Gas production from marine gas hydrate deposits through depressurization and CO₂ injection – novel test devices for studying sediment mechanical and hydraulic response and resolving mechanisms of yielding and sand production

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In recent gas hydrate production field trials, onshore in the Alaska permafrost [Schoderbek et al. 2013] and in the Nankai Trough offshore Japan [Yamamoto 2014], the extent of sediment destabilization and sand production exceeded predictions from numerical simulations. Gas production was substantially hindered by different technical issues resulting from sediment mobilization. Thus, there is increasing effort to improve the understanding of potential mechanisms and sequences of yielding and fluidization of gas hydrate-bearing sediments during gas production. Fundamental technical strategies for large-scale gas production from natural gas hydrate reservoirs are depressurization, thermal stimulation and chemical activation. It appears today that depressurization will be indispensable in any scenario. However, when facing suitable conditions, depressurization will likely be assisted by local thermal stimulation to overcome adverse effects from reservoir cooling and / or gas hydrate conversion after injection of a CO₂-rich fluid.

The injection of CO₂ into CH₄-hydrate-bearing sediments has the potential to drive natural gas production and simultaneously sequester CO₂ by gas hydrate conversion. A particular strategy using combined depressurization and injection of a N₂:CO₂ gas mixture was applied in the recent onshore test in Alaska. The development of a technology that combines depressurization with injection of heated supercritical CO₂ is a prime scientific target within the German SUGAR project. It was shown that the injection of heated supercritical CO₂ enhances hydrate conversion and CH₄ production yields [Deusner et al. 2012] particularly by altering transport pathways due to the dissociation of primary hydrates and the formation of secondary hydrates. Beyond improving gas production yields, the combined process aims at maintaining in situ hydrate saturation and structure, and causing limited impact on soil hydraulic properties and geomechanical stability.

Gas production from and fluid injection into natural gas hydrate reservoirs influence reservoir hydraulic and geomechanical behaviour by imposing characteristic, but unusual total and effective stress paths and effective loading / un-loading patterns. Significant over-consolidation and dynamic loading during and after production is probable. Varying gas hydrate saturations during dissociation, conversion and formation will drastically change the sediment hydraulic conductivity, and gas production will occur as non-stationary one-, two- or multi-phase fluid flow (Fig.1). The analysis and simulation of sediment mechanical behaviour relevant to gas hydrate production is therefore far from being straightforward, in particular because transient and dynamic changes of gas hydrate saturation and alterations of gas hydrate-sediment fabrics during and after production will lead to strong and, so far, un-resolved hydro-thermo-mechanical-chemical couplings of processes.

Natural gas hydrates occur in different manifestations, depending on sediment composition and formation history. They can be finely distributed in the sediment pore space or act as a cementing agent between sediment grains and become a load bearing sediment constituent that strengthens the sediment matrix. In recent years, geomechanical properties of gas hydrate-bearing sediments, strength parameters and stress-strain behaviour were studied. Strength, stiffness and strain were shown to be strongly dependent on gas hydrate formation pathways, gas hydrate-sediment structure, gas hydrate saturation, and effective stress conditions. Both compressive and dilative behaviour, as well as strain softening and hardening were observed upon axial strain. Also, there is evidence that soil critical strength after gas hydrate dissociation is reduced relative to original strength of gas hydrate-free soil [Hyodo et al. 2014]. Although artificial gas hydrate sediments which are usually used in laboratory studies might be substantially different from natural analogues, it seems possible to predict end member geomechanical behaviour, i.e. stress-strain relations of gas hydrate-bearing or gas hydrate-
free sediments, with some reliability. Based on this state of knowledge, there are various efforts to model sediment stress-strain behaviour, elastic-plastic yielding and deformation from shear stresses and particle flow triggered by drag forces during depressurization and gas hydrate dissociation [e.g. Uchida et al. 2012, Klar et al. 2013, Uchida et al. 2013]. However, there is very little experimental evidence which could justify the use of particular elastic-plastic yield criteria and flow rules, especially for modelling large strain deformation, failure and sand production, and which could be used as a basis for model development and validation.

It is our overall objective to evaluate geomechanical and hydraulic effects during and after gas production from gas hydrate-bearing sediments through depressurization and gas hydrate exchange from combined experimental and numerical studies. During depressurization, gas from gas hydrates is released with a particular dissociation rate once the thermodynamic conditions are outside the gas hydrate stability range, and it is not to be expected that there will be a significant gas hydrate build-up, except during process shutdown periods. In gas hydrate conversion by the injection of a CO_2-rich fluid, however, overall gas hydrate saturation is intended to be maintained and a substantial build-up of secondary gas hydrates might occur. Gas hydrate conversion and secondary hydrate formation potentially stabilize sediments during production but add significant complexity to the bulk conversion process resulting in distinct spatial and temporal changes in hydraulic and geomechanical properties.

In the SUGAR project we use various high-pressure flow-through systems on different scales equipped with different online and in situ monitoring tools (e.g. Raman microscopy, MRI and ERT [Kossel et al., 2012; Priegnitz et al. 2013]) to simulate different gas hydrate production scenarios and observe relevant processes on bulk and micro-scale. Different triaxial cell experimental systems were
designed as extensions to our NESSI system (Natural Environment Simulator for Sub-seafloor Interactions, [Deusner et al. 2012]). These systems enable versatile studies of sample geomechanical and hydraulic behaviour even during large deformations and particle flow. Key components are triaxial systems with ERT (Electric resistivity tomography) and high-resolution local strain analysis, a hollow-cylinder-type triaxial setup with a miniaturized borehole which allows to investigate fluid and particle transport at different fluid injection and flow conditions, and setups to test technical means and strategies for sand production control and management (e.g. sand screens). Further, the development of a large-scale high-pressure flow-through triaxial test system equipped with μ-CT is ongoing; also transfer of natural pressure core samples from the mobile drilling platform MEBO into triaxial experimental systems is planned within SUGAR. With the application of complementary experimental techniques we obtain the capability to link bulk mechanical behaviour with pore scale structures and processes and to observe sample geomechanical behaviour throughout different stages, starting from small scale local disturbance to large-scale deformation and failure.

In our presentation we will introduce the various experimental systems for geomechanical studies on gas hydrate-bearing sediments and present results from flow-through high-pressure experimental studies on different scales, which indicate that hydraulic and geomechanical properties of hydrate-bearing sediments are drastically altered during and after injection of CO₂. We discuss the results in light of the competing processes of hydrate dissociation, hydrate conversion and secondary hydrate formation.

References


