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Estimation of model parameters and properties for numerical simulation on geomechanical stability of gas hydrate production in the Ulleung Basin, East Sea, Korea

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ABSTRACT

The process of hydrate dissociation and production induced by depressurization incorporates intricate hydraulic, thermal, and mechanical phenomena. Thus, coupled thermal-hydraulic-mechanical (T-H-M) simulation is critically necessary to evaluate the geomechanical stability of hydrate production in hydrate-bearing sediments (HBS). However, methods of estimating the input model parameters and properties of the target reservoir, in particular in unconsolidated marine sediments, have received limited attention compared to studies on production simulators. The T-H-M properties of the marine sediments change considerably with depth, geological strata, and soil type of each layer. Therefore, it is important that representative layers and their corresponding T-H-M properties should be properly estimated to analyze the stability and productivity of methane gas recovery in the field. This study provides a comprehensive estimation for the model parameters and properties of unconsolidated marine sediments, based on vast data from field seismic surveys and laboratory experimental results with core samples, investigates empirical correlations between model parameters and methane hydrate saturation, and finally summarizes the estimated model parameters and properties, which can possibly be applied to on-going numerical research into stability assessment of the pilot gas hydrate (GH) production test, which is soon to be performed in the Ulleung basin.

1. Introduction

Methane hydrate, an ice-like solid compound in which methane molecules are locked within lattice structures of water, is the world's promising new energy source, one that could potentially replace oil and fossil fuel. Among various carbon resources, there are an overwhelming amount (over 11,000 Gt) of estimated methane (formed as gas hydrate) on the earth (Hacisalihoglu et al., 2008).

Methane hydrate will also be an important energy resource of South Korea. Based on the two drilling expeditions (UBGH1 in 2007 and UBGH2 in 2010), it has been revealed that the Ulleung basin contains not only gas hydrate-bearing sediments including highly concentrated sandy layer and fracture-filling chimneys which were formed from the late Miocene to the Quaternary (Kang et al., 2016). Its potential amount was estimated at about 0.6 billion tons (Lee et al., 2013a), which can provide usable energy for thirty years to the whole nation. Therefore, a national program for gas hydrate research and development has been carried by the Ministry of Knowledge Economy, a Korean Government department since 2004.

There are three main methods of gas recovery from methane hydrate layers (Holder et al., 1984; Makogon, 1997; Moridis and Collett, 2003; Pawar et al., 2005): (1) depressurization, in which the methane hydrate is dissociated by lowering the well pressure; (2) thermal stimulation, in which the hydrate is dissociated by injecting hot fluid into the production well; and (3) chemical stimulation, in which the hydrate is destabilized by injecting

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inhibitors and their combinations. For successful methane recovery from hydrate deposits, depressurization is considered the most productive and effective method to date (Collett, 2007; Moridis and Reagan, 2007).

When methane gas is produced from a hydrate deposit by the depressurization method, the types of hydrate deposit (i.e. arctic sands, marine sands, fractured mud, mounds, undeformed mud; Boswell and Collett, 2006) and the geological and geotechnical characteristics (e.g. in-place resource, geological formation, permeability, porosity, thermal conductivity, stiffness and strength) govern the methane productivity and geotechnical stability (i.e. seafloor settlement, sediment displacement, sand production, wellbore stability, etc.; Boswell and Collett, 2006). The Ulleung basin of Korea, the Gulf of Mexico, and the Nankai Trough are classified as *deep marine sand* and *fractured mud,* a type of formation that has a larger amount of methane gas than do the *arctic sands,* but that involves more technical difficulties in the process of gas production. The sediment of deep marine reservoirs typically contains unconsolidated mud layers in which large volume change and time-dependent compaction (herein consolidation) can be induced during depressurization (Kim et al., 2013a). Moreover, an anisotropic stress field, which can cause damage to production wells and production equipment on the seafloor, can be generated in a depressurized zone due to heterogeneity of sediments. Especially according to a recent study (Kim et al., 2014), it has been also indicated that the effect of gas presence in the marine sediment is significant to the variations of strength and stiffness properties. Therefore, the intricate geomechanical behavior and stability of the hydrate-bearing sediments should be evaluated by field-scale numerical analysis before any *in-situ* hydrate production test.

The process of hydrate dissociation and production induced by depressurization incorporates: (1) hydraulic process taking place in a depressurized and methane-dissociated range with water and gas flow, (2) thermodynamic endothermic reaction to decompose hydrate into methane gas and water at the equilibrium pore pressure and reservoir temperature, (3) thermal process of conduction and advection, and (4) mechanical phenomena aforementioned (e.g. volume change, consolidation). Thus, coupled thermal-hydraulic-mechanical (T-H-M) simulation is critically necessary for evaluating the precise geomechanical responses. In accordance with this, recent numerical studies on hydrate production have focused on geomechanical stability analysis using coupled TOUGH + HYDRATE and FLAC3D (Rutqvist et al., 2009; Rutqvist and Moridis, 2009), FLAC^{2D} (Klar et al., 2010; Kim, 2015), and FLAC^{3D} (Kim, 2015).

As mentioned above, numerical modeling that can simulate the coupled process is very important to accurately predict the reservoir behavior and stability during methane production, while methods to estimate the thermal, hydraulic, and mechanical input parameters and properties of the target reservoir have received limited attention. Model parameters are used for numerical analysis in the correlated governing equations and constitutive models; their values, which is to say the input properties, represent the thermal, hydraulic, and mechanical characteristics of the site. The T-H-M properties of the target reservoir sediments change considerably with depth, geological strata, and soil type of each layer. Therefore, it is important that representative layers and their corresponding T-H-M properties should be properly estimated to evaluate the stability and productivity of methane gas recovery in the field. For example, if a soil profile (or layering) is too simplified, the simulation cannot represent the field condition while if the soil profile is too detailed, the simulation will take too long time to analyze.

This paper provides a comprehensive estimation for model parameters and properties based on vast data from field seismic surveys and laboratory experimental results with core samples, investigates empirical correlations between model parameters and methane hydrate saturation, and finally summarizes the estimates model parameters and properties, which can be used in the T-H-M simulation of the geomechanical stability of methane production in the Ulleung Basin.

2. Site description and initial condition

2.1. Site description

The Ulleung Basin, one of the country's methane hydrate deposits, is located at the southwestern corner of the Korean East Sea (Fig. 1a). The first Ulleung Basin Gas Hydrate Drilling Expedition 1 (UBGH1) was completed in 2007; the second expedition (named UBGH2) was performed in 2010. The main objectives of the two expeditions were to estimate the amount of hydrate resource of the Ulleung Basin with geology and geochemical data, to investigate the geology and geochemical dominant factors, to evaluate the effect of hydrate leakage on the circumferential environment, and to select a proper site for a gas hydrate production field test (MKE, 2008). During the period of UBGH2 operation, 13 sites were explored and characterized for their geological, geophysical, geochemical, geomechanical, hydraulic, thermal, and petrophysical properties by using logging-while-drilling (LWD), wireline logging (WL), coring (e.g., conventional coring and pressurized coring), and laboratory experimental studies (Bahk et al., 2013; Kim et al., 2013a; Ryu et al., 2013). On the basis of the enormous data set derived from UBGH2, it was observed that a significant amount of hydrate exists as pore filling type in sandy layers and fracture filling or diffused-filling types in mud layers.

Site UBGH2-6, the most northern site of UBGH2, is considered a feasible pilot production test site based on the seismic survey and the core samples (Ryu et al., 2013). Three holes (e.g. UBGH2-6A, UBGH2-6B, UBGH2-6C; Fig. 1b) were drilled; UBGH2-6A was drilled for LWD and measurement-while-drilling (MWD); other holes (UBGH2-6B, UBGH2-6C) were cored, and WL was performed after coring at UBGH2-6C. The data set derived from the seismic survey indicated a potential base of gas hydrate stability zones, and the high occurrence of hydrate around the UBGH2-6 site was confirmed by hydrate-bearing sand layers inside the recovered cores (Ryu et al., 2013). Based on laboratory experimental studies with the UBGH2-6 core samples, the site contains fine-grained sediments intercalated with thin sand-rich layers. Most of the fine-grained sediment samples were classified as high plastic silty soils and exhibited high compressibility, high porosity, and low hydraulic conductivity (Kim et al., 2013a).

2.2. Initial conditions

Hydrates exist in solid phase according to circumferential pressure and temperature. Thus, the pore pressure and reservoir temperature of the target depth should be exactly investigated and input into the numerical modeling for the hydrate production simulation. During the UBGH2 Expedition, the water depth of site UBGH2-6 was observed by remotely operated vehicle (ROV) survey to be 2157 m; seafloor temperature and geothermal gradient were measured by CTD (Conductivity, Temperature, Depth) oceanographic device and determined to be 0.482 °C and 112 °C/km, respectively (Ryu et al., 2013); by analyzing the collected pore-water samples, salinity of seawater was determined to be 3.45 wt % (Ryu et al., 2012). Reservoir pressure was calculated as the summation of the hydrostatic pressure by considering the salinity of seawater, $P_w = \rho_w g\, z$, where P_w is the water pressure at the target depth [Pa], $\rho_w$is the brine water density [kg/m^3], g is gravity [m/s^2], and z is the depth below the sea surface [m]. The hydrate