The role of high-pressure flow-through experiments for evaluating the mechanical behaviour of gas hydrate-bearing soils

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ABSTRACT: Results from two recent field trials, onshore in the Alaska permafrost and in the Nankai Trough offshore Japan, suggest that natural gas could be produced from marine gas hydrate reservoirs at compatible yields and rates. However, both field trials were accompanied by different technical issues, the most striking problems resulting from un-predicted geomechanical behaviour, sediment destabilization and catastrophic sand production. So far, there is a lack of experimental data which could help to understand relevant mechanisms and triggers for potential soil failure in gas hydrate production, to guide model development for simulation of soil behaviour in large-scale production, and to identify processes which drive or, further, mitigate sand production. We use high-pressure flow-through systems in combination with different online and in situ monitoring tools (e.g. Raman microscopy, MRI) to simulate relevant gas hydrate production scenarios. Key components for soil mechanical studies are triaxial systems with ERT (Electric resistivity tomography) and high-resolution local-strain analysis. Sand production control and management is studied in a novel hollow-cylinder-type triaxial setup with a miniaturized borehole which allows fluid and particle transport at different fluid injection and flow conditions. We further apply a novel large-scale high-pressure flow-through triaxial test system equipped with μ-CT to evaluate soil failure modes and triggers relevant to gas hydrate production and slope stability. The presentation will emphasize an in-depth evaluation of our experimental approach, and it is our concern to discuss important issues of translating laboratory results to gas hydrate reservoirs in nature. We will present results from high-pressure flow-through experiments which are designed to systematically compare soil mechanical behaviour of gas hydrate-bearing sediments in relevant production scenarios focusing on depressurization and CO_2 injection. Experimental data sets are analyzed based on numerical models which are able to simulate coupled process dynamics during gas hydrate formation and gas production.

1 INTRODUCTION

In marine sediments and permafrost soils gas hydrates can be present in large amounts and at high relative saturations. Gas hydrate formation can occur whenever pressure-temperature (p-/T-) conditions are inside the gas hydrate stability region, and gas hydrate forming components such as CH_4 or CO_2 are available in sufficient amounts. Dependent on gas hydrate saturation and gas hydrate-sediment particle fabrics, the presence of gas hydrates contributes to marine sediment stiffness and strength, and it is important to understand and quantify this contribution for reliably predicting sediment mechanical behavior and assessing risks of ground subsidence or slope failure.

The lack of knowledge and simulation tools to predict dynamic mechanical behavior of gas hydrate-bearing sediments became apparent in recent gas hydrate production field trials, onshore in the Alaska permafrost (Schoderbek et al., 2013) and in the Nankai Trough offshore Japan (Yamamoto, 2013). Both tests were accompanied by substantial sediment yielding and sand production events, which were, however, following different patterns. In the onshore field test, natural gas production was initiated after N_2:CO_2 mixed gas injection and gas-hydrate exchange, and further enhanced through stepwise depressurization. In this field test, sand production was initially very high. Substantial technical problems occurred, including failure of technical components and extended production shutdown intervals. However, sand production rates decreased with ongoing gas production. In the first offshore field test in the Nankai Trough, gas production was achieved through depressurization only. In contrast to the results from the onshore permafrost test, sand production was low during early production and could be managed with applied standard technical means. However, after a few days, sudden and catastrophic sand production occurred, and the production test had to be canceled pre-maturely. The reasons for this distinct test specific behavior are currently unknown and might be related to numerous factors, such as site and reservoir characteristics, geological heterogeneities, gas hydrate alteration and dissociation dynamics, technical issues, or dynamic thermo-hydro-chemo-mechanical process coupling.

Gas hydrates contribute to sediment or soil mechanical behavior in various ways, and effects might be defined as primary and secondary, respectively. Primary effects result from direct and quasi-static interaction of gas hydrates and soil particles, and define sediment behavior in terms of soil stiffness and strength. The understanding of geotechnical behavior of gas hydrate-bearing sediments in this sense has improved tremendously in recent years, and with our current understanding, gas hydrates contribute to sediment strength by changing friction and dilatancy, Soil critical state models were successfully applied to simulate soil plastic yielding (Klar et al. 2013). Today, the availability of experimental tools and methods to analyze and visualize micro-structuring of gas hydrate-bearing sediments helps to develop physical understanding and improve constitutive models of bulk sediment behavior. For example, recent experimental studies on microscale gas hydrate-sediment structures have demonstrated the presence of a water layer between gas hydrates and quartz sand particles independent of gas hydrate formation methods (Chaouachi et al. 2015), which has implications for understanding strength of gas hydrate-bearing soil in terms of assumed cohesion and cementation. In contrast to primary effects, secondary, non-direct mechanical effects result from strong and dynamic thermo-hydro-chemo-mechanical process coupling. This definition emphasizes that under relevant non-equilibrium conditions with dynamic gas hydrate formation, alteration or dissociation, sediment mechanical stability becomes eventually dominated by multiphysics parameters such as hydraulic properties (e.g. absolute and relative permeability changes) or flow dynamics (e.g. multiphase fluid flow, gas migration or holdup). Quantitative effects emerging from multiphysics coupling are extremely complicated to predict, and coupled secondary effects could easily overprint simplified sediment stability and failure predictions based on quasi-static primary effects.

It is an important task to reveal and disentangle multiphysics effects, understand process coupling and resolve mechanistic details, and this importance is increasingly recognized. For example, large-strain deformation under deviatoric loading, and dynamic stress-strain behavior during depressurization or thermal stimulation was studied in triaxial experiments (Hyodo et al. 2013, 2014, Song 2014, Ghiassian and Grozic 2013). In the very recent past there have also been the first attempts to carry out studies on undisturbed pressure cores, which will clearly advance the field towards a much better understanding of the mechanics of the gas hydrate-bearing soils (Inada and Yamamoto 2015, Santamarina 2015, Yoneda et al. 2015). Numerical gas hydrate reservoir simulators have been used to study coupled processes during and after gas production from gas hydrates, and there is strong effort to build-in soil mechanical constitutive models and improve model couplings. Recently, a gas hydrate reservoir simulation algorithm was developed and applied for modelling particle mobilization and sand production as observed in the field trial offshore Japan (Uchida et al. 2015). A novel hydro-geo-mechanical gas hydrate simulator was developed recently at TU Munich (Gupta et al. 2015). It was calibrated and tested by matching experimental data from high-pressure flow-through triaxial experiments simulating gas hydrate formation and dissociation under isotropic compression at variable total and effective stresses and with dynamically changing gas hydrate saturations.

Using high-pressure flow-through triaxial experiments in combination with numerical simulation is the most direct and promising approach to understand multiphysics coupling and to improve physical process knowledge. High-pressure flow-through experimental systems, and different online and *in situ* monitoring tools have been successfully applied for testing various strategies for gas production from gas hydrate-bearing sediments (essentially depressurization, thermal stimulation and gas hydrate exchange after injection of CO_2 or CO_2-rich mixed gases). We used our NESSI system (*N*atural *E*nvironment *S*imulator for *S*ub-seafloor *I*nteractions) to study different CO_2 injection schemes and to improve gas hydrate exchange and natural gas production from gas hydrate-bearing soils (Deusner et al. 2012). The NESSI system is used in combination with Raman spectroscopy and IR-based gas analysis. These tools allow time-resolved monitoring of multiphase fluid flow (e.g. water, gas, liquid CO_2) as well as phase compositions (e.g. pure or dissolved compounds, mutual solubilities). Tomography techniques have been applied for disturbance-free and high-resolution analysis of process dynamics and influence of heterogeneities in gas-hydrate bearing soils. Magnetic resonance imaging (MRI) was applied to study phase distributions and permeability changes during gas hydrate formation (Kossel et al. 2014) and gas hydrate exchange after injection of CO_2. Electrical resistivity tomography (ERT) was applied to map fluid and solid phase distributions (Priegnitz et al. 2013). Further, X-ray CT was applied to visualize gas hydrate sediment structures and analyze permeabilities (Kneafsey et al. 2014, Kneafsey et al. 2011).

To better understand dynamic and coupled thermo-hydro-chemo-mechanical processes relevant to gas hydrate-bearing soils, we have developed novel high-pressure flow-through triaxial systems for large samples. The novel systems are used in combination with μCT or ERT, respectively, high-resolution local-strain measurement and continuous fluid composition monitoring with flow-through sensors, as described above. One system is equipped with a miniaturized perforated borehole, which allows passage and sampling of both fluids and solids. Major research objectives are to experimentally simulate coupled processes relevant to gas-charged or gas hydrate-bearing sediments in the context of slope stability and natural gas production. The experimental systems allow inducing and monitoring large-strain visco-elasto-plastic deformation, particle fluidization and sand production on different scales (pore-scale to bulk scale). Experimental data are used to develop and test numerical codes, and to define constitutive models based on high-resolution micro-scale data.

Here, we present details about the novel triaxial flow-through systems which were developed for studies of gas hydrate-bearing or gas charged soils and sediments, but might also be suitable for a range of related scientific topics in geomechanics and geotechnics. We further present results from experimental and numerical studies on depressurization, CO_2- or CO_2-mixed fluid injection and gas hydrate exchange from high-pressure flow-through experiments. We briefly define upcoming test cases. Preliminary test data with triaxial-CT and triaxial-ERT systems will be presented during ICEGT 2016.

2 MATERIAL AND METHODS

2.1 *Sample preparation and mounting*

Sediment samples were prepared from quartz sand (initial sample porosity 0.35, grain size 0.1 - 0.6 mm, G20TEAS, Schlingmeier, Schwülper, Germany), and mixed with deionized water. The partially water saturated and thoroughly homogenized sediments were filled into the triaxial sample cell equipped with a Viton sleeve to obtain final sample dimensions of 380 mm in height and 80 mm in diameter. Sample geometry was assured using a sample forming device. The sample was cooled to 2 °C after the triaxial cell was mounted inside the pressure vessel. Initial water permeability of gas hydrate-free sediment was 50×10^{-11} m^2.

2.2 *Gas hydrate formation*

Prior to gas hydrate formation the sediment sample was isotropically consolidated to 2 MPa effective stress under drained conditions. The sample was flushed with CH_4 gas and, subsequently, pressurized with CH_4 gas. During pressurization with CH_4 gas and throughout the overall gas hydrate formation period, formation effective stress conditions were maintained using an automated control algorithm. The formation process was continuously monitored by logging CH_4 gas pressure. Mass balances and volume saturations were calculated based on CH_4 gas pressure and initial mass and volume values. After completion of gas hydrate formation, the sample was cooled to -5 °C and stress control was switched to constant total isotropic stress control before the sample pore space was de-pressurized to atmospheric pressure and remaining CH_4 gas in the pore space was released. System re-pressurization and water saturation of pore space was achieved by instant filling and re-pressurization with pre-cooled (-1 °C) saltwater medium according to seawater composition. Hydrate dissociation during the brief period of depressurization was minimized by taking advantage of the anomalous self-preservation effect, which reaches an optimum close to the chosen temperature (Stern et al. 2003). After completion of gas – water fluid exchange, the sample temperature was re-adjusted to 2 °C.

2.3 *Flow-through experiments*

Experiments were carried out in the custom-made high pressure apparatus NESSI (*N*atural *E*nvironment *S*imulator for *S*ub-seafloor *I*nteractions, Deusner et al. 2012), which was equipped with a high-pressure triaxial cell mounted in a 40 L stainless steel vessel. All wetted parts of the setup are made of stainless steel. Saltwater medium was supplied from reservoir bottles (DURAN, Wertheim, Germany) using a HPLC pump S1122 (SYKAM, Fürstenfeldbruck, Germany). Pressure was adjusted with a back-pressure regulator valve (TESCOM Europe, Selmsdorf, Germany). Experiments were carried out in upflow mode with injection of CH_4 gas and seawater medium at the bottom of the sample prior and after gas hydrate formation, and fluid discharge at the top of the sample during depressurization. Axial and confining stresses, and sample volume changes were monitored throughout the overall experimental period. Pore pressure was measured in the influent and the effluent fluid streams close to sample top and bottom. The experiment was carried out at constant temperature conditions. Temperature control was achieved with a thermostat system (T1200, Lauda, Lauda-Königshofen, Germany). Produced gas mass flow was analyzed with mass flow controllers (EL FLOW, Bronkhorst, Kamen, Germany). For control purposes, bulk effluent fluids were also collected inside 100 L gas tight TEDLAR sampling bags (CEL Scientific, Santa Fe Springs CA, USA). The sampling bags were mounted inside water filled sampling containers. After expansion of the effluent fluids at atmospheric pressure, overall volume was measured as volume of displaced water from the containers.

2.4 *Numerical modelling*

To simulate gas hydrate formation and dissociation processes in the lab-scale triaxial compression experiment described in Section 2, we use the mathematical model and the numerical simulator developed by Gupta et al. (2015). This model considers kinetic hydrate phase change and non-isothermal, multi-phase, multi-component flow through porous medium. The model accounts for the effect of hydrate phase change on the mechanical properties of the soil, and also for the effect of soil deformation on the fluid-solid interaction properties relevant to reaction and transport processes (e.g., reaction surface area, permeability, capillary pressure).

3 NOVEL EXPERIMENTAL SYSTEMS

3.1 *Triaxial-CT*

3.1.1 *CT system*

In close collaboration APS and GEOMAR develop a new kind of triaxial test system combined with computer tomography. In contrast to existing triaxial CT systems, the triaxial cell is fixed and the CT scanner itself moves around the sample. Due to a high-precision alignment system, high-resolution tomography becomes feasible. As the cell is not in motion, the accuracy of the permeability and shear tests performed increases substantially compared to "moving cell" solutions. The thermodynamic processes of the gas hydrate formation and dissociation can be observed, as well as CO_2 injection and capturing. The system is designed for cell pressures up to 40 MPa. Therefore a special cell was constructed that allows the application of the cell pressure while remaining transparent for the X-ray tomography. As the system is currently in the patent process, further information and first testing results will follow soon.

3.1.2 *Evaluation Software*

Besides the experimental part of the CT-tests, the evaluation of the acquired data is a crucial task of the project. Commercial and open-source software solutions are available, but they are limited in the meaning of objectivity. For the evaluation a manual definition of the distinct phases (water, matrix, air, gas hydrates) is needed. The user defines the phases according to his experience and thus with eventual errors and mistakes. In order to ensure an objective definition of the phases a new program was developed based on machine learning technology (Chauhan et al. 2015, Chauhan et al. 2016). The algorithm learns from the data sets itself which phases are tomographically recorded. The phases are clustered and evaluated by their volumetric content. As there are several possibilities of suitable solver-algorithms, a module is incorporated that allows to select and to compare the results of different solver types. Depending on the specimen structure, the results of the different solvers scatter, in some cases substantially. The results of the machine learned analysis are visualized in 2D or 3D (see Fig. 1). Applying the histogram method, the volumetric distribution of the phases is calculated. Besides the absolute value of phase volumes, an evaluation of the pore-size distribution is implemented as well. The constructed pore model can be exported from the program for subsequent pore network and flow simulations, as well as for further elaboration and finite element analysis.

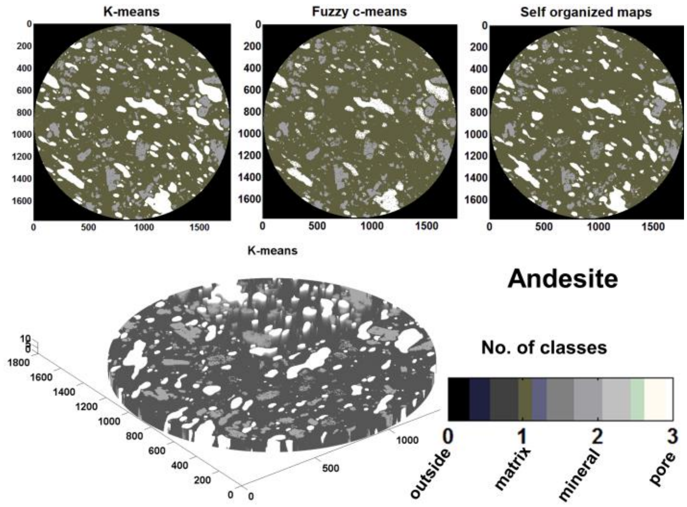

Figure 1. 2D segmented images and volume rendered plot of a respective sample using unsupervised networks (after Chauhan et al. 2016)

3.2 *Triaxial-ERT*

The system combines ERT and local deformation measurements (Fig.2). The triaxial test unit is designed for mounting of large samples (diameter 150 mm, height maximum 400 mm) and can be operated up to 40 MPa. Coupled fluid flow – mechanical loading tests can be performed with a perforated central well. Thus, scenarios of flow- or load-induced deformation and sand production can be simulated. The loss of sample solids through visco-plastic yielding or particle migration leads to local straining rather than homogeneous bulk deformation. Heterogeneous deformation is monitored at high-resolution using electromagnetic sensors. ERT is applied to simultaneously acquire information about heterogeneous phase distributions (e.g. spatial gas hydrate saturation, zones of gas hydrate dissociation and gas release, gas migration pathways, fractures, gas holdup regions, etc.). Combining tools, bulk sample behavior can be correlated with physically relevant heterogeneous processes.

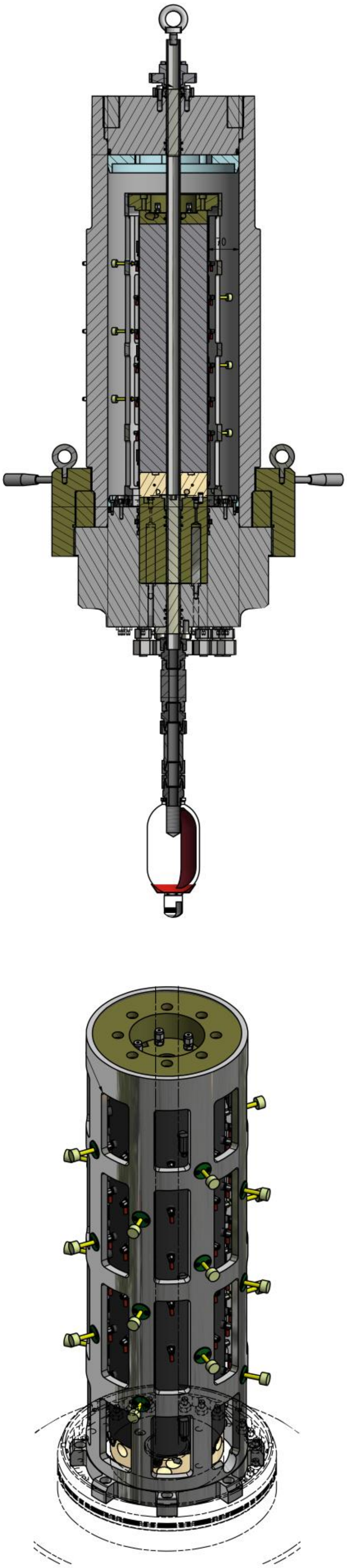

Figure 2. Scheme of high-pressure flow-through triaxial test system with electromagnetic sensors for local strain analysis, ERT and perforated well

4 RESULTS AND DISCUSSION

4.1 *Depressurization experiments*

Depressurization of gas hydrate-bearing reservoirs is the most mature approach for natural gas production from gas hydrates. Depressurization refers to a technical decrease in hydrostatic or pore pressure at a well using pumps. Obviously, depressurization changes effective stresses, induces fluid flow and phase changes, and gas hydrate saturations are effected relative to gas hydrate stability conditions. After shutdown of pumps, hydrostatic pressure will recover, with recovery rate being dependent on multiple factors including geological and sedimentological settings, permeability and reservoir dimensions.

First triaxial experiments on dynamic gas hydrate formation and dissociation were done without allowing particle flow (Fig.3), i.e. sediment particles were retained by the use of filter plates. The obligatory use of filter plates was problematic, since gas hydrate formation, water freezing or multiphase fluid flow caused substantial problems with permeability and often irreversible blocking. For similar reasons, near-well flow assurance might become a major issue in field application, and flow management and filtration means must be carefully chosen. The triaxial experiments were focused on dynamically altering gas hydrate saturations during gas hydrate formation or gas hydrate dissociation and dissociation induced gas flow in a water saturated sample. Pressure and loading constraints were chosen to mimic gas hydrate formation in weakly consolidated sediment which is confined by low-permeability layers at its upper boundary. Thus, usually effective stress is controlled during gas hydrate formation, and total stress is controlled during depressurization (Fig.4). Experimental data from isotropic compression experiments were used to calibrate a fully coupled numerical simulator, soil constitutive behavior was defined in the framework of poro-elasticity. Composite Young's modulus of gas hydrate-bearing sediment was modeled with additive soil and gas hydrate contributions, and it was found that composite modulus depends almost linearly on S_h during gas hydrate formation, while during the hydrate dissociation period the dependence of E_{sh} on S_h is smaller. Further experiments at different gas hydrate saturations have been carried out (Fig.5), and experimental data are now used to further develop the model approach and parameterization.

4.2 *Gas hydrate-exchange experiments*

The application of gas-hydrate exchange for natural gas production was discussed extensively in recent years, advantages essentially seen as being an emission neutral energy production technology and as a cure of depressurization induced process problems such as sediment cooling from endothermic gas hydrate formation. It was considered that gas hydrate exchange could also contribute to mechanical integrity during gas hydrate production by keeping gas hydrate-soil fabrics untouched. Although this certainly is a very idealized assumption, results from the Ignik Sikumi field test suggest, that gas hydrate exchange might at least partly prevent excessive sand production. At the moment, the mechanical consequences of CH_4-CO_2-hydrate exchange, even under most ideal assumptions are not understood, and different injection strategies and reaction proceedings (gaseous, liquid or supercritical CO_2 injection, N_2:CO_2 injection, continuous or discontinuous injection, mixed gas hydrate formation, etc.) will influence mechanical behavior in a very complicated and coupled way. The role of gas hydrate conversion for sediment mechanics is a very central topic for applying the new triaxial systems with tomography.

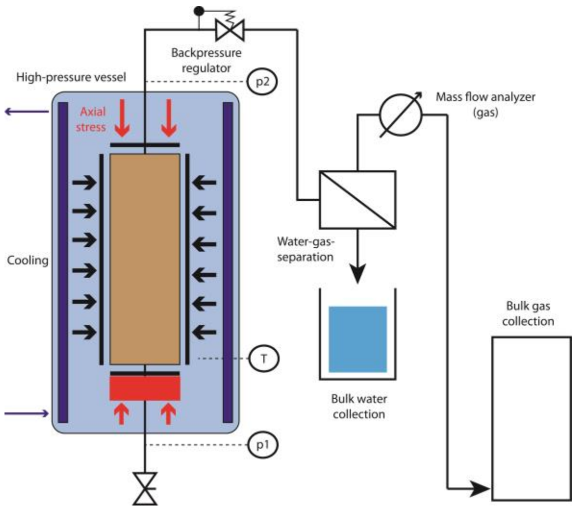

Figure 3. Experimental scheme for depressurization experiments

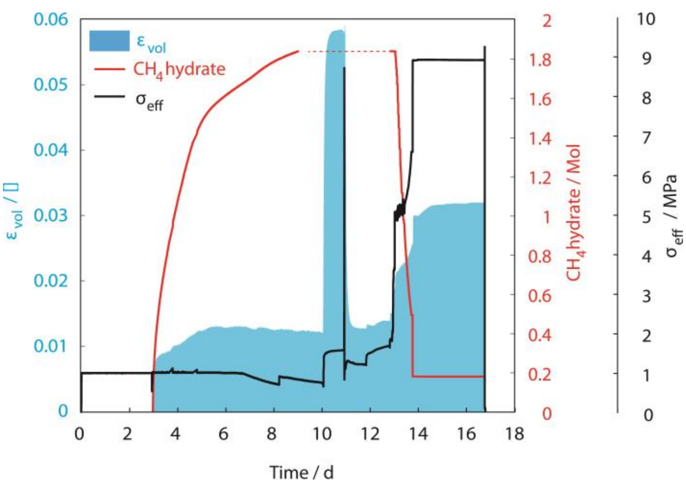

Figure 4. Converted data from dynamic gas hydrate formation and dissociation experiments

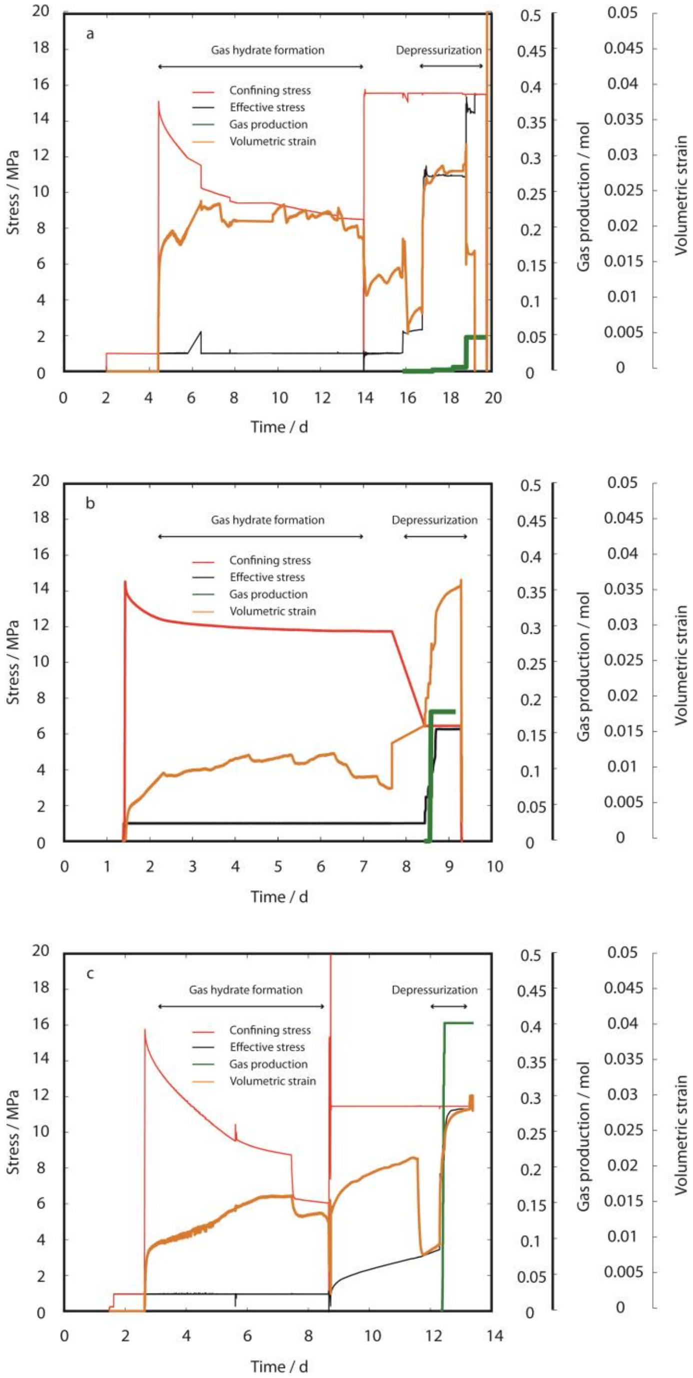

Figure 5. Raw data from dynamic gas hydrate formation and dissociation experiments with different initial gas hydrate saturations

4.3 *Important test cases*

4.3.1 *Slope stability*

Sub-marine slope stability is affected by different factors, and slope failure and sub-marine avalanches could be triggered by different mechanisms. The influence of gas migration, gas holdup, and gas charging of sediments is long recognized as an important factor, although mechanistically many unknowns remain. The impact of gas hydrates in slope stability is less well defined. As a primary effect, gas hydrates tend to increase sediment shear strength and could oppose destabilization. However, in a dynamic marine setting with processes as active gas ascent and seeping, or gas hydrate dissociation the presence of gas hydrates could well be destabilizing (e.g. by enabling pore pressure increase from acting as a low permeability barrier and causing sediment effective unloading, gas release from gas hydrate dissociation or defining failure planes). To improve the understanding of mechanical effects of gas charging, gas migration and gas hydrate dissociation for slope stability, the new flow-through triaxial systems with tomography will used to simulate relevant gas flow and gas release dynamics and investigate mechanical response on micro- and bulk scale. The objective is to improve coupled process understanding and constitutive laws used for mechanical modeling.

4.3.2 *Sand production*

The mechanisms and progress patterns of sand migration observed in field trials are not understood, and the phenomenon could potentially be explained by transient particle fluidization or plastic flow. To improve the understanding of sand production, and to define criteria and triggers for catastrophic soil failure, samples of gas hydrate-bearing sediments with different grain size distributions and gas hydrate saturations will be investigated under different deviatoric loading and flow conditions. Tomographic systems will be used to analyze phase distributions and soil-hydrate fabrics on the small (mm to cm) to micro-scale (few µm) in order to define zones and progression of initial disturbance, and to dynamically monitor transition of initial local disturbance to bulk failure. Certainly, studies to improve mechanistic understanding of sand production will be extended to study technical means of sand production management (e.g. application of sand screens or improved depressurization schemes avoiding peak shear loading on the particle scale). Also, the effect of different injection and gas hydrate formation and exchange schemes will be tested.

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