Mechanical behaviour of gas hydrate-bearing sediments: Effects from changing gas hydrate-sediment fabrics and non-homogeneous gas hydrate distributions

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Abstract

The presence of gas hydrates changes the mechanical properties of marine sediments, with increased gas hydrate saturations usually being related to higher shear strength, increased stiffness and stronger dilatancy. In current numerical modelling approaches, the contribution of gas hydrates to soil mechanical and hydraulic properties is often defined to be exclusively dependent on gas hydrate saturations. However, other parameters strongly influence the stress-strain behavior, e.g. gas hydrate-sediment fabrics, fluid distribution and migration characteristics, and sediment lithology. In addition to that, our experimental data suggest that gas hydrate-sediment fabrics undergo rapid re-arrangement under loading and deformation, which results in unusual secondary hardening and dilatancy behavior. Thus, for the geomechanical analysis of gas hydrate-bearing sediments, e.g. in the scope of evaluation of marine slope stabilities, risks of drilling operations and natural gas production scenarios, a large number of parameters and processes must potentially be considered, and the development and calibration of constitutive models becomes complicated and prone to intolerable uncertainties.

In our experimental-numerical approach we use advanced high-pressure triaxial systems to simulate relevant conditions and processes in gas hydrate-bearing sediments. The experimental systems are used in combination with tomographic techniques (X-ray-CT, and ERT), which facilitate time-resolved analysis of stress-deformation behavior with a high spatial resolution based on 3D sample reconstruction. The objective of our studies is to improve the physical understanding of time- and strain-dependent changes in gas hydrate-sediment fabrics, and to increase the reliability of constitutive models by identifying parameters and processes which determine the mechanical behavior on larger scales.

Results

One of the key research objectives is to identify potential mechanisms and triggers for large strain deformation and sand production during natural gas production from gas hydrate-bearing sediments, which strongly affected the outcome of recent field trials. Mechanical destabilization during gas production could potentially be triggered by factors inherent to particular gas production schemes, e.g. specific stress-strain conditions or fluid flow forces. However, it is likely that mechanical failure is not exclusively related to production schemes, but gas hydrate-sediment fabrics and spatial phase distributions, as well as sediment consolidation and gas hydrate formation histories play important roles. Thus, we hypothesize that mechanical failure of sediments during gas production is related to dynamic non-equilibrium and strongly coupled thermo-hydro-chemo-mechanical processes during gas hydrate formation, alteration and dissociation.

Geomechanical tests have shown that gas hydrate-bearing sediments with grain-coating gas hydrates, which form in the presence of excess gas (Fig. 1, red curves), result in a high peak and residual strength, whereas mechanical strength is substantially lower in the presence of pore-filling gas hydrates (Fig. 1, blue curves). It was observed that sediments in the presence of gas hydrates show a marked secondary hardening behavior, which is not observed in gas hydrate-free sediment. This behavior could be related to stress-strain-induced particle damage or ongoing alteration of gas hydrate-sediment fabrics. Shear test data are used to derive and calibrate constitutive stress-strain relations (Fig. 2) for numerical modeling. The relevance of non-equilibrium processes, and strain-induced changes in phase distributions and gas hydrate-sediment fabrics was even more apparent in the presence of two-phase fluids. Flow-through experiments with injection of methane or CO_2 were used to analyze the geomechanical effects of focused gas migration and non-homogeneous gas hydrate distributions, which is particularly important at gas seeps and in fine-grained low permeable sediments (data not shown). Gas migration and gas hydrate formation around gas channels and in fractures result in rapid gas hydrate formation and increase in load-bearing capacity which could have strong effects on sediment consolidation and sediment mechanical integrity.

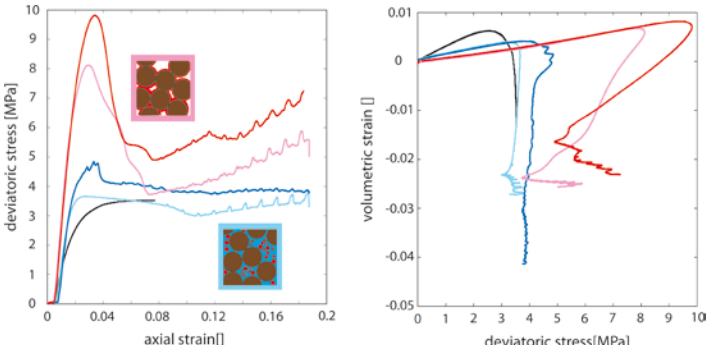

Fig. 1: Stress-strain behavior under deviatoric loading (σ1‘ > σ2‘ = σ3‘)

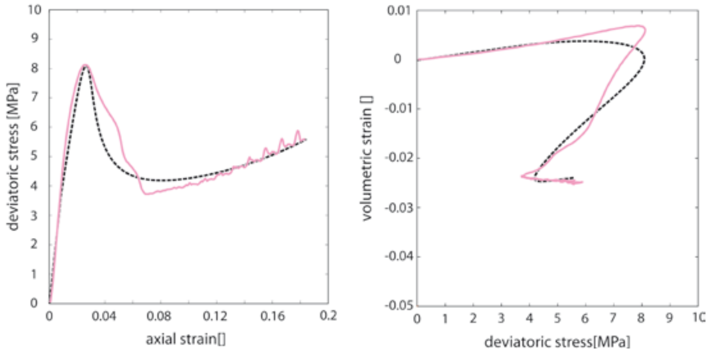

Fig. 2: Comparison of experimental and numerical results from shear tests

To simulate dynamics of coupled processes, to resolve phase distributions or to monitor progression of failure on relevant scales, it was necessary to develop novel experimental approaches. Within the German gas hydrate initiative SUGAR, we have developed novel triaxial test units for high-pressure flow-through studies that are suitable for analyzing mechanical implications of gas production from gas hydrate-bearing sediments. The systems are used in combination with tomographic monitoring tools, electrical resistivity tomography (ERT) or μ-CT, and can be used to monitor stress-strain behavior resulting from particle transport and sand production. The triaxial test units are designed for large samples (150 mm diameter, height maximum 400 mm) and can be operated at pressures up to 40 MPa and temperatures between -30 and 30 °C. The triaxial test unit with μ-CT is equipped with a rotating CT- scanner to facilitate flow-through studies with large sample specimen. The system allows for observation of processes on different length scales and in user-specified regions of interest. Due to a high-precision alignment system (vertical and rotational), high-resolution tomography becomes feasible (Fig. 3).

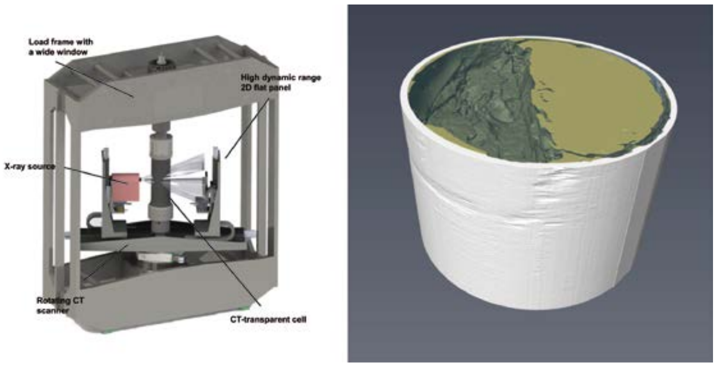

Fig. 3: High-pressure triaxial testing system with X-ray-CT (left) and surface view of the segmented core sample (clay in polycarbonate liner, voxel res 28 μm)