within a clathrate (cage like) structure of water molecules under moderate (relative to conventional oil and gas reservoir conditions) pressure and temperature. Vast amounts of hydrocarbons are trapped in hydrate deposits (Sloan, 1998). Such deposits occur in two distinctly different geologic settings where the necessary low temperatures and high pressures exist for their formation and stability: in the permafrost and in deep ocean sediments near the sea floor.

The three main methods of hydrate dissociation are (1) depressurization, in which the pressure is lowered to a level lower than the hydration pressure P_H at the prevailing temperature, (2) thermal stimulation, in which the temperature is raised above the hydration temperature T_H at the prevailing pressure, and (3) the use of inhibitors (such as salts and alcohols), which causes a shift in the P_H-T_H equilibrium through competition with the hydrate for guest and host molecules (Sloan, 1998). Dissociation results in the production of gas and water, with a commensurate reduction in the saturation of the solid hydrate phase.

Gas hydrates exist in many configurations below the sea floor including massive (thick solid zones), continuous layers, nodular, and disseminated occurrences each of which may affect the seafloor stability differently. The hydrates in all of these configurations may be part of the solid skeleton that supports overlying sediments, which ultimately support platforms and pipelines needed for production from conventional oil and gas resources, and from the eventual production from hydrate accumulations.

During dissociation, the basal zone of the gas hydrate becomes under-consolidated and possibly over-pressured because of the newly released gas (Schmuck and Paull, 1993), leading to a zone of weakness (i.e., low shear strength, where failure could be triggered by gravitational loading or seismic disturbances) that can ultimately result in submarine landslides (McIver, 1977; Paull et al., 1996). Possible mechanisms that can induce dissociation in Hydrate-Bearing Sediments (hereafter referred to as HBS) include an increase in salinity, a drop in the sea level and an increase in the sediment temperature (e.g., by warmer ocean bottom water, or by non-insulated pipes conducting fluids produced from deeper and warmer reservoir) can induce such dissociation.

Hydrate dissociation in HBS produces an enhanced fluidized layer at the base of the gas-hydrate zone. Submarine slope failure can follow, giving rise to debris flows, slumps, slides, and collapse depressions such as described by Dillon et al. (1998). Failure would be accompanied by the release of methane gas, but a portion of the methane is likely to be oxidized unless the gas release is catastrophic. A scenario illustrating submarine slope failure is shown in **Figure 1**. The possible connection between gas-hydrate boundaries and submarine slide and slump surfaces was first recognized by McIver (1982). Several hydrate-related occurrences of oceanic land-slides are discussed in the literature. These include sediment slides and slumps on the continental slope and rise of West Africa (Summerhayes et al., 1979), slumps on the U.S. Atlantic continental slope (Carpenter, 1981), large submarine slides on the Norwegian continental margin (Evans et al., 1996; Bugge et al., 1988), sediment blocks on the sea floor in fjords of British Columbia, and massive bedding-plane slides and rotational slumps on the Alaskan Beaufort Sea continental margin (Kayen and Lee, 1993).

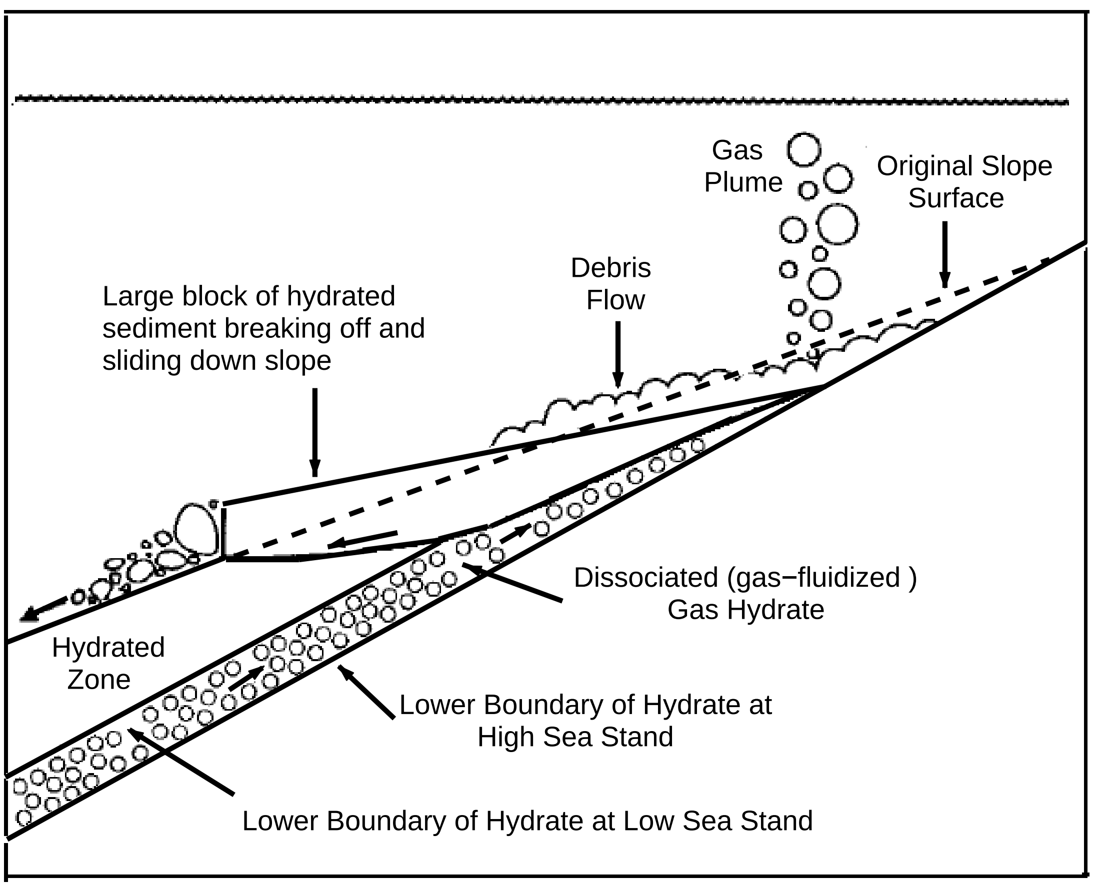

Figure 1 – Diagram showing the effects of gas hydrate dissociation on oceanic hill slope failures and gas release. Adapted from McIver (1982).

For the aforementioned stability concerns, the placement of wells and seafloor platforms associated with oil production is strongly influenced by the presence of gas hydrate on the sea floor or within the sediment lithology. These concerns will be far more pronounced if gas production from oceanic gas hydrate accumulation becomes an economically viable option. Currently, there is a lack of understanding of the mechanical and thermal properties of oceanic sediments containing gas hydrates. The general perception of instability of hydrate-bearing sediments, coupled with the lack of knowledge on the overall geomechanical behavior of such sediments, has resulted in a general strategy of avoidance of such sediments when locating offshore production platforms. By locating production platforms at sites not selected for optimum operation but dictated by the need to avoid the hydrate accumulations, the cost of production can increase significantly. Warmer oil from depth may cause gas hydrate in the neighborhood of a well or pipeline to dissociate, reducing the stability of the supports, and placing significant investments at risk. Such concerns would increase exponentially if gas is to be produced from marine hydrate accumulations, thus posing a serious impediment to the development of such resources.

Few data are available to allow one to manage the risks associated with gas hydrates on the sea floor. Understanding the thermal properties is important because heat transfer through the system is one factor that controls the rate at which the sediments are altered due to hydrate dissociation. Understanding the mechanical properties for a range of hydrate-sediment compositions will allow the prediction of stability and the management of the risks. Measurements of thermal properties have been made of mixed quartz sand and hydrate laboratory samples in addition to pure hydrate samples (Cherskii et al., 1983; Cook and Leaist, 1983; Kneafsey et al., 2005; Moridis et al., 2005a; Stoll and Bryan, 1979; Waite et al., 2002), and strength measurements have been made on laboratory-made pure methane hydrate samples (Durham et al., 2003; Stern et al., 1996). A series of measurements of mechanical, thermal, and electrical properties of tetrahydrofuran hydrate in sediment is underway (Santamarina et al., 2004). Tetrahydrofuran hydrate is stable at atmospheric pressure and near-freezing temperatures; and dissociates to tetrahydrofuran and water without the formation of a gas phase. The applicability of these measurements to the strength of gas hydrate-bearing sediments as would be found below the sea floor has yet to be established. Another study of the mechanical behavior of hydrate bearing sediments concluded that it is essential to collect more data (Hyodo et al., 2005).

The available information is not sufficient to design seafloor platforms or wells (let alone permit the design of future gas production systems from hydrates) in the vicinity of HBS considering the safety, environmental, and economic risks posed by unstable seafloor behavior. We are developing the necessary knowledge that will allow the determination of the envelope of safe conditions when locating and operating an offshore production platform for either conventional oil or gas production, or for production from gas hydrates. This knowledge will also provide the necessary tools to evaluate the expected stability performance of hydrate-bearing sediments, and to select optimal sites for production facility installation.

3. Technical Approach

Objective

The main objective of this research is to develop the necessary knowledge base and quantitative predictive capability for the description of geomechanical performance of hydrate-bearing sediments (HBS) in oceanic environments. The focus is on the determination of the envelope of hydrate stability under conditions typical of those related to the construction and operation of offshore platforms.

Scope of Work

To achieve the objectives of the proposed study, the following approach is being employed:

1. The geomechanical behavior of oceanic HBS has been investigated using pore-scale models (conceptual and mathematical) of fluid flow, stress analysis, and damage propagation.
2. Laboratory studies will be conducted in 2007 to (i) evaluate the conceptual pore-scale models, (ii) calibrate the mathematical models, (iii) determine dominant relations and critical parameters defining the geomechanical behavior of HBS, and (iv) establish relationships between the geomechanical status of HBS and the corresponding geophysical signature.
3. A robust numerical simulator of hydrate behavior in geologic media has been coupled with a commercial geomechanical code, thus developing a numerical code for the stability analysis of HBS under mechanical and thermal stresses.
4. Numerical studies will be conducted to analyze the HBS stability performance under conditions (i) representative of an offshore platform installation and operation, and (ii) typical of oceanic hydrate accumulations under production.

Organizations

There are four organizations initially involved with this project. These four are as follows:

- Texas A&M University (TAMU)
- University of California at Berkeley (UCB)
- Lawrence Berkeley National Laboratory (LBNL)
- Schlumberger (SLB)

4. Project Milestones

Phase I - October 1, 2005 to September 30, 2006

Status of Milestones for Phase I as of September 30, 2006

TAMU	Completion of literature survey on typical sediments containing gas hydrates in the ocean	Sept 2006	We have completed the literature review. All papers and reports have been found and we have prepared a report summarizing the literature
TAMU	Completion of recommendations on how to create sediments in the laboratory	Sept 2006	The information has been summarized in this report
TAMU	Demonstration that typical sediments can be created in a repeatable manner in the laboratory and gas hydrates can be created in the pore space	Nov 2006	This milestone is still in progress although we have made substantial progress. We may not have it completed before we begin Phase II. However, it will be one of the first things we do for Phase II.
UCB	Development of a conceptual pore-scale model based on available data and reports	July 2006	This milestone has been completed. After trying testing several approaches, we have selected the one based on most comprehensive contact mechanics.
UCB	Testing the developed concepts on simple configurations and verification of the result against known measurements and observations	Sept 2006	The approach has been tested on simple and not very simple configurations of grains. Right now we are in the middle of incorporation of tangential forces. There is a chance that this work will continue into October, subject to obtaining a relevant data set.
LBNL	Completion of FLAC3D routines	Aug 2006	Completed
LBNL	Completion of TOUGH-Fx/HYDRATE modifications and extensions	July 2006	Completed
LBNL	Completion of the TOUGH-Fx/FLAC3D interaction interface	Sept 2006	Completed
LBNL	Component integration and final testing of the coupled geomechanical numerical model TFxH/FLAC3D	Oct 2006	Completed
SLB	Demonstration that Petrel can be used to develop an earth model for providing data to the TOUGH-Fx/FLAC3D	July 2006	Surfaces have been exported to FLAC. We have demonstrated that surfaces can be transferred to FLAC 3D

5. Results of Work During the Reporting Period

The following summarizes the progress during this reporting period and current status of the work for each task that is part of PHASE I (Budget Period I) – Initial Fundamental Studies and Model Development.

<u>Task 1.0 – Research management plan</u>

The research management plan has been written and approved by DOE.

<u>Task 2.0 – Technology Status Assessment</u>

The Technology Status Assessment report was written and approved by DOE.

<u>Task 3.0 – Fundamental Studies Part I</u>

<u>Subtask 3.1</u> **<u>- Fundamental studies of pore-scale geomechanical behavior of hydrates in porous media</u>**

The University of California at Berkeley is evaluating the issue of mechanical strength and failure of hydrate sediments, to include the following:

- Using Discrete Element Method (DEM) to model the impact of hydrate dissociation on mechanical strength of the formation at pore-scale level;
- Studying the stress field modification caused by fluid flow and fluid pressure depletion using simulation of the evolution of the rock flow properties; and
- Modeling of formation strength loss using simulation of the process of inter-grain bonds failure and loss of pressure support due to the dissociation.

UCB has published a number of papers on pore modeling prior to this project, and those papers can be found at http://petroleum.berkeley.edu/papers/patzek/twppapers.htm

UCB began their work by considering the mechanical properties of gas hydrates imbedded in a subsea sediment layer (for now, unconsolidated), referred to as HBS. No matter how the mechanical/thermal properties of HBS are described (as a part of the matrix, or cementation agent between the sediment grains, or as different solid grains), these properties will change when the hydrate dissociates. Dissociation will release fresh water and gas and increase the local pressure, while reducing the temperature (due to the highly endothermic nature of the dissociation). Noting that this process stabilizes the hydrate, additional heat or pressure drop is required to continue hydrate dissociation. To understand the effect of dissociation on the mechanical properties of the solid (and fluid to which it joins), a micro-mechanical description of contact mechanics has been incorporated.

As a first approximation, only water and ice present in the pores was considered. Then, the layer of spherical grains in contact with spherical ice crystals has been modeled. As melting begins, one needs to calculate the amount and state of water and gas that will form using thermodynamic considerations. Then, using mass balance together with momentum balance, contact mechanics will enable calculation of forces, stresses and strains close to the contract regions of the spheres. This, together with the material properties of the individual grains/fluids, can be used to formulate a macroscopic constitutive model for the composite layer, and its dependence on the amount of dissociation. Note that currently, again as a first approximation, the Hertzian model has been used, which assumes that the solid response is purely elastic and linear, and there is no cementation and adhesion. The Hertzian model, together with several geometrical assumptions (e.g., the grain contact area is much smaller than the size of the grain and its radius of curvature), simplifies the boundary conditions, and allows the use of the extensive analytical results available in literature for such elastic composites.

UCB has evaluated the micromechanics of grain to grain or grain to hydrate interaction. The Hertzian model has been extended to contact mechanics of several grains. The natural coupling between inter-grain interactions makes the problem very complex. The objective is to obtain a simple, but still representative model. More specifically, attempts have been made to identify the key parameters that can describe the mechanics of a conglomerate of several grains and to develop a meaningful linearization procedure. This model then has been used to simulate interaction of large numbers of grains and to account for loss of strength when some bonds break due to dissociation taking place. Local rock failure in one location leads to a redistribution of the load and may cause failure elsewhere, and this chain of failures continues resulting in damage propagation. This is why from the very beginning the microscopic model is strongly coupled. A Newton-Raphson iterative procedure is being used for solving the coupled contact problem.

We have extended the Herzian contact mechanics simulations to 3D configurations. The complexity of the problem increases dramatically with the number of grains. The principal result is the development of a numerical procedure, which makes possible resolution of multiple contacts without evaluation of the Jacobian. Decoupling the calculations of the equilibrium forces and the geometry of the deformed granular medium leads to an efficient and relatively simple iterative procedure. After debugging and testing, we have verified the efficiency of the approach. For a relatively simple pack of grains, the convergence is practically immediate. To make simulations sensible in the context of hydrate-bearing formation, a good understanding of hydrate distribution in the pore space will be needed in the future.

One of the difficulties in modeling contact interactions in a large pack of grains is the variability of contacts at increasing load. As the stress increases, individual grains are deformed and displaced. Therefore, some pairs of grains, interacting at the initial stress level, may lose the contacts and discontinue interaction as the load grows. A loss (or gain) of a contact requires a revision of the entire system of equilibrium equations. A new regularization method allows for partial elimination of computationally expensive bookkeeping to account for disappearing contacts. The idea is to characterize the lost contacts and vanishing interaction forces by replacing them with small but non-zero attraction. Consequently, the simulations simplify making possible to preserve the structure of the system of equilibrium equations for a broader range of applied stresses. In addition, a posteriori analysis of the signs and the magnitudes of the contact forces points to most likely locations of potential rock failure.

The iterative procedure of solving the system of equilibrium equations has been reorganized and streamlined for handling large packs of grains. All contacts have been classified into two groups: the primary and secondary ones. The primary contacts are used to compute the balance of forces via a simple robust procedure. The output of this procedure is then applied to update the grain locations based on the Hertzian contact forces. Once the geometric structure of the pack has been computed, the secondary forces are updated as well, and the iteration is repeated. Each iteration includes a series of straightforward computations, but does not require solution of a system of equations of high order. For several stopping criteria, the procedure demonstrated high rate of convergence. This work will be continued towards development of efficient and robust procedure capable to handle very large unstructured grain packs with large numbers of intergranular contacts.

We have also started developing a fundamental thermodynamic model of ice/rock interactions in a homogeneous and heterogeneous rock. We are taking into account flow of water in along the corner filaments in angular pores. We hope to capture the $1/r^2$ dependence of rock damage seen in experiments, but not predicted by the existing theories.

Currently we are focusing on improving the scheme that was developed to model the mechanical behavior of a pack of spherical grains. A staggering scheme has been proposed, in which the system of equations could be solved directly, while only some of the variables are updated on each iteration. This procedure is simple and efficient when considering a small, structured pack with uniform properties.

A major achievement has been the development and implementation of a variational method. The contact forces have been expressed through the gradient of potential energy of all individual contacts. The minimum of this function correspond to the equilibrium configuration. This approach has been implemented using the method of steepest descent. A prototype tool for simulating a compression experiment on a granular material to extract the stress-strain curve has been developed. The new procedure provides fast and stable convergence. Large heterogeneous packs of grains have been pressed to an equilibrium configuration after relatively small number of iterations. While the work on refining this tool by incorporating higher-order methods will be continued, the next model development step will be incorporation of shear tractions into the contact model.

We have worked on (1) preparing the framework and development of the code to simulate hydrate-bearing sedimentary rock deformation with account for the tangential contact stresses and (2) running Hertzian contact simulations on a large grain pack in order to compare the results of simulations with available data. The latter task also included the collection of material for submitting a conference presentation and further publication of the result in a peer-reviewed journal.

In both tasks, significant progress has been achieved. For verification, a grain pack generated by other methods has been investigated using our approach. As a side effect, it has helped to make the code performance robust in a wide variety of anomalous situations. It has been found that our algorithms produce significantly denser grain packs before grain deformation starts. In conjunction with high computational efficiency, this fact positions our approach ahead of alternative methods. Simulations of further compression show that the strain-stress curve becomes linear once a loose pack becomes compacted. This makes possible estimation of macroscopic elastic moduli of a rock using grain-scale simulations. The next steps will be estimation of a representative grain pack for given grain size and grain stiffness distributions. Based on the results obtained thus far, a proposal for a conference presentation will be submitted. At the same time, the work on incorporation of tangential stresses will be continued, so that both normal and tangential stresses will be coupled into a single comprehensive model.

We have spent time focused on the verification of the model against available experimental data and on the incorporation of tangential forces. The simulations used heterogeneous packs of spherical grains generated by other codes as an input. The properties of the grains were assigned according to the values reported in literature for quartz sand. First, our code produces a tight compact pack by grain rearrangement only. Then, additional compaction is applied, and the resulting macroscopic stress is calculated in several loading/unloading cycles. Two types of experiments have been simulated: hydrostatic compression, i.e. equal strain increments in all 3 principal directions, and uniaxial tests, i.e. strain variation in one direction only. The first experiment makes possible evaluations of the bulk modulus, whereas the second one yields both Young modulus and Poisson ratio.

Results agree with laboratory data and validate the model: the calculated stiffness falls within the range of values reported in literature for dense sand and sandstone. For tightly compressed packs obtained using high confining stress, the elastic coefficients are closer to those of sandstone. For larger deformations, the calculated stiffness increases with the density of the pack, and the process is, in general, nonlinear. The latter phenomenon is well documented in literature. Sequential loading-unloading cycles produce different stress-strain curves. Such hysteretic effects can be explained by the irreversible rearrangements of the grains. Tracking displacements and deformations of individual grains confirms this explanation.

The incorporation of tangential forces is a tedious task requiring cumbersome calculations. This work has been continued. The concept of quasi-static equilibrium is employed, in order to make the computations efficient.

Subtask 3.2 **Literature Review and Development of Models**

Schlumberger has been working internally on developing new methods for extracting mechanical properties from log measurements in weak sediments. There is good potential to tie that work to the discrete particle modeling work being done at U.C. Berkeley and interpretation of the new Sonic Scanner tool to the rock properties measured in the laboratory.

Schlumberger has also been investigating how to use Petrel as a platform for entering geologic and reservoir data into the ToughFX-FLAC3D model when it is completed. There are two requirements for using Petrel to populate FLAC3D with geological surfaces and rock properties. One is to demonstrate that FLAC3D can import surfaces and properties from Petrel. The other is to verify that Petrel can generate the geologic structures characteristic of the hydrate zone offshore. After a series of meetings between Schlumberger and ITASKA, ITASKA has told us they can import properties and surfaces from Petrel. They have demonstrated the ability to import into FLAC3D surfaces generated in Petrel. For the second part, Schlumberger is working internally to characterize geologic structure from 2D seismic lines crossing the hydrate zone in the Gulf of Mexico.

We have evaluated Petrel's structural modeling and file export formats. It appears that Petrel may not export the type of files needed by FLAC 3D. We met with representatives from Itaska and Petrel to discuss linking the two codes. We found that it is possible to link the two codes. The FLAC models are idealized geological models; as such, the FLAC models may not capture as much geometric detail as we might need in some cases.

The Itaska Consulting Group (http://www.winternet.com/~icg/offices_icg.html) also has software that can be used to solve geomechanical problems. Schlumberger is looking into how the Itaska software can be used with existing Schlumberger software, like Petrel. Schlumberger is working with Itaska to develop an interface from Petrel to FLAC3D. Schlumberger sent to Itaska, several surfaces generated in Petrel. We then discussed how to specify material parameters required by FLAC3D. For example, should we read them in from Petrel, or do we populate them using FLAC "fish functions"? One of the main outcomes of the discussion was the need to simplify the geological model. The models sent from Petrel appear to be more detailed than what are normally used in FLAC3D.

We have been in touch with Western Geco to gain access to a portion of their high resolution 3D seismic data over the hydrate bearing sediments in the GOM. The plan is to review the data to characterize the structural modeling requirements for Petrel. We also found a person in WesternGeco who will help us develop a Petrel model that we can then export to FLAC3D. We recieved the proposal from ITASKA to create the interface between Petrel and FLAC3D. Schlumberger approved the budget for the ITASKA proposal to create an interface linking Petrel to FLAC3D. We also held meetings with WesternGeco to identify a test data set to "demonstrate" the link. We have the go ahead for build the FLACD interface to Petrel.

The forward plan is to work with WesternGeco to build a simple but representative Petrel Model from the Gulf of Mexico, and have ITASKA import it into FLAC3D. The first pass will be to import the surfaces. If we have time, we will try to import rock properties also.

Schlumberger has also approved the donation of Petrel licenses to Texas A&M University, University of California at Berkeley and Lawrence Berkeley National Laboratories as part of the cost sharing commitment.

***Subtask 3.3* – Description of hydrate-bearing zones as documented by the Ocean Drilling Program and the Chevron-DOE Gulf of Mexico JIP to determine typical gas hydrate bearing sample characteristics**

We have reviewed the available literature from the Ocean Drilling Program and the Chevron – DOE Deep Water Gulf of Mexico Joint Industry Project to gather information necessary to describe the hydrate-bearing zones encountered by these groups in their drilling and coring operations. Investigation includes evaluation of the analysis of the samples of hydrate-bearing cores obtained by the ODP in Oregon, Blake Ridge, and other projects, such as the one in Japan gathering data on the Nankai Trough deep water areas, to determine the chemical and mineral characteristics of those samples.

We have collected the information on the sediments recovered from the Gulf of Mexico, the Nankai Trough, Blake Ridge, the Cascadia Margin, and India. In Gulf of Mexico, there are a total of 35 samples analyzed for the geochemistry and lithology of the sediments. In most of the cases, the sediments which were inferred to host hydrates were hemipelagic sediments. The sediments also contained authigenic carbonates (carbonates generated in-situ).

In the Nankai Trough, gas hydrate has been observed in sandy and silty layers. The mudstone overlying the sandy and silty layers is pretty much free of hydrates. This has been confirmed by pore water chemistry.

The graduate student working on this project, Tarun Grover, worked as a summer internship with Schlumberger in Denver. In his summer job, Tarun developed 1D, 2D and 3D Mechanical Earth Models (MEM) for use in geomechanical simulators, like FLAC. He also used Schlumberger's well bore stability models and their fracture design models to validate the MEM, and couple the MEM with Eclipse.

We developed an 'Interim' report on the lithology and sediment characteristics of hydrate hosting sediments in Blake Ridge and the Cascadia Margin. The Interim report was an attachment to the June 2006 Monthly Report. The final report will be in the Phase I report, and will include additional information on the sediment characteristics in the Gulf of Mexico, the Nankai Trough and other areas of world.

Figure 1 shows the types of deposits that are found in the natural gas hydrates from the core recovery. Our main goal is to generate a step by step methodology to create the disseminated and veins of gas hydrates in the laboratory. From searching the civil engineering literature, we found that there have been some experiments to study the mechanical properties of the unsaturated (gas + water) sediments. Vanoudheusden et al [2004] have studied the mechanical behavior of unsaturated marine sediments using experiments as well as theoretical approaches. In their paper, the soil properties are important to study any mechanical behavior. The important soil properties are void ratio, permeability, consolidation coefficient and Atterberg limits. In the Ocean Drilling Program cruises on various locations, these properties have been estimated by extensive laboratory tests.

Figure 1 – Geometries of natural gas hydrates (Source: ODP Initial Reports leg 204)

***Subtask 3.4* – Definition of methodology for creation of Synthetic Hydrate-Sediment mixture samples**

We have prepared a detailed description of the methodology and techniques required to create synthetic hydrate-sediment samples that provide chemical and mineral characteristics representative of the actual hydrate bearing cores reviewed under Subtask 3.3 activities. The report will be part of our Phase I report. DOE will review the proposed sample creation methodology and will provide concurrence with proposed techniques or may request definition of alternate sample creation techniques. The methodology developed under this activity will be used in the preparation of all samples used to conduct laboratory testing under Task 7 activities.

We first searched the literature to find papers on how to build the synthetic sediments in laboratory for experimental work. We have compiled information on the methods used to build representative and reproducible samples of sediments in a laboratory setting. We have worked with Dr. Giovanna Biscontin in the Civil Engineering Department at Texas A&M University, and she referred us to a thesis by Jocelyn Grozic from University of Calgary who has done some work on lab testing of unconsolidated marine sediments containing gas. We have reviewed that thesis and other papers on the methods to build artificial marine sediments. We also coordinated our efforts with individuals in the Department of Geology and Geophysics at Texas A&M University.

We have performed a detailed literature search on the types of sediments and porous media used so far in the experimental studies by different researchers. According to the literature, most of the people have carried out experiments in sand packs or glass beads to represent the natural porous media. The motivation for the experiments has been to study the thermal properties, thermodynamic properties, acoustic properties and electrical properties of hydrate bearing sediments. However, few of these experimental setups have generated the data that can be directly applied to the field studies of hydrate bearing sediments in offshore environments. Moreover, some of the experiments use the Tetrahydrofuran (THF) to form the hydrates in porous media.

Task 4.0 – Development of the coupled geomechanical numerical model

Lawrence Berkeley National Laboratory (LBNL) successfully coupled the TOUGH-Fx/HYDRATE model with FLAC3D. The TOUGH-Fx/HYDRATE model is used to predict the evolution of pressure, temperature, saturation distribution, and salt concentration in hydrate-bearing systems undergoing changes through any combination of mechanisms that can induce hydrate dissociation or formation (change in pressure, temperature and in the concentration of inhibitors). The FLAC3D model is a geomechanical model (Itasca Consulting Group, 1997) for soil and rock mechanics engineering. Simulations using the coupled code will execute the two component codes on compatible numerical grids and will link the component codes through synchronization coupling modules and external files, which serve to pass relevant information between the field equations that are solved in the respective codes.

LBNL designed new FLAC3D-FISH routines to accomplish the following:

(a) The implementation of a constitutive model describing the geomechanical behavior of HBS as a function of phase saturations (and hydrate saturation in particular), and accounting for the effects of temperature and inhibitors (e.g., salts);

(b) Routine for calculating coupled geomechanical effects in the geologic media of HBS (both at the medium grain level and at the reservoir skeleton level) and describing deformation caused by thermal strain, effective stress or swelling/shrinkage in response to changes in the concentration of inhibitors (e.g., shale swelling upon release of fresh water from hydrate dissociation); and

(c) Reading the HBS-specific inputs, reading the TOUGH-Fx/HYDRATE outputs from external files, and creating standardized output files (to be read by TOUGH-Fx/HYDRATE for property update).

Significant effort was invested in the TOUGH-Fx/HYDRATE code modification to ensure seamless coupling with FLAC3D. Thus, appropriate subroutines were designed and developed to invoke FLAC3D as a standard system procedure. Finally, the standard TOUGH-Fx/HYDRATE computational processes were redesigned and substantially modified by (i) deactivating the standard treatment of permeability as a region-wide constant, (ii) deactivating of the standard model of porosity as a region-wide variable affected by pore compressibility and expansivity, and (iii) replacing (i) and (ii) by the full models of evolving permeability and porosity as functions of hydraulic, thermal and mechanical changes. The new design packages incorporate all the geomechanically-affected hydraulic properties in a self-sufficient module based on the principles of Object-Oriented Programming (OOP).

Coding was completed in the modifications that involve (i) deactivating the standard treatment of permeability as a region-wide constant, (ii) deactivating of the standard model of porosity as a region-wide variable affected by pore compressibility and expansivity, and (iii) replacing (i) and (ii) by the full models of evolving permeability and porosity as functions of hydraulic, thermal and mechanical changes. The recoded code segment packages all the geomechanically-affected hydraulic properties in a self-sufficient module based on the principles of Object-Oriented Programming (OOP). Additionally, the design and coding are very general, and allow interaction with any package (in addition to FLAC3D) that can provide the stress and strain information needed to update the hydraulic properties.

The redesign of the core code of TOUGH-Fx/HYDRATE to accept FLAC3D as a standard system procedure has been completed. An important improvement of the redesigned code includes an option to update the geomechanically-affected hydraulic properties (permeability, wettability and capillary pressure) at a user-controlled frequency. The recoded code segment packages all the geomechanically-affected hydraulic properties in a self-sufficient module based on the principles of Object-Oriented Programming (OOP). Additionally, the design and coding are very general, and allow interaction with any package (in addition to FLAC3D) that can provide the stress and strain information needed to update the hydraulic properties.

We have worked on the subject of describing medium deformation (subsidence) caused by (i) loss of the cementing hydrates and (ii) load transfer from the hydrate to the porous medium in the process of dissociation. The evaluation of the two possible options (i.e., adding an equation describing the mass balance of the solid porous medium, or allowing the deformation of the grid blocks) is nearing completion, and the grid deformation approach appears to be the most promising.

The redesign of the FORTRAN 95/2003 core code of TOUGH-Fx/HYDRATE to accept FLAC3D as a standard system procedure has been completed. Further code modifications of TOUGH-Fx/HYDRATE will be very minor, and will be needed only in the course of integration of/synchronization with the FLAC3D component of the package. This being the case, the effort until the end of the first year of the study will focus exclusively on the development of the FLAC3D subroutines and the integration of the package. The FLAC3D component of the work involves the description of the medium deformation (subsidence) caused by (i) loss of the cementing hydrates and (ii) load transfer from the hydrate to the porous medium in the process of dissociation. The evaluation of the two possible options (i.e., adding an equation describing the mass balance of the solid porous medium, or allowing the deformation of the gridblocks) is nearing completion, and the grid deformation approach appears to be the most promising.

With the completion the redesign of the FORTRAN 95/2003 core code of TOUGH-Fx/HYDRATE to accept FLAC3D, and of the coding of the FISH-FLAC3D routines, the only tasks remaining for the completion of the FY2006 activities are (a) the communication, synchronization and data exchange between the two component codes, and (b) code testing of the coupled simulator in a series of three realistic tests.

LBNL has focused on the communication, synchronization and data exchange between the component codes of the geomechanical model, i.e., TOUGH-Fx/HYDRATE and FLAC3D. Significant effort was invested in the optimization of synchronization, which is now accomplished using a single external file. Additionally, the library of geomechanical processes in TOUGH-Fx/HYDRATE was expanded to include additional models relating changes in stress and strain to (a) changes in porosity and permeability and/or (b) failure.

LBNL staff tried to reach an arrangement with the developers of FLAC3D for access to portions of the source code and to the memory management of FLAC3D. The negotiations were unsuccessful because the developers of FLAC3D are unwilling to share their source code with LBNL. Because this approach would result in significant increases in computational efficiency of the coupled geomechanical model since FLAC3D and TOUGH-Fx/HYDRATE would be sharing the same memory (thus eliminating the need to read and write external files), we intend to pursue the matter at a later time, after developing an approach that would address the concerns of the FLAC3D developers. The coding effort based on reading external files continues unaffected.

6. Conclusions from the Reporting Period

On the basis of the work performed during this reporting period, the following conclusions are presented.

- We have developed a technique for estimating the elastic moduli of a heterogeneous grain pack by modeling mechanical interactions among the grains. Each grain is elastic, and the contact deformations are modeled using Hertz and Mindlin theories. We model the deformation of a grain pack as a sequence of static equilibrium configurations. Each configuration is sought by minimization of the potential energy of the pack. For a loose configuration, our algorithm produces a more realistic tighter pack than other methods. We capture and analyze hysteretic events, such as different loading and unloading responses or abrupt breakage of grain clusters. The computed bulk modulus estimates match experimental values reported in literature. The current progress has been presented at two conferences.

- We have coupled the TOUGH+/HYDRATE code with FLAC3D, which is a commercial code that is widely used in soil and rock mechanics engineering, and for scientific research in academia. TOUGH+/HYDRATE allows the study of flow and transport of fluids and heat in hydrate deposits, and accurately describes the thermodynamics of hydrates as they are distributed among fifteen possible states. The coupled model, TH+/FLAC is the first of its kind. The model can be used for the analysis of hydraulic, thermal, flow and geomechanical behavior in HBS, and is a unique tool for the analysis of the effect of hydrate dissociation processes on the structural stability and possible displacement of HBS and of their overburden materials.

- We have completed a comprehensive literature review to characterize the sediments containing hydrates that have been recovered from scientific cruises. The various regions that have been explored for gas hydrates and were reviewed in our work include Blake Ridge (Offshore South Carolina), Gulf of Mexico, Offshore Oregon (Cascadian Margin and Hydrate Ridge), Nankai Trough (Offshore Japan), Offshore Peru and various other regions explored by the Ocean Drilling Program (ODP). After analyzing all the sediments, we have recommended that three sediment mixtures that we can use for mechanical properties testing in Phase II of this project.

- We have been developing a method to use Petrel as a platform for entering geologic and reservoir data into the ToughFX-FLAC3D model when it is completed. There are two requirements for using Petrel to populate FLAC3D with geological surfaces and rock properties. One is to demonstrate that FLAC3D can import surfaces and properties from Petrel. The other is to verify that Petrel can generate the geologic structures characteristic of the hydrate zone offshore. We are also working to characterize geologic structure from 2D seismic lines crossing the hydrate zone in the Gulf of Mexico so we can use that information in our modeling efforts.

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