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Research Paper

A state-dependent critical state model for methane hydrate-bearing sand

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ABSTRACT

Methane hydrate exists in the pores of methane hydrate-bearing sand (MHBS) and is considered to be a potentially significant source of methane and thus energy for mankind. However, before conducting a large-scale extraction of methane from MHBS, it is crucial to simulate the mechanical behaviour of MHBS and evaluate its stability during drilling and methane production. In this paper, a state-dependent critical state model for MHBS is presented. The critical state of MHBS is discussed, and critical state line formulations are introduced as functions of hydrate saturation. A simple nonlinear bonding and linear debonding law is incorporated considering the cementing mechanism of hydrate. A modified state-dependent dilatancy is proposed to account for the effects of stress level, internal state (density), bonding strength and hydrate saturation. Determination of the model parameters is described in detail. The proposed model is employed to predict results of drained triaxial compression tests on MHBS. Satisfactory performance is demonstrated, i.e., the model can adequately capture the stress–strain and volume change behaviours of MHBS over a wide range of hydrate saturations, confining pressures and densities using a unified set of parameters.

1. Introduction

Gas hydrate is a crystalline compound formed from a combination of water and low molecular weight gas, e.g., methane and carbon dioxide. Methane hydrate is the most commonly occurring natural hydrate and is considered as one of the potential sources of energy for the future [1–4]. Natural methane hydrate occurs in abundance in deepwater marine sediments and permafrost regions where appropriate temperature and pressure conditions exist [5,6]. Coarse-grained sediments tend to contain methane hydrates in pore spaces, while in fine-grained sediments, methane hydrates often exist in the forms of discrete nodule, vein, veinlet and layer. According to field investigation, more methane hydrates tend to occur in coarse-grained sediments (i.e., Nankai Trough and Mallik-Mackenzie Delta) than in fine-grained sediments (i.e., Hydrate Ridge and Blake Ridge) [7]. Thus, more attention has been given to extracting natural methane hydrates from coarse-grained reservoirs due to economic benefits. Understanding the mechanical properties of methane hydrate-bearing sand (MHBS), a natural soil deposit, is crucial to evaluate its stability during drilling and methane production [8–10].

Past studies have shown that the mechanical properties of MHBS are significantly influenced by the presence of hydrates (hydrate saturation and hydrate accumulation habit), confining pressure and density [11–18]. It should be noted that the hydrate saturation (S_h), which is widely used in the literature to describe the hydrate content in sediments, is defined as follows [11]:

$$S_h = \frac{V_h}{V_h + V_V} \tag{1}$$

where V_h and V_V are the volumes of the hydrate and the pore space, respectively. For a given hydrate saturation, the hydrate accumulation habit within the soil pore space is one of the biggest factors influencing the response of MHBS under different loading conditions. Waite et al. [19] presented the following three possible hydrate accumulation habits in coarse-grained sediments:

(1) Pore filling – hydrates exist only within the pore space and do not contribute to the load bearing of the soil skeleton.
(2) Load bearing – hydrates form part of the soil skeleton that contributes to the stability of the soil structure [20].
(3) Grain cementing – hydrates act as bonding agents to cement the soil grains at intergranular contacts.

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Different hydrate accumulation habits lead to different mechanisms of deformation for MHBS. Fig. 1(a) illustrates the pore-filling mechanism of hydrates. This figure shows that the hydrate exists only in the pore space and does not come into contact with soil grains. Under this condition, the hydrate primarily affects the pore fluid stiffness and conduction properties [21]. The load-bearing mechanism is depicted in Fig. 1(b), where hydrates bridge neighbouring soil grains and become part of the load-bearing framework mainly derived from dilation enhancement and frictional resistance at the hydrate-grain contacts. Fig. 1(c) shows the cementing mechanism of hydrates. In this case, the hydrate cements the intergranular contacts, and a small amount of hydrate can dramatically increase the stiffness and shear strength of the host sand by bonding adjacent grains together [22].

In the last decade, experimental studies on synthesised MHBS have been widely reported in the literature [11,13,14,16,17,23,24]. However, only a few attempts have been made towards modelling the behaviour of MHBS. Freij-Ayoub et al. [25], Rutqvist and Moridis [26] and Klar et al. [27] developed extended Mohr–Coulomb models for MHBS, which consider the stiffness, strength parameters and dilation angle of MHBS as functions of hydrate saturation. However, the strain-softening behaviour and debonding of hydrate were not modelled, and the volume change of the specimens could not be satisfactorily predicted. Uchida et al. [28] and Lin et al. [29] extended the Cam-Clay model for MHBS by taking into account the degradation of hydrate bonding based on the concept of critical state soil mechanics. However, the critical state of MHBS was assumed to be independent of the presence of hydrates in the above critical state-based model. This assumption is unlikely to be true and will be discussed in the following section. Moreover, the associated flow rule was adopted, which had been proved inappropriate in sand modelling, thus resulting in an inaccurate volume change prediction of MHBS. In addition to hydrate saturation, density is also an important factor that can significantly influence the mechanical behaviour of MHBS. So far, the mechanical behaviour of MHBS has not been captured over a wide range of densities using a unified set of parameters.

In this study, a state-dependent critical state constitutive model for MHBS is developed. The critical state behaviour of MHBS is introduced based on the experimental data from large-strain triaxial compression tests conducted by Hyodo et al. [13]. A modified state-dependent dilatancy is presented to account for the effects of stress level, internal state, bonding strength and hydrate saturation. A simple bonding and debonding law is used to describe the evolution of the hydrate-induced bonding. Details of the model formulation and parameter calibration are described. The accuracy of the model is demonstrated by comparing its predicted values with results from the drained triaxial tests on MHBS under various hydrate saturations, densities and confining pressures.

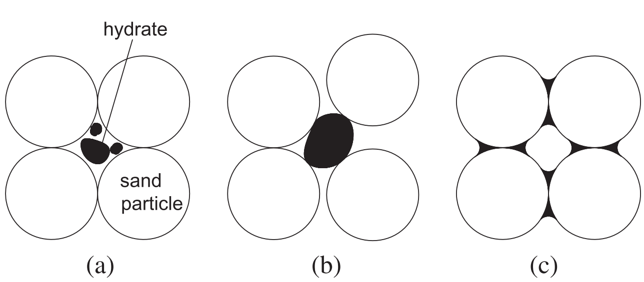

Fig. 1. Three possible hydrate accumulation habits in coarse-grained sediment: (a) pore filling, (b) load bearing, and (c) grain cementing.

2. Model formulation

The proposed model is developed within an elasto-plastic framework and takes into account of the possible occurrences of irrecoverable plastic strains. The total strain increment ($d\varepsilon$) is the sum of the elastic strain increment ($d\varepsilon^e$) and the plastic strain increment ($d\varepsilon^p$). The model assumes an elastic behaviour if the soil remains inside a yield surface and a plastic behaviour commences once the yield surface is reached. The model is formulated in a p'–q space. Mean effective stress and deviator stress are defined as $p' = (\sigma'_1 + 2\sigma'_3)/3$ and $q = \sigma'_1 - \sigma'_3$, respectively, where σ'_1 and σ'_3 are the major and minor principal stresses, respectively. The work conjugate strain rates for p' and q are $d\varepsilon_v$ and $d\varepsilon_q$, respectively (volumetric strain increment $d\varepsilon_v = d\varepsilon_1 + 2d\varepsilon_2$ and shear strain increment $d\varepsilon_q = 2(d\varepsilon_1 - d\varepsilon_3)/3$, where $d\varepsilon_1$ and $d\varepsilon_3$ are the principal strain increments). Under the above elasto-plastic framework, $d\varepsilon_v$ and $d\varepsilon_q$ are decomposed into

$$d\varepsilon_v = d\varepsilon_v^e + d\varepsilon_v^p \tag{2}$$

$$d\varepsilon_q = d\varepsilon_q^e + d\varepsilon_q^p \tag{3}$$

where $d\varepsilon_v^e$ and $d\varepsilon_v^p$ are elastic and plastic volumetric strain increments, respectively, and $d\varepsilon_q^e$ and $d\varepsilon_q^p$ are elastic and plastic shear strain increments, respectively.

2.1. Elastic strain

According to the theory of elasticity, $d\varepsilon_v^e$ and $d\varepsilon_q^e$ are calculated as

$$d\varepsilon_v^e = \frac{dp'}{K} \tag{4}$$

$$d\varepsilon_q^e = \frac{dq}{3G} \tag{5}$$

where K and G are the elastic bulk and shear moduli, respectively.

For clean sand, G can be expressed by the following empirical equation [30]:

$$G = G_0 \frac{(2.97 - e)^2}{1 + e} \sqrt{p' p_a} \tag{6}$$

where G_0 denotes a model parameter, and p_a is the atmospheric pressure, taken as 100 kPa.

For MHBS, Uchida et al. [28] suggested that G is the summation of the shear modulus of the sand skeleton and the shear stiffness increase due to the presence of hydrates. The shear stiffness increase was assumed to be a linear function of hydrate saturation. As expressed by Eq. (6), G of the sand skeleton is a function of the void ratio and the effective stress. However, the dependence of the shear stiffness increase on the void ratio and the effective stress is unknown for MHBS. In the proposed model, it is assumed that Eq. (6) is still applicable for MHBS, and G_0 is affected by hydrate saturation. Fig. 2 shows the resonant column test results in terms of G_0 for MHBS reported by Clayton et al. [24]. The MHBS specimens were prepared using the 'partial water saturation' method, in which methane hydrate was formed by flushing pressurised methane gas through unsaturated sand specimens and cooling into the hydrate stability zone. An approximately linear relation between G_0 and hydrate saturation is observed. Based on the above observation, it is assumed that G_0 increases linearly with increasing hydrate saturation for MHBS:

$$G_0(S_h) = G_0 + \xi S_h \tag{7}$$

where $G_0(S_h)$ and G_0 are model parameters for MHBS and clean sand, respectively, and ξ is a positive model parameter denoting