Comprehensive Research on the Deformation Response of the Reservoir during the Methane Hydrate Extraction in Deep Sea

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Methane hydrate is a clathrate solid constituted of methane gas molecule trapped within the hydrogen-bonded of water molecules. Methane hydrate has huge energy storage capacity; thus, increasingly more governments worldwide are paying close attention to this material. Methane hydrate is distributed in the deep seabed and in permafrost and forms under specified temperature and pressure conditions. Due to the dissociation of methane hydrate during the gas production process, the seabed becomes unstable and even induces marine subsea landslide. Therefore, it is important to study the mechanical properties of methane hydrate-bearing specimens to exploit the methane gas safely from the methane hydrate reservoir and predict the stability of the marine slope.

The multiple failure test method is an efficient compress test method for studying the mechanical properties of rock. The method can use one sample to obtain the main mechanical properties under different confining pressure conditions. To verify the feasibility of this method and to evaluate the damage mechanism in testing the mechanical properties of the methane hydrate-bearing specimen (MHS), an experimental apparatus has been designed to supply high-pressure and low-temperature testing conditions. The specimen was compressed successively under the confining pressure conditions of 2MPa, 6MPa and 10MPa. The mechanical properties of MHS using the multiple failure test method can coincide well with the test results in the conventional single loading test method. The feasibility of using the multiple failure test method to study the mechanical behavior was verified based on experimental data. Furthermore, the damage mechanism of MHS was investigated by using a discrete element method with two test methods.

In order to understand the deformation mechanism of methane-hydrate specimens, a method for generating discrete-element method numerical simulation models of MHSs is proposed to study the deformation mechanism of MHSs. First, numerical models that consider the saturation of methane hydrate, following which the bi-axial compression of these models is simulated. The mechanisms controlling the shear strength of MHSs are verified and modified by investigating the stress–strain response behavior, crack-development process, and evolution of the void change rate of MHSs. The increases of the peak strength and secant elastic modulus of the MHS with the increment of confining pressure follow parabolic relationships. Under different loading rates, the peak strength tends to increase parabolically with the increment of loading rate, while the relationship between the secant elastic modulus and loading rate is linear. Based on the testing results, empirical formulas of peak stress and elastic modulus are proposed for different confining-pressure and strain-rate conditions.

MHS distributes under the seabed in different deposit angles according to the bottom simulating reflector exhibitions. The mechanical properties of the combined sediment composed soil and MHS dominate the stability of the slope. In this work, the simulation model was generated considering the deposit angles, the confining pressures, the loading velocities and the hydrate saturation by using discrete element method, and the mechanical response was studied. With deposit angle increasing, the peak strength increased first and then decreased. The elastic modulus decreased first and then increased with the increment of deposit angles. The peak strength and stiffness of sediments increased with increasing the hydrate saturation. The confining pressure enhanced the peak strength in linear, and the elastic modulus increased first and then decreased in a parabolic equation. Under different loading velocities conditions, the peak strength linear increased and the elastic modulus logarithmic increased with increasing loading velocity.

Submarine slope instability may be triggered by earthquakes and tsunamis. Methane hydrate sediments are commonly buried under submarine slopes. Submarine slides would probably be triggered once the MHS are damaged under cyclic loading conditions. For this reason, it is essential to research the mechanical response of MHSs under dynamic loading conditions. In this study, a series of drained cyclic biaxial compressive tests with constant stress amplitudes were numerically carried out with the distinct element method. The cyclic loading number decreased as the hydrate saturation increased when the MHS were damaged. The failure mode of the MHS was shown to be dependent on the dynamic stress amplitude and hydrate saturation. The microstructure of MHS during the cyclic loading shear process was also analyzed. The results can help us to understand the mechanical behavior of MHS during the cyclic loading process and develop micromechanical-based constitutive models.

The dissociation of methane hydrate will decrease the strength of the methane hydrate reservoir. The submarine slope will be deformed and the sand particle will be activated due to the dissociation of methane hydrate. Even worse, the submarine landslide may be triggered during the gas production from methane hydrate reservoirs. Therefore, the deformation response of the submarine slope should be studied in the large-scale production of methane hydrate. In present work, the thermal-fluid-mechanical coupled model was introduced, and the deformation of the marine slope and the sand production were analyzed considering the influence of the slope angle and the cyclic loading condition. When the slope angle is horizontal, the distribution of the subsidence of the methane hydrate sediment layer and the upper sediment is axisymmetric. When the slope angle is 5°, the pore pressure was higher in the right hand of the wellbore than that in the left hand of the wellbore. The deformation tendency of the upper sediment is following the slope direction, and thus, the stability of the slope is poorer than that of other slope angle conditions. Sand production always started on the upper and the bottom of the methane hydrate sediment layer around the wellbore, and the prediction distance of sand production increased with increased mining time. The prediction distance of sand production also increased with the increase of the cyclic amplitude.