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| 論文題目 | Microscopic and Macroscopic Characterization on Mechanical Properties of Gas Hydrate<br>（ガスハイドレートの力学特性に関する微視的及び巨視的評価） | | |

Gas hydrate has been considered to be a scientific curiosity since it was discovered at the beginning of 19th century. Because a huge amount of natural gas is compressed in the clathrate structures of water molecules-forming network that is widespread occurrence all over the world, it becomes an important potential energy resource which is good substitution for traditional fossil fuel. Hence, exploration and development of gas hydrate have attracted great attentions in industry until the present. Mechanical properties of gas hydrate are crucial factors to predict the stability of the formation during natural gas production as well as geophysical exploration (e.g. seismic exploration) for the future energy resource. This thesis is aimed to characterize mechanical properties (i.e. mechanical strength, elastic property and acoustic impedance (AI)) of gas hydrate with regard to exploration and development. Target scale of the methods is wide from microscopic perspective by Molecular Dynamics (MD) simulation to macroscopic view using AI inversion. The main contents are summarized as follows:

The first chapter introduces the background knowledges of gas hydrate research and reviews the contemporary research status. Meanwhile, the structures of the individual chapters and objectives of relevant sub-topics (Chapters 3, 4 and 5) are presented.

Chapter 2 is composed of methodologies of MD simulation, rock physics modelling and AI inversion. Basic concepts and relevant calculation algorithms are explained in this chapter.

In Chapter 3, the difference of mechanical strength between gas hydrate (sI) and normal ice is compared with constant compressive deformation test (CCDT) from nano-scale performed by MD simulation. As reported by previous researches (compressive creep tests (CCT)), the strength of gas hydrate is nearly 20−40 times as large as that of normal ice, and gas hydrate is a kind of strain hardening materials while strength of normal ice weakens after ultimate strength at strain of ~0.02. This indicates that the strength of hydrate-bearing formation would greatly reduce after hydrate decomposition which will induce geo-hazard, like landslide. However, the microscopic origin of the difference is unknown so far. By MD simulation, gas hydrate indeed exhibits strain hardening if it is confined to a certain finite cross-sectional area along the normal to the compression direction. The “guest” molecules exhibit no long distance diffusion during the deformation process and appear to be responsible for the strain-hardening phenomenon. The methane hydrate is stronger than normal ice, however, their overall magnitudes are comparable by CCDT. As CCT implies extremely slow loading speed, further investigation will be conducted concerning strength magnitude.

Chapter 4 presents high resolution pressure-temperature (P-T) diagrams of elastic moduli of $CH_4$ and $CO_2$ hydrate for the first time. The P-T range covers the conditions of arctic permafrost and marine sediments where natural gas hydrate occurs. On the basis of the P-T diagrams, elastic wave velocities of hydrate-bearing sediments can be evaluated to monitor the formation situations in real time during natural gas production or Carbon Capture and

Storage. In addition, it is discovered that the shear modulus and Young's modulus of the $CO_2$ hydrate increase anomalously with increasing temperature whereas those of the $CH_4$ hydrate decrease regularly with increase in temperature. Therefore, the thermal effect can enhance the stability and rigidity of the $CO_2$ hydrate, which has rarely been reported with regard to the crystalline materials. By MD simulations, it is shown that this anomaly is originated from kinetic behavior of the linear $CO_2$ molecule. The aspherical shape of the water molecules-forming cages limits free rotational motion of the $CO_2$ molecule at low temperature. With increase in temperature, the $CO_2$ molecule can rotate easily, and make the whole structure more stable and rigid.

In Chapter 5, rock physics modelling and AI inversion are employed to investigate gas hydrate saturations in the Kumano Forearc Basin located in the Nankai Trough. This facilitates characterizations on natural gas hydrate *in situ* in term of its distribution in the pore space and spatial saturations. As traditional seismic data and well logging data can only identify the existence of gas hydrate by respective indicators, this chapter presents an improvement with quantification on natural occurrence of gas hydrate and a successful application on gas hydrate occurrence in the Kumano Forearc Basin. The results suggest that gas hydrates are probably attached with mineral grains surface and are not floating in the pore fluid. Furthermore, gas hydrates are highly concentrated near the outer ridge at seaward side which is due to overpressure, abundant gas supply and the ancient splay faults in this area. The tectonic activities within underlying accretionary prism significantly influence the hydrate saturation and distribution in the Kumano Forearc Basin. Therefore, it is necessary to consider dynamics of the underlying accretionary prism when characterize hydrate saturation and distribution in the forearc basin. These implications may be available to the forearc basins in other plate convergent margins as well.

Chapter 6 concludes the achievements of this thesis, and makes suggestions for the future work concerning improvement of comparisons between simulation results to experimental data.