GEOMECHANICAL PERFORMANCE OF HYDRATE-BEARING SEDIMENTS IN OFFSHORE ENVIRONMENTS

Technology Status Assessment

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TABLE OF CONTENTS

1 Description of the Problem

Because of concerns about the geomechanical stability of Hydrate-Bearing Sediments (HBS), 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. Such concerns increase exponentially if gas is being produced from marine hydrate accumulations (and, to a lesser extent, from permafrost deposits), thus posing a serious impediment to the development of such resources.

Currently, there is a lack of understanding of the thermo-mechanical properties of sediments containing gas hydrates, especially in marine deposits. 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 field development, but dictated by the need to avoid the hydrate accumulations, the cost of production can increase significantly.

Warmer fluid (rising through HBS from deeper formations) may cause gas hydrate near a well or pipeline to dissociate, reducing the stability of the supporting formations, and placing significant investments at risk. Hydrate dissociation may also be caused by direct mechanical loading of HBS (e.g., caused by the weight of structures) in a manner akin to ice melting stemming from increased pressure.

The main objective of this study is to evaluate the response of marine HBS to thermal and/or mechanical loading. Thermal loading occurs when heat from hot reservoir fluids (produced from deeper reservoirs) flows into the HBS through un-insulated pipes. The resulting rise in temperature in the HBS can have serious consequences. Even before dissociation is attained, a rising temperature is expected to affect the mechanical strength of hydrate-bearing sediments – possibly severely, given the narrow temperature range between hydrate stability and dissociation. When the temperature reaches the hydrate equilibrium temperature, hydrate dissociation occurs by thermal stimulation. This leads to the rapid release of large amounts of gas, which can in turn result in the evolution of high pressures. This higher pressure can result in formation fracturing, with potentially serious consequences if the fracture plane crosses the confining (impermeable) top boundary of an underlying reservoir, thus allowing the escape of the reservoir fluids. It is also possible that the increased pressure, if sufficiently high, can have detrimental effects on the wellbore assembly, including cement fracturing and wellbore collapse.

Another problem that can be potentially caused by thermal or mechanical loading is the deterioration of the structural stability of the geologic formation in the vicinity of the wellbore or of anchoring sub-oceanic structures. Hydrates are very effective cementing agents, and their dissociation can lead to significant geomechanical changes in the affected region (including subsidence). Unless accounted for, these changes can pose a hazard to the structural stability of wellbores as wells as platform-supporting (anchoring) structures. The reason for the concern is demonstrated in the photograph of **Figure 1**, which shows a dissociating core of a marine HBS. While the more isolated inner portion of the core (where hydrate still remains) appears "solid" and structurally strong, the medium in the outer annular space (where hydrate dissociation is in progress or has already occurred) has a fluid and very weak consistency because of the loss of the cementing hydrate and shows evidence of escaping gases (bubbling). Because of its consistency, the remaining watery mud is characterized as “soupy sediment”. The impact of its evolution on the structural stability of marine HBS demands evaluation, especially in the case of compressible sediments such as muds and clays. Depletion of the cementing hydrate can result in load transfer to the structurally weak porous medium, with potential consequences of displacement, subsidence, and failure/fracturing of the HBS.

Finally, during dissociation, the basal zone of the gas hydrate becomes under-consolidated and possibly over-pressurized because of the newly released gas, leading to a zone of weakness characterized by low shear strength (where failure could be triggered by gravitational loading or seismic disturbances), which can result in submarine landslides.

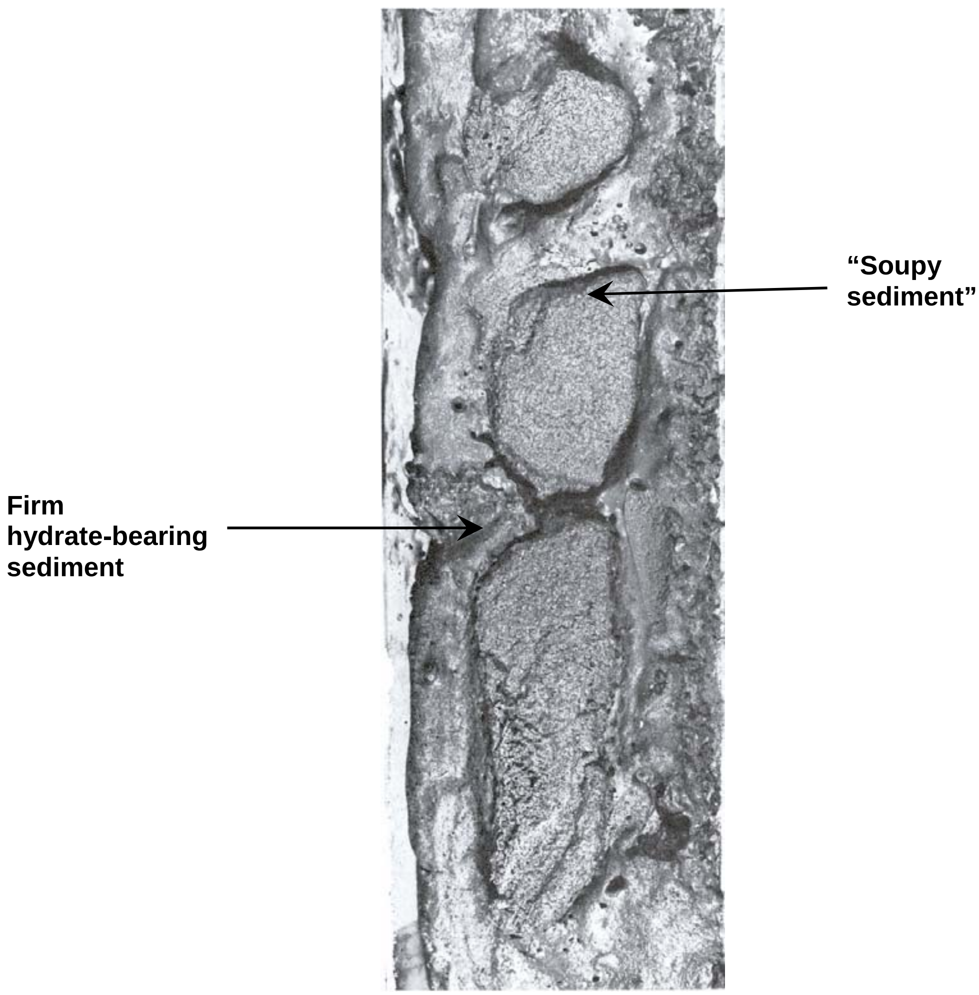

Figure 1 – Dissociating sample of a marine HBS core. Note the firm appearance of the hydrate-bearing inner core, as opposed to the “soupy sediment” (soft mud of fluid consistency with evidence of bubbling gas) in the dissociating outer annulus (source: Deep Sea Drilling Program, Leg 67, courtesy of C.K Paull of the Monterey Bay Research Institute).

2 Status of the problem

Given the potentially catastrophic consequences of the compromise of the stability of HBS, and the significant uncertainties regarding the behavior of HBS (stemming from the rather embryonic state of fundamental knowledge on the subject), the development of quantitative predictive capabilities for the description of the geomechanical properties of HBS (and of the factors and parameter affecting them) is critically important to allow safe operation in (and/or resource recovery from) hydrate accumulations. Below, we discuss the knowledge requirements for the development of reliable models, as well as the corresponding state of knowledge of each:

2.1 Fundamentals of hydrate hydraulic, thermal and thermodynamic behavior in HBS

The subject has received significant attention over the last several years, and a body of information has become available. More specifically, the state of knowledge is as follows:

2.1.1 Reliable quantitative constitutive relationships and corresponding parameters.

Hydrate hydraulic and thermal relationships, and associated parameters, have been developed (or are being developed), and cover the spectrum of hydraulic behavior (including the effects of the hydrate presence on the capillary pressure and the fluid relative permeability of HBS), to thermal system behavior (composite thermal conductivity and specific heat of HBS), to real gas properties and behavior, to thermodynamics (including mass transfer and phase relationships). While the thermodynamics of pure CH_4 systems are rather well defined, the thermodynamics of composite hydrates (i.e., of more than one gas, quite common in oceanic systems) are far more complex and less well known, and can have very important implications in marine deposits (a mere 1% concentration in a gas other than CH_4 can change the P-T equilibrium by 40%). The statistical thermodynamics approach of Sloan (1998) can describe the properties and behavior of such complex hydrates, but may be cumbersome to use within the context of large-scale domain simulations, and need experimental verification prior to application.

2.1.2 Integrated models for system behavior in complex geologic media.

Several such integrated models (incorporating the constitutive relationships discussed above) have become available over the last few years. Examples of such models include TOUGH-Fx/HYDRATE (Moridis, 2003; Moridis et al., 2005 – developed by Lawrence Berkeley National Laboratory, USA), MH21 (Kurihara et al., 2005 – developed by the Japan Oil Engineering Co.), STOMP/HYDRATE (White et al., 2005– developed by the Pacific Northwest National Laboratory, USA). It is expected that these models will readily incorporate all the new advancements in any fundamental relationships discovered in the laboratory.

2.2 Geomechanical behavior of HBS.

The state of knowledge on this subject is in its infancy. Actually, it is expected that the joint TAMU-UCB-LBNL project will significantly advance the knowledge base on the subject. More specifically, within this area, knowledge on the following specific issues is needed:

2.2.1 Reliable geomechanical constitutive relationships and corresponding parameters.

There have been no quantitative relationships describing the geomechanical behavior and structural performance of HBS as a function of phase saturations in the porous media. There are no predictive relationships that can relate hydrate phase behavior to porous medium displacement, subsidence, compaction and failure (fracturing). Additionally, because information on the subject is scant, it is very difficult (and probably inadvisable) to extrapolate knowledge obtained from ice-bearing systems to HBS. While ice has been used as a reasonable conceptual analog, the only currently available study on the cementing properties of hydrates (Durham et al., 2006) have indicated that hydrates impart far more structural strength (at least an order of magnitude larger) to porous media than similar saturations of ice. While this information can be used to predict the lower limit of geomechanical behavior of hydrates, it is rather qualitative in nature and cannot be used for any type of quantitative predictions.

2.2.2 General models of geomechanical system behavior in complex geologic media.

This area is rather well developed, and a variety of reliable models for the description of the geomechanical behavior of geological systems are available. An example of such a model is FLAC3D (Itasca Consulting Group, 1997). This model is widely used in soil and rock mechanics engineering, and for scientific research in academia. FLAC3D (as all similar packages) has built-in constitutive mechanical models suitable for soil and rocks, including various elastoplastic models for quasistatic yield and failure analysis, and viscoplastic models for time dependent (creep) analysis. Additionally, such models allow the incorporation of new constitutive models (developed in the process of the study of a specific system of interest). Therefore, the availability of such models provides a base upon which to build simulators specific to HBS, once the relevant constitutive relationships and the corresponding parameters become available.

2.3 Interrelations between hydraulic, thermal, thermodynamic and geomechanical processes in HBS.

As in Section 2.2 above, the state of knowledge on this subject is in its infancy, and significant progress on the subject is expected as a result of the joint TAMU-UCB-LBNL project. More specifically, within this area, knowledge on the following specific issues is needed:

2.3.1 Reliable geomechanical constitutive relationships and corresponding parameters.

There have been no quantitative relationships describing the relationship between stress and strain and the hydraulic properties of HBS (i.e., intrinsic permeability and capillary pressure). There is no information on the effect of temperature on the geomechanical response of HBS, as there is no information on the fracturing performance of HBS. Although it is possible to extrapolate existing relationships (and the corresponding parameters) using ice as an analog for hydrates, it must be indicated that this can only serve as a first-order approximation that can provide an estimate of the lower limit of the expected HBS response. Hydrate-specific relationships and parameters are needed for reliable predictions of the HBS system behavior. The laboratory component of the joint TAMU-UCB-LBNL effort (scheduled for the second year of the project) is expected to address this knowledge gap.

2.3.2 Models of coupled hydraulic, thermodynamic and geomechanical processes.

To accurately describe the complex interrelationship of the hydraulic, thermal, thermodynamic and geomechanical processes in HBS, coupled models (combining the simulators described above) are needed. No such models are currently available. Although it is possible to use the models in tandem in a set of sequential predictions, the process is cumbersome and can carry significant risks of inaccuracy because the lack of coupling inherent in such an approach does not adequately describe the process interrelationship and the strong nonlinearities involved in such systems. The development of such a coupled model (the first of its kind) is viewed as a very significant step in the advancement of our capability to predict the geomechanical behavior of HBS, is considered a significant scientific breakthrough and a quantum leap in our knowledge and understanding of the HBS behavior, and represents one of the most important goals of the joint TAMU-UCB-LBNL project.

3 Our Approach

A new approach is required to understand, evaluate and predict the geomechanical behavior of oceanic sediments containing gas hydrates because no tools nor much information on the subject are currently in the public domain. The development of deep water, conventional oil and gas fields in the Gulf of Mexico, West Africa and South America have shed light on the fact that the industry needs to understand and be able to model the geomechanical behavior of oceanic sediments containing gas hydrates in order to operate platforms, sub-sea facilities and pipelines safely. The information from this project will also be very useful to companies trying to plan wells, facilities and pipelines in future developments of gas hydrate deposits in order to produce natural gas. To achieve the objectives of the project, the following strategies shall be employed:

- The geomechanical behavior of oceanic hydrate bearing sediments (hereafter referred to as HBS) will be investigated using pore-scale models (conceptual and mathematical) of fluid flow, stress analysis, and damage propagation.

- Laboratory studies will be conducted 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.

- A robust numerical simulator of hydrate behavior in geologic media will be coupled with a commercial geomechanical code, thus developing a numerical code for the stability analysis of HBS under mechanical and thermal stresses.

- 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.

3.1 Modeling the effect of gas hydrates at the pore level

Prediction of mechanical stability of hydrate-bearing sediments (HBS) relies on coupled simulation of fluid flow and mechanical deformation and damage of the rock. Such a simulation requires input parameters such as rock strength, permeability, relative permeabilities, and capillary pressure curve. These macroscopic parameters are derived from the geometric structure of the solid skeleton, the strength of the inter-granular bonds, and the relative number of the bonds broken due to hydrate dissociation and possible rock failure under stress. The objective of Task 3 is to analyze the impact of the presence and dissociation of hydrates on the mechanical stability of the rock in presence of fluid flow. This analysis relies on pore-scale modeling of HBS.

A code based on Distinct Elements Method (DEM) has been developed at UC Berkeley over the past three years. It provides a capability of simulation and visualization of rock strength and failure under various stress conditions. We will enhance the model of inter-granular contact mechanics and incorporate the *physics of interaction between hydrate residing in the inter-granular space and rock grains* into the simulations. The objective of the study will be creating a framework allowing for computation of constitutive relationships suitable for TOUGH-Fx/HYDRATE – FLAC3D simulations. Pore-scale simulations will use three-D high-resolution images of computer-generated sedimentary rocks. This analysis will provide clues to what processes and phenomena define rock strength or failure in the course of hydrate formation or dissociation.

3.2 Building an integrated porous media fluid flow – geomechanical model

The design and operation of gas production from marine hydrate accumulations needs to take into consideration geomechanical changes that affect the structural stability of the HBS. Potentially significant subsidence and structural weakening of the hydrate may affect the stability of the well assembly, while pressure rises may cause inadvertently fracturing of the HBS and its confining boundaries, in addition to damaging the wellbore system. Because of these concerns, the placement of wells and seafloor platforms is strongly influenced by the presence of gas hydrates on the sea floor or within the sediment lithology, and will be even more so if gas production from oceanic gas hydrate accumulations becomes an economically viable option.

In the area of prediction of the geomechanical behavior of HBS, knowledge gaps exist in the following areas:

- Understanding of the mechanical and thermal properties of sediments containing gas hydrates, especially in marine deposits.
- Coupled models of hydrate behavior and geomechanical performance. Currently, there are models describing the fluid behavior in hydrate-bearing geological media, as well as pure geomechanical models (i.e., not accounting for the interactions with concurrent fluid flow). The extremely nonlinear relationships between flow, thermal, and geomechanical properties does not allow the independent (or even sequential) use of hydrate flow and geomechanical models, but necessitates the coupling of these models.

Thus, LBNL is in the process of developing a coupled code that can describe the interaction of (a) hydraulic, thermal, thermodynamic and phase behavior of hydrates and the corresponding fluids in hydrate accumulations with (b) the geomechanical response of hydrate-bearing sediments. LBNL has developed TOUGH-Fx/HYDRATE, the most-advanced code currently available for the simulation of system behavior in geological media containing gas hydrates. This code predicts 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 (changes in pressure, temperature and in the concentration of inhibitors). In the joint TAMU-UCB-LBNL project, LBNL is coupling TOUGH-Fx/HYDRATE with an existing state-of-the-art geomechanical model FLAC3D. This model is widely used in soil and rock mechanics engineering, and for scientific research in academia. FLAC3D has built-in constitutive mechanical models suitable for soil and rocks, including various elastoplastic models for quasistatic yield and failure analysis, and viscoplastic models for time dependent (creep) analysis. For analysis of the mechanical behavior of methane hydrates, which exhibit significant strain hardening behavior, existing models for strain-hardening/softening plasticity can be readily utilized. Moreover, new constitutive models (to be developed in a later phase of this project) governing the evolution of macroscopic rock damage are to be implemented into the elastoplastic analysis with FLAC3D.

3.3 Coupling our research with industry needs

Schlumberger's proposed work is aimed at developing the capability of constructing 3D geomechanical earth models of weak-marine sediments containing gas hydrate. Geomechanical models are used to predict the response of hydrate bearing sediments to changes in earth stress and/or temperature. Typically, geomechanical models are developed in three stages:1) developing a 3D structural framework model; 2) property modeling, characterizing the sediments and their spatial distribution and 3) (stress modeling) calculating and calibrating the initial 3D state of stress. Schlumberger's Petrel software is state-of the art commercial geologic modeling package used for framework and property modeling. We will review the structural styles characteristic of the deep-marine-sedimentary environment, including the shapes of sedimentary bodies and fault geometry. We will work with Petrel developers to make changes to the software required to accurately model these geobodies. It is envisioned that modifications to fault geometry might be required. Petrel's property modeling tools should be adequate. For this project, stress modeling will be done in FLAC3D. We will work with developers and ITASKA to determine if Petrel models can be exported to FLAC3D. If not, we will work with Petrel developers to create an interface with FLAC3D.

Although Petrel has tools for distributing geologic and geomechanical parameters, characterizing the geological and constitutive properties of hydrate bearing marine sediments is still a research topic within the geoscience and the petroleum engineering communities. Of particular interest is measurement of the spatial distribution of hydrates at the pore scale and determining its role in strengthening the sediments. Is the hydrate distributed as veins, nodules or as a homogeneously-cemented sediment?

Schlumberger has just introduced a new acoustic logging tool that measures radial profiles of acoustic properties. This tool has the potential for radically improving our ability to characterize weak sedimentary rocks. Schlumberger proposed to conduct a review of existing constitutive models of sediments that would include an examination of standard elastoplastic damage models and encompass the extensive literature on frozen sediments. This work has not received funding. Subject to funding, Schlumberger will conduct the review and suggest possible approaches that combine inversion of sonic and seismic velocities for elastoplastic and damage parameters in order to enable a prediction of the rock mechanical behavior. However, we will follow closely the work at UC Berkeley with the aim of translating their pore-scale DEM work to log interpretation.

Theory of Acoustic Radial Profiles for damage detection using 2^{nd} and 4^{th} damage tensors obtained from wave velocity measurements shall be further developed such that the damage parameters obtained from acoustic and seismic measurements could be used to predict the rock mechanical behavior in hydrate bearing sediments.

4 Expected Results and Future Needs

There could be several barriers to success, such as being able to successfully conduct geomechanical and other experiments on reformulated oceanic sediments in the laboratory. Many of the typical sediments will be silty, shaly mixtures of minerals and it may be difficult and/or time consuming to actually get methane hydrates to form and dissolve in the pore system of these sediments. We will have to develop novel laboratory methods to achieve our goals.

One product of the joint TAMU-UCB-LBNL project will be TFxH/FLAC3D, a computer model that can be used to determine and predict the coupled geomechanical and fluid flow behavior of oceanic sediments containing gas hydrates. This tool, the first of its kind in the world when it becomes available, can be used for both seafloor stability studies and for investigating the issues of formation and well bore stability when trying to produce natural gas from gas hydrate deposits.

UCB will develop information that will let us better understand how gas hydrates form and dissolve in the pores of sediments. This software will be used in both the design and analysis of laboratory experiments and to better simulate gas hydrate deposits.

SLB will modify Petrel to allow its use to build earth models with the data needed to simulate sediments above, within and beneath gas hydrate deposits so we can use the earth model results as input into TFxH/FLAC3D and other models.

Guidelines will be published describing typical oceanic sediments containing gas hydrates and how to reproducibly mix and test these samples in the laboratory. Results from laboratory experiments using these samples will add to the scientific literature.