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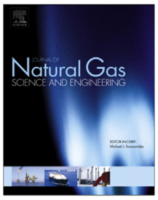

A thermodynamics-based critical state constitutive model for methane hydrate bearing sediment

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ABSTRACT

A constitutive model is proposed to analyze the mechanical behavior of methane hydrate-bearing sediment (MHBS) based on thermodynamic principles and the critical state concept. This new model is developed based on a more generalized mechanical dissipation hypothesis compared to conventional models and describes more significant mechanical properties of MHBS, such as the non-elliptical yield surface and different slopes of the critical line in different deviatoric stress directions, by introducing two spacing ratios. The non-associated flow rule is based on Ziegler's orthogonality condition instead of a plastic potential function, which guarantees that the model does not violate the laws of thermodynamics. The shape of the yield surface governed by the spacing ratios γ and α influences the stress–strain curve and dilatancy behavior. It is necessary to provide a precise description of the spacing ratio and the shape of the yield surface. The model can predict the stress softening and dilatancy during the drained shearing process for specimens with different hydrate saturations and different hydrate accumulation habits. The satisfactory performance of the model is demonstrated.

1. Introduction

Methane hydrates are a new energy resource that has attracted significant attention in recent years due to their massive reserves, extensive distribution and high energy density (Kvenvolden et al., 2001; Collett, 2002; Fujii et al., 2009; Song et al., 2014). Large amounts of methane hydrates are buried under the permafrost and on the edges of the continental shelf (Fig. 1). The exploitation of hydrates will cause many geologic hazards. For example, the loss of hydrates in sediment voids by hydrate dissociation may lead to sediment deformation and a loss of shear resistance (Rutqvist et al., 2009; Ning et al., 2012) and may eventually cause deformation of the seabed (Kimoto et al., 2007) and submarine landslides (Sultan et al., 2004; Maslin et al., 2010). Furthermore, methane gas extraction may exacerbate global warming (Glasby, 2003; Archer, 2007). Therefore, the mechanical properties of methane hydrate-bearing sediment (MHBS) has attracted the attention of researchers (Winters et al., 2007; Waite et al., 2009; Miyazaki et al., 2010; Li et al., 2011; Yun et al., 2007; Hyodo et al., 2009).

MHBS is a multiphysical and multiphase material due to the existence of different types of materials, including liquid, gas, soil particles and hydrate particles, all of which interact differently. Different governing equations have been developed to analyze the responses to specific boundary conditions and initial conditions for practical engineering problems (Liu and Yu, 2013; Kimoto et al., 2007, 2010; Klar et al., 2013; Zhao et al., 2013). Moreover, a constitutive equation that governs the relationship between stress and strain is necessary to describe the deformation of sediments by an external load. The effective stress principle implies that the deformation of the sediment skeleton is caused by the effective stress rather than the total stress. Sediment deformation is always governed by the effective stress. Therefore, the proposed constitutive model is based on the effective stress analysis.

The sediment skeleton consists of soil particles and hydrate particles. The soil particles are in contact with each other and bear the external load. They form the soil skeleton. However, the role of hydrate particles differs for different accumulation habits and the saturation. The behaviors of hydrate particles are generally categorized into two types based on the occurrence modes of hydrates in MHBS pores. The first category is pore-filling behavior, in which hydrates may bridge neighboring grains, which makes the MHBS

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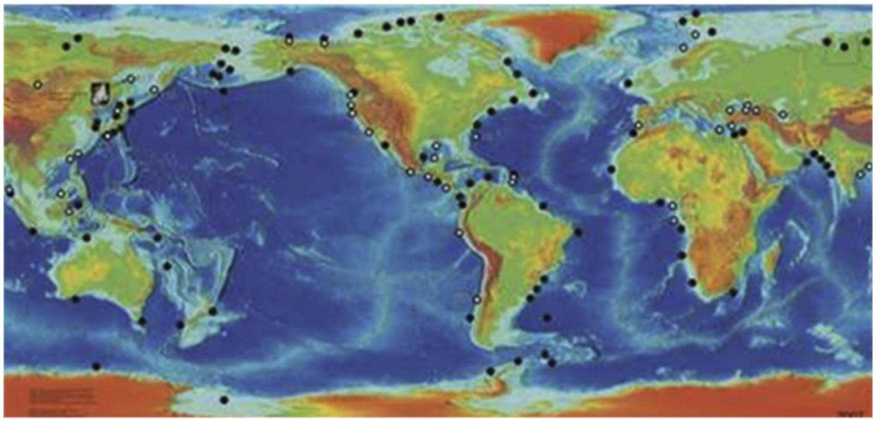

Fig. 1. Global distribution of methane hydrates (Kvenvolden and Lorenson, 2001).

denser than sediment without hydrates. When the hydrate saturation is high, some pore-filling hydrates bear the external load. Several researchers have recognized these hydrates as load-bearing hydrates (Yun et al., 2007). The second category is cementing behavior (Dvorkin et al., 2000; Fernandez et al., 2001), in which hydrates are located on the contact surface of the grains and cause the MHBS to act as a bonded soil. These two occurrence modes of methane hydrates in pores influence the strength of the skeleton in different ways.

Although the skeleton consists of two different materials, it is not necessary to build individual constitutive models for the soil and the hydrates. Klar et al. (2010) assumed that the location of the hydrates that are attached to soil particles cannot be changed if the location of the hydrate particles remains unchanged; these two materials are likely to yield together (Klar et al., 2010). In addition, we also neglect the possibility of hydrates being pushed out from the soil skeleton. If the amount of hydrates that is pushed out is large, the relative motion between the hydrate skeleton and soil skeleton will become the dominant factor. However, this would not occur for medium and low hydrate saturations.

Phase changes govern the fractions of different components and change the hydrate saturation. Changes in hydrate saturation influence the resistance of the sediments. The impact of phase changes on the stress–strain relationship can be described by the variation in hydrate saturation. Therefore, a constitutive model that describes the mechanical properties of the MHBS skeleton should include the relationships between stress, strain and hydrate saturation.

Previous research (Waite et al., 2004; Hyodo et al., 2005, 2013a,b, 2014; Li et al., 2013; Yoneda et al., 2015) on the mechanical properties of MHBS has demonstrated that due to the presence of hydrates that enhance the density and cementing of the material, (1) the strength and stiffness of MHBS depend on the hydrate saturation, (2) the hydrate's contribution to the shear behavior arises from cohesion rather than friction, and (3) the dilation angle increases with increasing hydrate saturation. These MHBS properties will be modeled in the following sections, and other properties, such as the influences of the shape of the yield surface on the stress–strain and dilatancy curve, will also be discussed.

One key to modeling MHBS is the description of the dependence of the hydrates on changes in the strength and stiffness of the MHBS and on degeneration of the skeleton structure during shearing. The peak strength of MHBS with a high hydrate saturation is greater than that of soil without hydrates or an MHBS with a lower hydrate saturation. Additionally, the strength reduction has been tested for constant hydrate saturation. The strength reduction and dilatancy of MHBS with a high hydrate saturation during shearing has been demonstrated to be greater than that of MHBS with a low hydrate saturation. These phenomena occur because a large amount of hydrate increases the density of MHBS. That leads MHBS behave as dense soil, in which the particles need to overcome greater resistance and roll over other particles to find relatively steady positions. At the same time, the hydrates bond with the soil particles, which strengthens the sediment skeleton. Several constitutive models of dense soil and bonded soil have been developed (Lade et al., 1989; Wang et al., 2008). Many researchers (Kimoto et al., 2010; Klar et al., 2010; Uchida et al., 2012; Lin et al., 2015) have proposed constitutive models of MHBS in which the hydrate saturation is considered to be related to the hardening parameters and the yield surface. Following these studies, we propose a constitutive model of MHBS. Compared with previous models, the new model is based on the dissipative function and Ziegler assumption. The influence of the spacing ratios γ and α, which govern the shape of yield surface, on stress–strain relationship and dilatancy are considered.

Conventional plasticity constitutive models can be used to accurately describe the stress–strain relationship of sediment. However, many of these models are based on Drucker's stability postulate and the plastic potential theory. The yield condition, flow rule and hardening law are determined independently and occasionally contradict each other, which may result in a violation of the laws of thermodynamics. Collins and Kelly (2002) analyzed the thermomechanical validity of several classical critical state models and proposed a generalized family of new models. One result of this analysis was the demonstration that the original Cam clay model violates the second law of thermodynamics. The newly developed constitutive model framework for sediment guarantees that the laws of thermodynamics are satisfied due to the use of a mechanical dissipative incremental function and a free energy function without the application of retrospective criteria. These two functions and their derivatives must be determined from the mechanical properties of the research object, and a dimensional balance should be included in the formula's derivation. In recent years, this framework has been used to construct a constitutive model for geomaterials. Ziegler and Wehrli (1987) described the mechanical properties of a Coulomb material with generalized thermodynamics. A few years later, French researchers (Lemaitre et al., 1990; Maugin, 1992; Besseling et al., 1994) modified this theory to make it more rigorous. Rate-independent theoretical frameworks have been established (Houlsby, 1981; Collins et al., 1997; Houlsby et al., 1999; Puzrin et al., 2001; Houlsby et al., 2007), and a continuous critical state model was developed by Einav et al. (2003) and Einav and Puzrin (2004). In addition, Einav (2007a,b) proposed a thermodynamics-based constitutive model for granular materials