

Development of a Numerical Simulator for Analyzing the Geomechanical Performance of Hydrate-Bearing Sediments

Rutqvist, J. and Moridis G.J.

Lawrence Berkeley National Laboratory, Berkeley, California, USA

ABSTRACT: In this paper, we describe the development and application of a numerical simulator that analyzes the geomechanical performance of hydrate-bearing sediments, which may become an important future energy supply. The simulator is developed by coupling a robust numerical simulator of coupled fluid flow, hydrate thermodynamics, and phase behavior in geologic media (TOUGH+HYDRATE) with an established geomechanical code (FLAC3D). We demonstrate the current simulator capabilities and applicability for two examples of geomechanical responses of hydrate bearing sediments during production-induced hydrate dissociation. In these applications, the coupled geomechanical behavior within hydrate-bearing sediments are considered through a Mohr-Coulomb constitutive model, corrected for changes in pore-filling hydrate and ice content, based on laboratory data. The results demonstrate how depressurization-based gas production from oceanic hydrate deposits may lead to severe geomechanical problems unless care is taken in designing the production scheme. We conclude that the coupled simulator can be used to design production strategies for optimizing production, while avoiding damaging geomechanical problems.

1. INTRODUCTION

Methane hydrates occur naturally offshore in shallow depths below the ocean floor and onshore beneath the permafrost. They contain enormous quantities of methane gas, which if economically producible could provide significant contributions to future energy supplies. Interest in gas hydrates has increased in recent years, with governments (as well as several oil- and gas-producing companies) initiating projects for drilling and testing of hydrate-bearing sediments (HBS). Several production methods, including depressurization, thermal methods, and inhibitor injection, are being considered for extraction of gas from HBS. However, any type of production operation within HBS may pose a significant hazard, because thermal and mechanical loading can result in hydrate dissociation, with potentially adverse consequences for the structural integrity and stability of the sediment. At the same time, our knowledge about geomechanical behavior of HBS during decomposition and their effects on operation safety is very limited. Thus, we need to incorporate the necessary formulations for geomechanical behavior in current hydrate simulators, as well as experimentally determine the geomechanical properties of hydrate formations [1].

In this paper, we present development of a numerical simulator for geomechanical-performance analysis of HBS. The simulator is developed by coupling a robust numerical simulator of coupled fluid flow and

thermodynamic hydrate behavior in geologic media (TOUGH+HYDRATE), with a geomechanical code (FLAC3D). The objective is to build a simulator that can be used for scientific and engineering analyses of hydrate stability, including well bore and reservoir instability during production from oceanic and permafrost hydrate formations. Because of very limited data on the geomechanical behavior of HBS, we cannot develop a universally valid constitutive model for coupled geomechanical behavior of HBS at this time. Rather, we rely on soil- and rock-mechanics constitutive models, corrected with empirical coupling relationships derived from observations of a few available experimental data. The capabilities of the simulator are demonstrated, first by solving a small-scale (200 gridblocks) illustrative example of geomechanical changes in an HBS during production-induced hydrate dissociation and ice-formation, and second by solving a larger-scale (about 10,000 gridblocks) modeling of gas production from an oceanic HBS, representing the Tigershark formation in the Gulf of Mexico.

2. GENERAL MODELING APPROACH

The starting point of our approach is the TOUGH+HYDRATE simulator [2-4], which describes hydraulic, thermal, and thermodynamic behavior in geological media containing gas hydrates. This code predicts the evolution of all the important thermophysical properties (e.g., pressure, temperature,

phase saturation distribution, salt concentration) in hydrate-bearing systems undergoing changes through any combination of mechanisms that can induce hydrate dissociation or formation, (i.e., changes in pressure, temperature, and/or in the concentration of inhibitors, such as salts and alcohols). To consider geomechanical effects, the TOUGH+HYDRATE code is coupled with the FLAC3D [5] geomechanical simulator. This simulator 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 quasi-static yield and failure analysis, and viscoplastic models for time dependent (creep) analysis, that could be used directly or modified for analysis of the geomechanical behavior of HBS.

In the resulting coupled simulator (hereafter referred to as T+F), the two constituent codes—TOUGH+HYDRATE and FLAC3D—are linked through a coupled thermal-hydrological-mechanical (THM) model of the HBS (Fig. 1). The THM model is consistent with the porous media model (one of the several available as options in TOUGH+HYDRATE) that describes media deformation as a result of geomechanical changes. Based on this THM model, a number of coupling functions are derived, as described below.

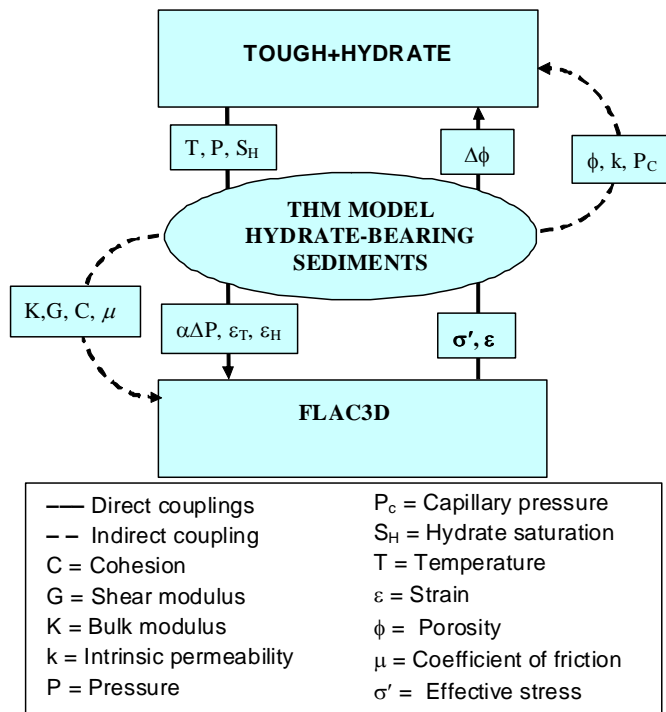


Fig. 1. Coupling of TOUGH+HYDRATE and FLAC3D for analyzing the geomechanical behavior of hydrate-bearing sediments.

3. COUPLING FUNCTIONS FOR HBS

The basic couplings between hydrological and mechanical processes in the deformable porous media are considered through:

- (i) An effective stress law that defines how a change in pore pressure affects mechanical deformation and stress
- (ii) A pore-volume model that defines how a change in stress or strain affects the fluid flow

In addition, there are numerous couplings—including changes in mechanical and hydrological properties—that are the consequences of changes in effective stress and pore volume. The relationship between hydraulic and geomechanical properties is further complicated by couplings related to temperature changes, and the possible effects of inhibitors. (Salts are present in all oceanic hydrate deposits, and salts and alcohols are occasionally used to enhance hydrate dissociation.) These coupling routines were developed within the framework of the object-oriented FORTRAN 95 architecture of TOUGH+ [4] and the FISH programming language available in FLAC3D [5].

Note that while all these interactions are accounted for in T+F using generally accepted models, information on the specific parameters describing the HBS behavior is currently scarce [6], because this area of research has so far received scant attention. Specialized laboratory experiments are needed to (a) validate and verify the mathematical models, and (b) determine the corresponding parameters.

In Fig. 1, the data exchanges between TOUGH+HYDRATE and FLAC3D are illustrated with arrows going through the central THM model. The arrow on the right hand side of Fig. 1 shows the transmission of the effective stress σ' and strain ε (that are computed in FLAC3D) to TOUGH+HYDRATE for calculation of the updated porosity ϕ and the corresponding porosity change $\Delta\phi$. This mechanically induced $\Delta\phi$ has an immediate effect on fluid flow behavior. For example, if a change in σ' and ε causes ϕ to decrease, the pore pressure is expected to rise, especially if the permeability is low. Two models for mechanically induced porosity changes are implemented in the current version of T+F:

- (i) A poroelastic model (based on the approach proposed by Settari and Mourits [7]) that considers macroscopic stress/strain changes and grain deformability
- (ii) An empirical model (proposed by Rutqvist and Tsang [8]) that describes a nonlinear change in porosity as a function of the effective mean stress

The $\Delta\phi$ computed from either of these models is used to estimate changes in k by means of empirical equations

[4, 8]. The updated ϕ and k values are in turn used to estimate changes in the hydraulic and wettability properties of the porous medium (i.e., aqueous- and gas-phase relative permeabilities k_{rA} and k_{rG} , and capillary pressure P_c) by employing appropriate scaling equations that are available as options in T+F [4, 9].

The arrow on the left side of Fig. 1 depicts the flow of data obtained from TOUGH+HYDRATE (namely the pressure P , temperature T , and phase saturations S_β) to FLAC3D for processing and estimation of their impact on the effective stress αAP (α being Biot's effective stress parameter), as well as on thermal and swelling strains (ε_θ and ε_{sw} , respectively). Additionally, changes in P , T , and S_H result in changes in other HBS mechanical properties that are listed in Fig. 1. These include the bulk modulus K , the shear modulus G , the cohesion C and the coefficient of internal friction μ . The T+F model includes an empirical relationship to adjust the HBS geomechanical properties for changes in the solid-phase saturations, i.e., hydrate and ice saturations (S_H and S_I , respectively). T+F allows the implementation of alternative models, as more laboratory data and theoretical models relating S_H and S_I to mechanical properties become available.

The earlier work of Rutqvist et al. [10] (involving joint thermal, flow, and geomechanical processes) incorporated a loosely coupled scheme of flow and geomechanical component codes, and was used to analyze coupled THM problems related to nuclear waste disposal and CO₂ geological sequestration. In the current T+F model, the two component codes TOUGH+HYDRATE and FLAC3D are seamlessly integrated. FLAC3D is invoked from within the FORTRAN 95 body of TOUGH+HYDRATE using system call, resulting in tighter and more rigorous coupling and substantially improved efficiency. Moreover, new FLAC3D FISH variables have been developed for a more efficient transfer of TOUGH+ parameter directly to the FLAC3D grid-elements, avoiding interpolation between TOUGH+ mid-element nodes and FLAC3D corner nodes.

Three coupling schemes are available in T+F:

- (i) *Jacobian*: This is the highest level of iterative coupling, in which all the geomechanical and flow parameters are continuously updated (in every Newtonian iteration of every time step), and their changes are accounted for in the computation of the Jacobian matrix.
- (ii) *Iterative*: In this scheme, the geomechanical and flow parameters are corrected at the end of each Newtonian iteration of each time step, and the contribution of their changes between Newtonian iterations are not accounted for in the computation of the Jacobian matrix.

- (iii) *Time-step*: This represents the weakest coupling option, and involves correction of the geomechanical and flow parameters once in (at the end of) each time step. As in the iterative scheme, the parameter changes do not contribute to the computation of the Jacobian matrix.

The full Jacobian option is a *sequentially implicit* scheme, whereas the iterative and the time-step coupling options are *sequentially explicit* schemes. The full Jacobian scheme is necessary for problems in which pore-volume (direct) couplings dominate, i.e., when a mechanically induced $\Delta\phi$ gives rise to a relatively strong and rapid change in pore pressure, and where it is necessary to rigorously preserve the fluid mass and heat balances. In problems where the so-called property changes (indirect) couplings dominate, iterative or time-step coupling schemes are sufficient.

4. CONSTITUTIVE GEOMECHANICAL MODELS FOR HBS

A few available geomechanical tests have shown that the stress-strain behavior of HBS are affected by hydrate content, temperature, and strain rate. In general, the stress-strain behavior may show a marked strain hardening or a strain hardening/softening behavior depending on the hydrate content. Candidate constitutive geomechanical models existing within the FLAC3D include:

- (i) Standard Mohr-Coulomb model
- (ii) Strain-hardening/softening Mohr-Coulomb model
- (iii) Modified Cam-clay model

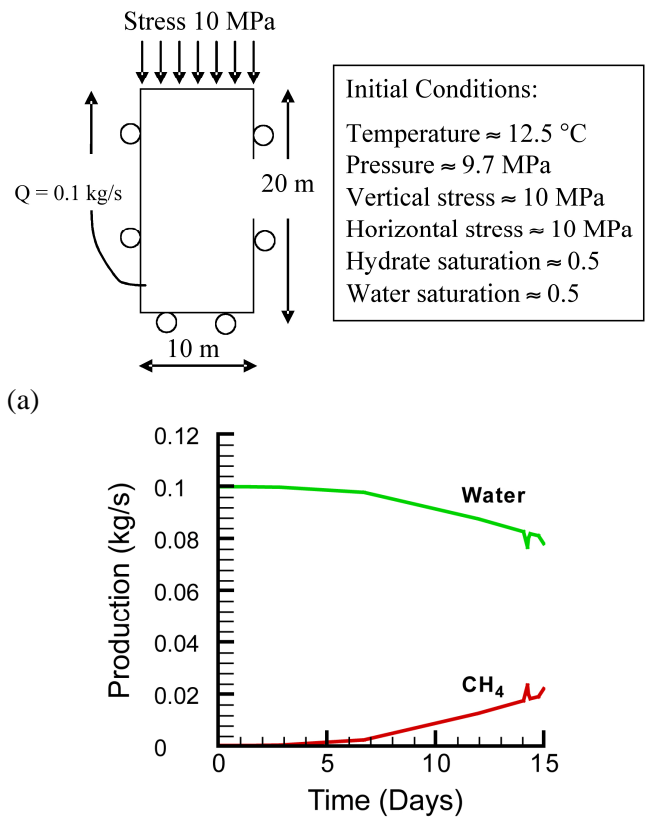
The standard Mohr-Coulomb model has been applied to study seafloor stability marine sediments, in some cases including marine hydrate bearing sediments (e.g. [11]). This constitutive model has been used to explain the triggering mechanisms of submarine landslides. Strain hardening/softening processes that have been observed in laboratory tests on HBS can be accommodated using the strain-hardening/softening Mohr-Coulomb model. The modified Cam-clay model is the most sophisticated of the three, but should be the most realistic for simulation of soft clay behavior, particularly under sequential loading/unloading conditions. However, the selection of the basic mechanical constitutive model depends on the particular application and available data. In many cases, the standard Mohr-Coulomb model is sufficient, particularly when there are limited data for deriving the material parameters required for the more sophisticated geomechanical models. The effect of strain rate can be modeled using one of the existing creep models available in FLAC3D, including creep analysis using the power law, which is commonly used for frozen soil.

Applying one of these geomechanical constitutive models as a starting point, we find that a number of geomechanical parameters and couplings require special treatment in the case of hydrate-bearing sediments. The effect of hydrate content and temperature on stress-strain behavior has already been mentioned. More specifically, a number of experiments as well as field investigations, have shown that stiffness and strength increases with hydrate content (e.g. [12]). Moreover, temperature and strain rate can have a strong impact on the strength of hydrates and hydrate bearing sediments [6, 13]. These effects are considered by identifying and applying coupling functions that describe the effect of hydrate saturation and temperature on the elastic and strength properties of the HBS.

In the following simulations, the geomechanical properties of HBS were taken from the laboratory experiments of Masui et al. [12] on hydrate-bearing Toyoura sand. A standard Mohr-Coulomb elasto-plastic model was used, and the parameters describing the geomechanical properties are corrected for pore-filling solid content (hydrate and ice). According to the experimental results of Masui et al. [12], we assumed that certain mechanical properties (bulk and shear modulus, and cohesion) increase linearly with hydrate saturation. For example, the cohesion varies from 0.5 MPa at 0% hydrate saturation, to an extrapolated 2.0 MPa at 100% hydrate saturation. This linear model matches the laboratory data quite well over the range of hydrate content relevant to this study. Additionally, following the experimental results of Masui et al. [12], the friction angle is considered independent of the hydrate saturation S_H and equal to 30° .

5. A SMALL SIMULATION TEST

We present a hypothetical simulation test of methane production from an HBS. Fig. 2 presents the model geometry, boundary conditions, and initial conditions corresponding to pressure, temperature, and stress in an oceanic HBS. The boundary conditions are no heat and mass transfer, and fixed displacement (rollers) at bottom and lateral boundaries, whereas the top boundary is free to move, but closed to fluid flow. The model is discretized into 200 (10 by 20) elements. We simulate a constant production for 15 days, which leads to a significant reduction in both pressure and temperatures, with associated hydrate dissociation as well as formation of ice. As mentioned above, the geomechanical properties of HBS were taken from recent laboratory experiments on hydrate-bearing Toyora Sand [12]. At the initial conditions, with a hydrate saturation of about 50%, the bulk and shear modulus are 375 and 343 MPa, respectively, and the cohesion is 1.13 MPa.



(a)

(b)

Fig. 2. A small simulation test: (a) test model and (b) production rates of water and CH_4 .

Fig. 3 presents the evolution of thermal, hydrological, and mechanical parameters during the 15 days of production. Fig. 4 through 6 present the distribution of saturations, mechanical properties and deformation after 15 days. Near the production well, pressure declines from 10 to 3 MPa, and as a consequence of the pressure decline, temperature declines from 12 to approximately 0°C (Fig. 3a). Changes in pressure and temperature cause gradual hydrate dissociation until about 14 days, when ice starts to form near the production well (Fig. 3b and 4). Changes in solid saturation (hydrate+ice) have a direct impact on the mechanical properties (compare Fig. 4 and 5). During the first 14 days, there is gradual softening of the sediment as the hydrate is dissociated (Fig. 3c and d). After 14 days, the HBS recovers towards more competent mechanical properties in a stiffening of the bulk modulus and a hardening of the strength, as ice cements the host sediment.

In general, the pressure decline results in an increased effective stress and a substantial settlement (Fig. 3e and f). The system behaves essentially in a poro-elastic manner, although plastic failure is achieved towards the end of the simulation as the strength is reduced and the principal stress field becomes more anisotropic (leading to shear failure).

Fig. 7 shows the evolution of the principal stress path (maximum versus minimum effective principal stress) and its relation to the evolution of compressive strength. The host sediment is loaded (increased effective stress) as a result of the pressure depletion. At the same time, the increasing strength associated with increasing confining effective stress is partially offset by a softening caused by hydrate dissociation. Mechanical yielding is on-set after about 10 days. Thereafter, the stress path follows that of maximum strength until about 14 days, when ice is formed to strengthen the sediment.

The 20 cm settlement shown in Figs. 3f and 6b is caused by the combined effects of pore-pressure decline and contraction from cooling, which in turn are affected by mechanical property changes (softening and hardening). Overall, the settlement is quite uniform, although the greatest volumetric strain occurs near the production point.

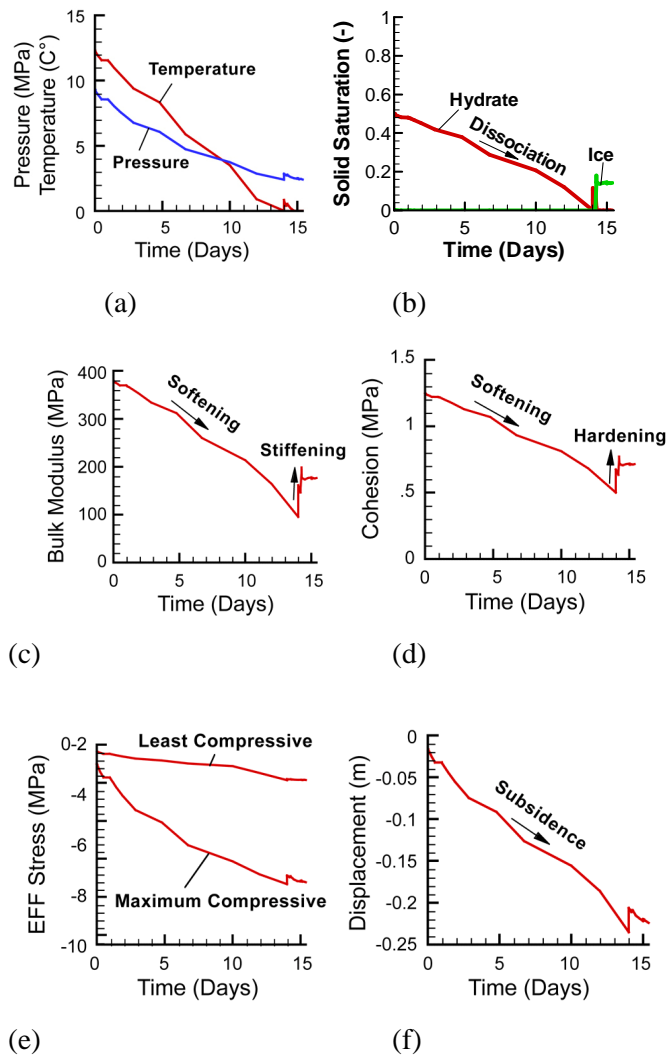


Fig. 3. Evolution of (a) pressure and temperature (b) solid saturation (c) bulk modulus, (d) cohesion, (e) effective principal stresses at the point of production, and (f) subsidence of the top surface.

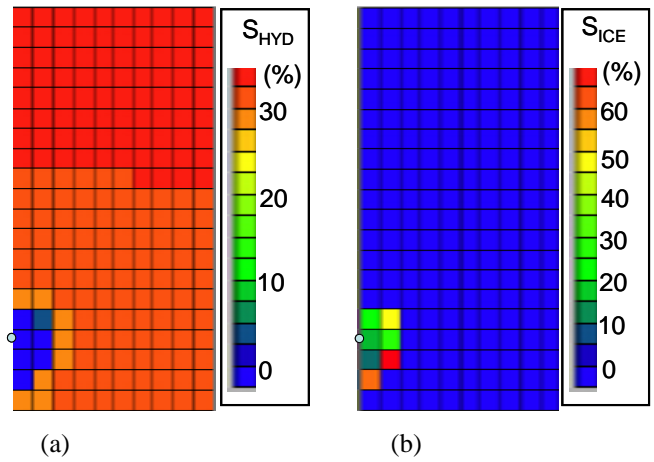


Fig. 4. Calculated distribution of (a) hydrate saturation and (b) ice saturation after 15 days of production.

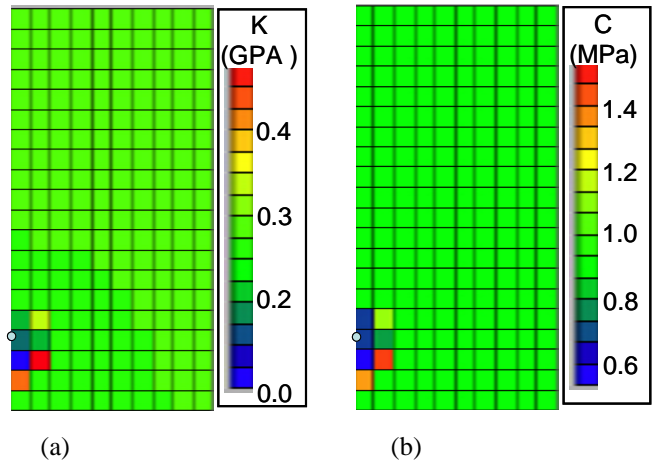


Fig. 5. Calculated distribution of (a) bulk modulus and (b) cohesion after 15 days of production.

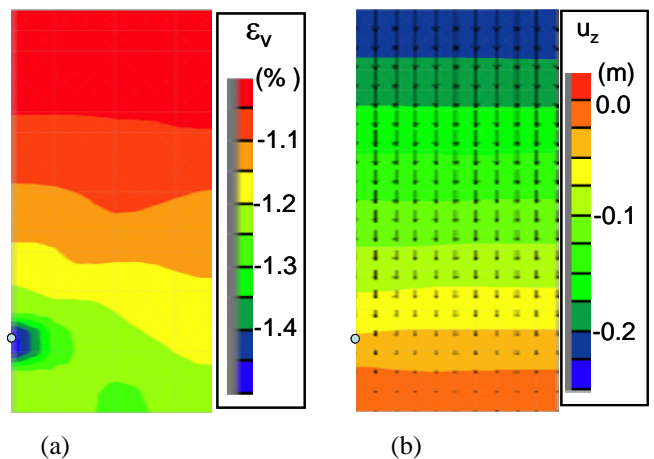


Fig. 6. Calculated distribution of (a) volumetric strain and (b) vertical displacement after 15 days of production.

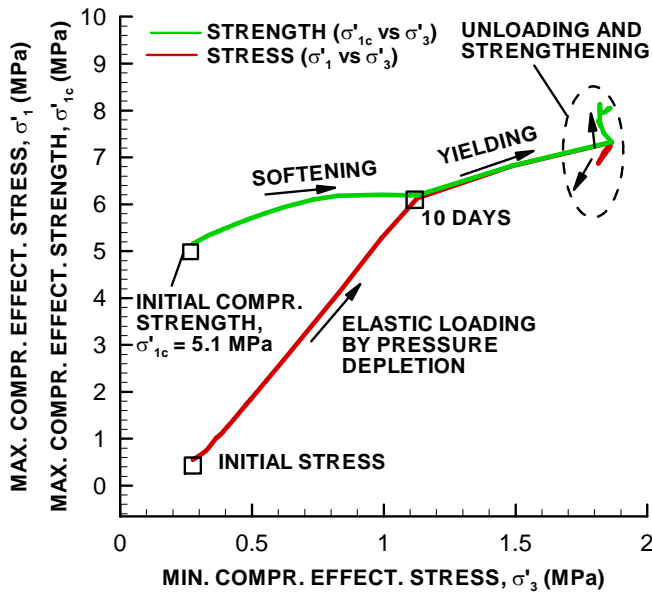


Fig. 7. Calculated path of stress state (σ'_1 vs σ'_3) and compressive strength (σ'_{1c} vs σ'_3) at the production point.

6. ANALYSIS OF GAS PRODUCTION FROM THE OCEANIC TIGERSHARK FORMATION

In this simulation example, we study geomechanical response during depressurization-induced gas production from a so-called Class 3 hydrate deposit, i.e., one composed of a single hydrate interval and bounded by confining (impermeable) layers, with no underlying zone of mobile fluids [5]. The model setup involves a system of parallel horizontal wells, with a well spacing of 1,000 m (Fig. 8). Hydrate is depressurized by applying a constant pressure $P_w = 2.8$ MPa at the well. Because of the symmetry of the well configuration, and the production approach, only a fraction of the affected domain needs be modeled. Fig. 8 shows the configuration of the parallel well system (upper part), and the geometry of the simulated domain (lower part) which represents a unit length (= 1 m) of the horizontal well.

The geologic system in this study is based on that of the Tigershark area located in the Alaminos Canyon Block 818 of the Gulf of Mexico [15, 16]. Log data from an exploration well in about 2750 m (9000 ft) of water at the site indicated the presence of an 18.25 m (60 ft) thick, sandy, hydrate-bearing layer (10,530 to 10,590 ft drilling depth) with a porosity ϕ of about 0.30 and Darcy-range intrinsic permeability [15]. Preliminary calculations indicate that the S_H is in the 0.6–0.8 range, and that the base of the gas hydrate stability zone at this location occurs at or slightly below the base of the HBS [15, 16].

Details of production and geomechanical performance for this type of oceanic hydrate deposit, including well-bore instability, are presented in Rutqvist and Moridis

[16] and Rutqvist et al. [17]. In this paper, we present only a few results to demonstrate the applicability of the simulator for analyzing reservoir-scale evolution of coupled hydraulic, thermodynamic, and geomechanical processes. The geomechanical properties are again those derived by Masui et al. [12] from hydrate-bearing Toyoura sand. In this case, the initial hydrate saturation is about 70%, which implies that the initial bulk and shear modulus are 498 and 454 MPa, respectively, and the cohesion is 1.55 MPa.

Fig. 9 presents the calculated evolution in the rates of gas release and gas production (Q_R , Q_P respectively) during 2 years of production. The results indicate that both gas release into the reservoir and production from horizontal wells are at their highest very early after the initiation of the operation (when the maximum pressure differential ΔP_w applies to the well). Q_R continues to decline monotonically during the entire production period, whereas Q_P shows a more complex behavior, one that is affected by the evolution of a dissociation front and associated changes in flow porosity and permeability within the HBS [15].

Fig. 10 shows the temporal evolution of pressure, temperature, hydrate saturation, and effective principal stresses at 0.5 and 10 m away from the production well. Fig. 11 shows the spatial distribution of temperature, pressure, hydrate, and gas saturation after 1 year of production. Because the HBS is hydraulically confined by shales, depressurization is rapid and effective, leading to hydrate dissociation and cooling, owing to the strongly endothermic nature of the hydrate reaction (Fig. 10a and b). The P distribution (Fig. 11a) indicates a rather uniform depressurization of the reservoir, from initially 33 MPa to about 3 MPa, as dictated by the constant pressure $P_w = 2.7$ MPa at the well. The cooling of HBS (a direct consequence of the hydrate dissociation) is evidenced by the low temperature (from its original level of about 32°C) in the formation (Fig. 11b). Depressurization-induced hydrate dissociation occurs within 1 hour near the well ($x = 0.5$ m) and has propagated to $x = 10$ m in 20 days (Fig. 10b).

Fig. 11c shows that after 1 year of production, hydrate dissociation has taken place near the well bore as well as at the upper and lower parts of the hydrate layer. The upper and lower dissociation interface develops as a result of heat flow from adjacent upper and lower shales. As hydrate is progressively dissociated, much of the released gas accumulates below the base of the top shale because of the buoyancy-driven gas rise (Fig. 11d).

Fig. 10c shows that the effective principal stresses at 0.5 and 10 m changes quickly, from an initially isotropic stress, to become anisotropic. Overall, the production (and the corresponding depressurization) tends to increase the shear stress in the reservoir, which is

proportional to the difference between the maximum and minimum principal stresses. Near the wellbore (at $x = 0.5$ m), the stress field first reacts to the local pressure changes (see pressure evolution in Fig. 10a). At 10 m, the stress evolution is somewhat delayed, corresponding to the pressure evolution at 10 m. After about 10 days, the principal stress magnitudes at 0.5 and 10 m merge, indicating that the stress becomes uniform and anisotropic along the entire reservoir.

Fig. 12 presents the path of the maximum and minimum principal effective stresses. The principal stresses at 0.5 and 10 m quickly merge and follows the same path of increasing effective stress. After 1 day, the stress state moves slowly toward the Mohr-Coulomb failure line for a dissociated HBS ($S_H = 0$). The failure condition is never reached within 2 years of production and would probably not be reached for another 10 or 20 years. However, even if mechanical failure is not achieved on the reservoir-scale, the depressurization causes significant settlement (about 0.8 m over the 18 m thick reservoir), which would be important to consider in the well engineering design. Analysis of casing stability by Rutqvist et al. [15] also shows that the vertical compression of the reservoir results in increased loading against the upper part of the casing (perforation) of the horizontal well. The vertical compaction against the stiff casing causes increased compressive stress normal to the casing which then exceeds the compressive strength of the material. Such shearing of the material breaks bonds between particles, which then may loosen, resulting in production of solids (e.g., sand grains) and formation of cavities around the well bore perforation.

7. CONCLUDING REMARKS

In this paper, we have described the development of a numerical simulator for analyzing the geomechanical performance of hydrate-bearing sediments, by the coupling two simulators: TOUGH+HYDRATE (for fluid flow and thermodynamic hydrate behavior) and FLAC3D (for coupled geomechanical behavior). The development and testing of the simulator is ongoing; in this paper, we have presented two examples that demonstrate its capability and applicability for studying geomechanical performance related to methane production from oceanic hydrate-bearing sediments. The results showed that depressurization-based gas production from oceanic hydrate deposits may lead to severe geomechanical changes, which could jeopardize the production unless care is taken in designing the production scheme. The coupled simulator developed within this study can be used to help design production strategies for optimizing production, while avoiding damaging geomechanical problems. For the next step in model development and testing of the coupled simulator we will focus on the back-coupling from geomechanics

to fluid flow, i.e., mechanically induced changes in hydrological properties and their impact on methane production.

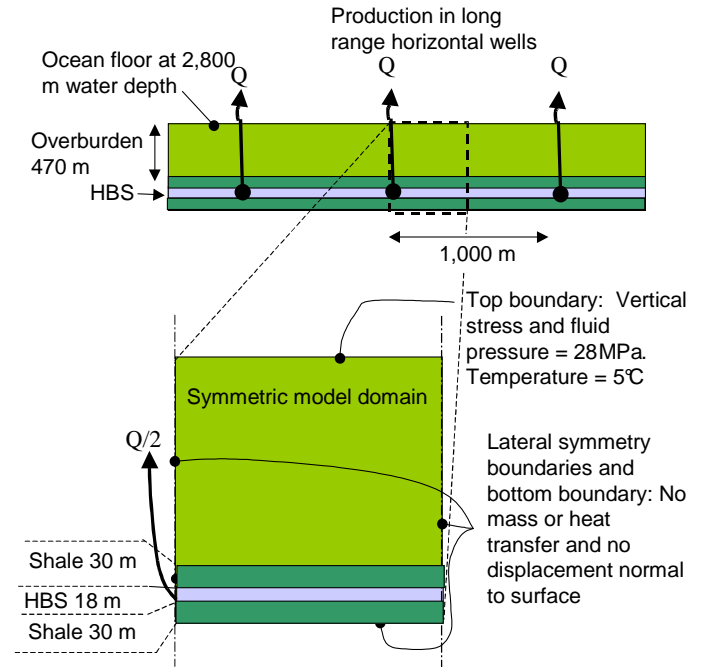


Fig. 8. Model geometry, boundary conditions, and domain description for constant pressure production from a Class 3 oceanic hydrate deposit using long-range horizontal well.

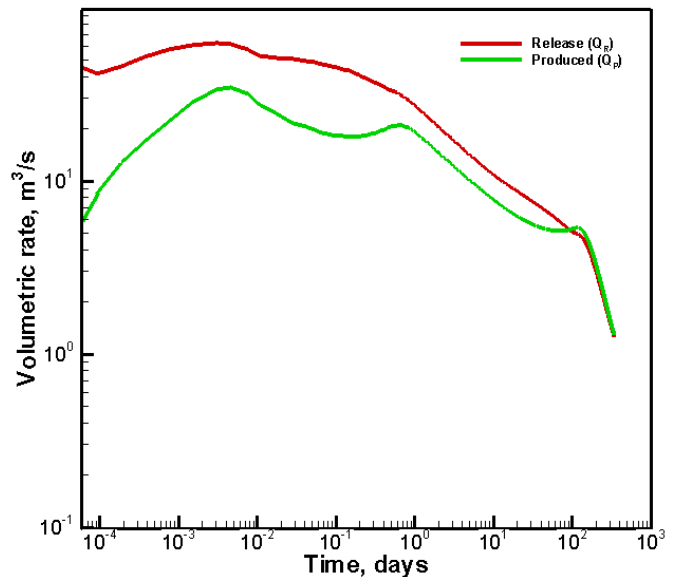
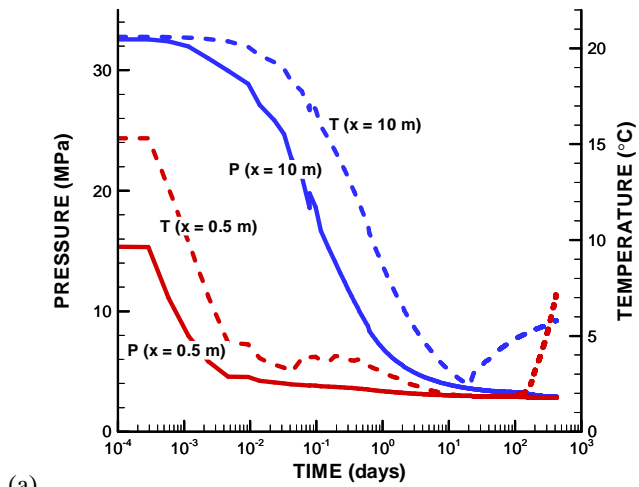
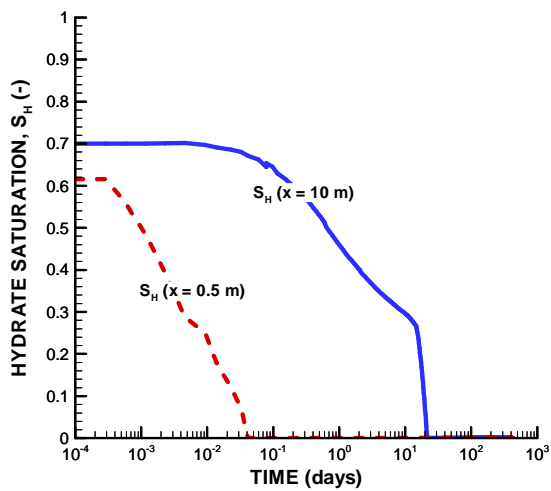


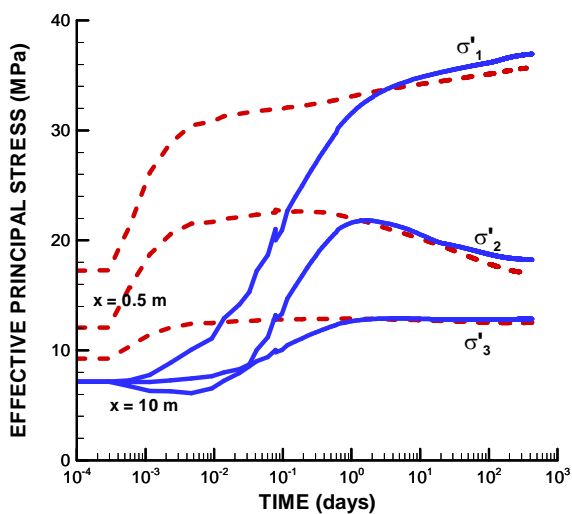
Fig. 9. Gas release and production rates during 2 years of constant pressure production.



(a)

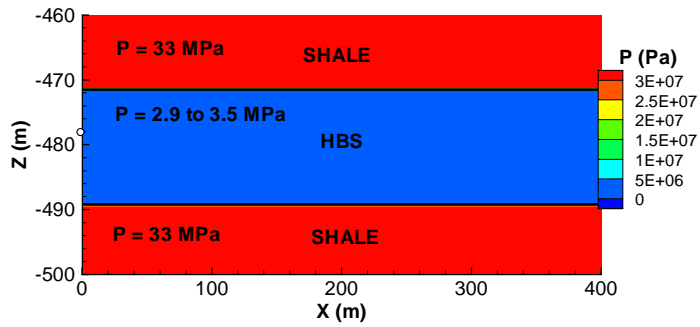


(b)

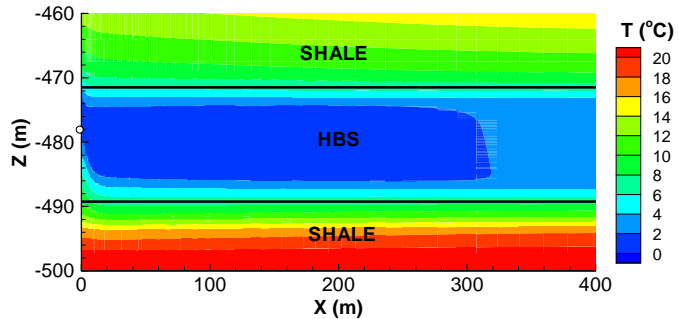


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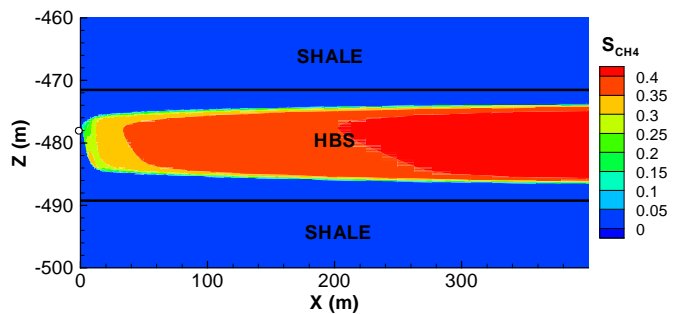
Fig. 10. Calculated evolution of (a) pressure and temperature (b) hydrate saturation and (c) effective principal stresses at 0.5 and 10 m distance from the well bore during 2 years of constant pressure production.



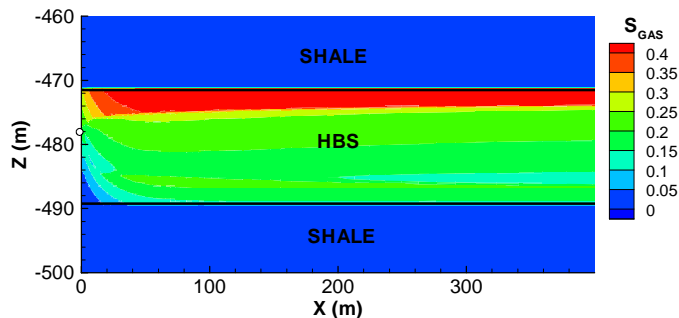
(a)



(b)



(c)



(d)

Fig. 11. Calculated distribution of (a) pressure, (b) temperature (c) hydrate saturation, and (d) gas saturation after 1 year of constant pressure production.

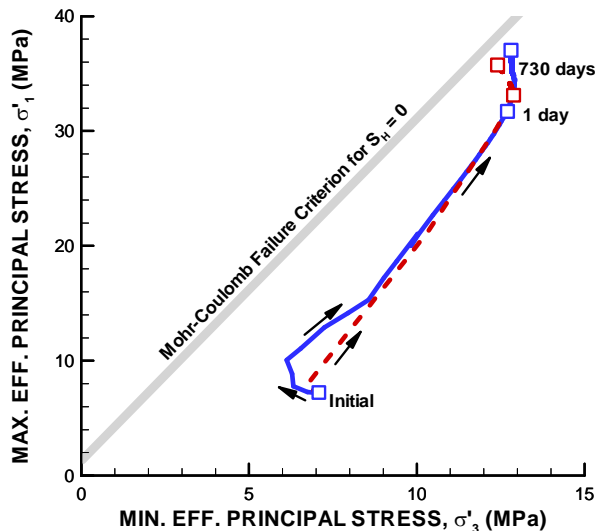


Fig. 12. Calculated path of stress state (σ'_1 vs σ'_3) at a distance of 0.5 m (dashed red line) and 10 m (solid blue line) from the production well.

ACKNOWLEDGMENTS

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