Geomechanical Modeling of Gas Hydrate Bearing Sediment

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ABSTRACT: Gas hydrate bearing sediments (GHBS) are natural sediments that formed in permafrost and submarine settings where the temperature and pressure conditions maintain the stability of hydrate. Gas hydrate bearing sediment has been recognized as possible future energy resources and it also closely related with many engineering and environment problems. This manuscript presents a constitutive mechanical model for hydrate bearing sediments. The model incorporates the concept of partition stress, plus several other concepts to capture the complex behavior of GHBS. Experimental data from triaxial and oedometric tests conducted on manufactured and natural specimens are selected to demonstrate the model's capability. Attention was paid to model the behavior during hydrate dissociation under loading. The model performance was highly satisfactory in all the cases studied. It managed to properly capture the main features of GHBS mechanical behavior and it also assisted to interpret the behavior of this type of sediment under different loading and hydrate conditions.

1 INTRODUCTION

Gas hydrate bearing sediments (GHBS) are naturally occurring soils characterized by the presence of ice like gas (e.g., CH_4 or CO_2) hydrates in its pore space. Water molecules clustered around methane molecules form a solid compound called methane hydrate that are naturally found in marine sediments and permafrost regions, where the (high) pressure and (low) temperature conditions guarantee the hydrates stability(Collett, 2002, Mahajan et al., 2007). Perturbations in pressure, temperature or water-chemistry may move the methane hydrates from its stability zone triggering hydrate dissociation. GHBS represents an attractive source of energy, it is estimated that significant methane reserves are in the form of hydrates.

However, GHBS are also associated with issues and drawbacks. For example, massive submarine landslides are in occasions related to hydrate dissociation from subsea sediments. This type of phenomenon generally involves large areas and may affect pipelines and other submarine infrastructure. A number of engineering problems (e.g. blowouts; platform foundation failures; and borehole instability) are sometimes triggered by hydrate dissociation. Furthermore, the venting of methane to the atmosphere during uncontrolled hydrate dissociation can negatively contribute to greenhouse effects (Beaudoin et al., 2014). These factors have triggered significant research efforts to study the physical, chemical and mechanical behaviour of methane hydrate bearing sediment.

In this study, a new elasto-plastic model based on the stress partition concept and the HIerarchical Single Surface (HISS) framework (Desai et al., 1986, Desai, 2000) was selected to provide a general and adaptable geomechanical model for hydrate bearing sediments. Recently published experimental data based on synthetic and natural specimens involving different S_h were adopted to validate the proposed approach. The model application and validation do not limit to cases in which S_h is maintained constant during the tests (as in previous works), but also include experiments in which dissociation is induced under constant stress.

2 MODEL DESCRIPTION

The elasto-plastic framework contemplates the presence of two basics components: sediment skeleton and hydrates. The stress-partition concept proposed by (Pinyol Puigmartí et al., 2007) for clayed cementing materials is adapted in this work for describing the behavior of HBS because of its ability to describe two different structures on the global response of GHBS under different loading and hydrate saturation conditions, particularly during hydrate dissociation. As for the hydrates, a damage model that considers the material degradation due to loading and dissociation was suggested.

As for the sediment skeleton, a model based on critical state soil mechanics concepts is adopted, which is an appropriate approach for describing the elastoplastic behavior of the soils. The particular constitutive equations adopted hereafter are based on a modification of the HISS elasto-plastic model. The proposed framework also incorporates sub-loading and dilation enhancement concepts. Some basics components of the model are introduced below, a detailed description can be found elsewhere (Sánchez and Gai, 2016, Sánchez et al., 2017, Gai and Sánchez, 2017,).

The total volumetric strain (ε^v) accounting for both, sediment skeleton and hydrate deformations (i.e. subscript *ss* and *h*, respectively) can be calculated as:

$$\varepsilon^v = \varepsilon^v_{ss} + C_h \varepsilon^v_h \tag{1}$$

where C_h is the volumetric concentration of methane hydrate; which in turn is equal to the porosity times the hydrate saturation (i.e., $C_h = \phi S_h$). The relationships that link hydrates and soil skeleton strains are proposed following an approach similar to (Pinyol Puigmartí et al., 2007)

$$\varepsilon^v_h = \chi \varepsilon^v_{ss} ; \qquad \varepsilon^q_h = \chi \varepsilon^q_{ss} \tag{2}$$

where χ is the strain partition variable that evolves during loading.

As for the hydrates, previous studies suggested that hydrate strength enhancement can be damaged during shearing (Lin et al., 2015, Uchida et al., 2012). It is assumed that loading degradation occurs when the stress state arrives to a predefined threshold value 'r_0'. When the stresses are below a pre-established threshold, a linear elastic response of the material is assumed via the following relationships:

$$\boldsymbol{\sigma}_h = \mathbf{D}_{h0} \boldsymbol{\varepsilon}_h \tag{3}$$

where $\boldsymbol{\sigma}_h$ corresponds to the stresses taken by the hydrate and $\mathbf{D}_{h0}$ is the methane hydrate elastic constitutive matrix of the intact material. Loading damage takes place when the changes in the stress state is such that the secant elastic energy reaches r_0. In this case the damage variable L (i.e. $+\infty > L \geq 0$) increases and the stiffness reduces. The damage evolution is determined by means of the function below:

$$r_{(L)} = r_0 e^{r_1 L} \tag{4}$$

where r_1 controls the damage rate. The evolution law for the partition variable is defined by:

$$\chi = \chi_0 e^{-\frac{L}{2}} \tag{5}$$

where χ_0 is an initial reference value assumed for the partition variable.

As for the sediment skeleton, a critical state constitutive model based on a modified HISS framework was adopted. The model incorporates sub-loading concepts, as well as hardening and dilation enhancement mechanisms associated with the presence of hydrates in the sediments. The modified HISS model involves a single and continuous yield surface that can adopt different shapes depending on the selected parameters. The HISS yield surface (F) is given by:

$$F = \frac{a}{3M^2} q_{ss}{}^2 - 9\gamma \left[\left(p'_{ss}\right)^2 - \left(p'_{ss}\right)^n p_c{}^{2-n} \right] \tag{6}$$

where a and γ are model constants; n is the parameter related to the transition from compressive to dilative behavior; p_{ss}' and q_{ss} are the mean effective nd deviatoric stresses, respectively, both associated with the sediment skeleton; M is the slope of critical line in the q_{ss}-p_{ss}' space; and p_c is the effective preconsolidation pressure. The Modified Cam-Clay yield surface corresponds to a particular case of this model. The yield function incorporating the strength enhancement (p_d) associated with the presence of methane hydrate can be expressed as

$$F_b = \frac{a}{3M^2} q_{ss}{}^2 - 9\gamma \left[\left(p'_{ss}\right)^2 - \left(p'_{ss}\right)^n (p_c + p_d)^{2-n} \right] \tag{7}$$

Sub-loading concepts are incorporated in the formulation to account for any irrecoverable strain that may occur in GHBS when stresses are inside the yield surface, and also for having a smooth transition between elastic and plastic states. The three yield surfaces considered in this model are presented schematically in Figure 1.

$$F_S = \frac{a}{3M^2} q_{ss}{}^2 - 9\gamma \left[\left(p'_{ss}\right)^2 - \left(p'_{ss}\right)^n \left[R(p_c + p_d)\right]^{2-n} \right] \tag{8}$$

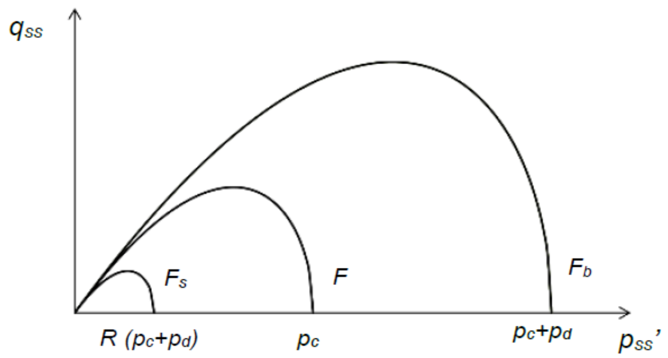

Figure 1: Yield surfaces considered in the model

The principle of virtual work was advocated to obtain the final expressions relating the external effective stress **σ**' with the total strain increment.

3 MODEL APPLICATION

The tests reported by (Hyodo et al., 2014) were selected to study the effect of hydrate saturation on the behavior of GHBS. A series of triaxial compression tests on synthetic methane hydrate soils were conducted at different (constant) hydrate saturations (S_h), namely: S_h=0; S_h=24.2%; S_h=35.1%; and S_h=53.1%. All the samples were prepared at a similar porosity (i.e. ϕ~40%). The effective confining pressure for all the tests was 5 MPa. The samples where isotropically consolidated first and then subjected to shearing. The model parameters were determined using back-analysis based on two tests, the one involving sediments without hydrates (i.e., S_h=0) and the test related to the highest hydrate saturation (i.e., S_h=53.1%). Then, this model (without modifying the parameters adopted before) was used to predict the behavior of the samples with S_h=24.2 and S_h=35.1 %. The detailed parameters adopted in the analyses can be found at Table 1 (Sánchez et al., 2017).

Table 1**:** Soil parameters adopted in the modeling of HBS.

Properties	S_h=0	S_h=24.2%	S_h=35.1%	S_h=53.1%
M	1.30	1.30	1.30	1.30
λ	0.16	0.16	0.16	0.16
κ	0.004	0.004	0.004	0.004
p_c (MPa)	10.0	10.0	10.0	10.0
a	3	3	3	3
n	1	1	1	1
γ	-1/9	-1/9	-1/9	-1/9
C_h	0	0.096	0.138	0.213
α	-	32	32	32
β	-	1.0	1.0	1.0
r_1	-	4.1	4.1	4.1
r_0	-	1e-5	1e-5	1e-5
η	42	42	42	42
χ_0	-	1	1	1
K_h (MPa)	-	9600	9600	9600
G_h (MPa)	-	4300	4300	4300

Figures 2a & b show the comparisons between experimental and model results for the different hydrate saturations in terms of deviatoric stress and volumetric strain versus axial strains. The compression behavior was dominant in all the samples, but the one with S_h=53.1% showed a dilatant response with a slight stress-softening behavior. The relatively high confining pressure at which the tests were performed (i.e. σ'_c=5 MPa) could be one reason for the predominant hardening behavior with positive volumetric strains observed in these tests. In all the tests, the initial stiffness and shear strength increase with S_h. The model was able to match very well the stress-strain curves for all the experiments under study. Quite good agreements were also observed in terms of volumetric behavior (Fig. 2b).

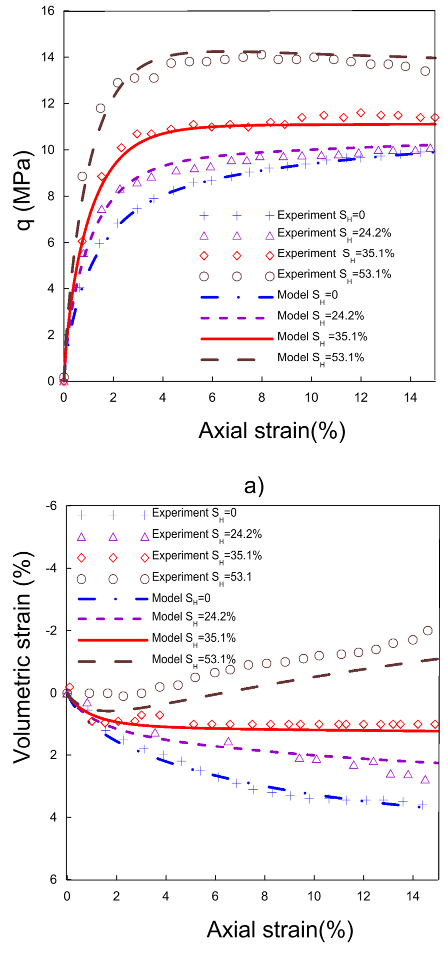

Figure 2: Comparisons between model and experimental results for synthetic samples of HBS prepared at different Sh: a) stress-strain behavior; and b) volumetric es ;(experimental data from (Hyodo et al., 2014)).

The tests conducted by Santamarina et al. (2015) were selected to study the effect of hydrate dissociation under loading conditions. Figure 3a presents the results related to specimen coded as 'core 10P', initial S_h=74%. This sample was loaded until σ'_v=3 MPa, at this normally-consolidated conditions, the effective stress was hold constant and hydrate dissociation was induced. After hydrate dissociation, the sample was loaded up to σ'_v=9 MPa and then unloaded. The model managed to capture very satisfactorily the main trends observed in this test. The yield stress and unloading-reloading behavior are quite well modeled in both specimens. It is worth to highlight the model ability to reproduce the volumetric strains observed during dissociation at constant stress in this test. Figure 3b presents the contributions of stress from hydrates and soil skeleton respectively. This information provides insight regarding how the stress is transferred between soil matrix and hydrate during loading and dissociation process which would be helpful in understanding the mechanical response of GHBS. The detailed parameters adopted in the analyses can be found at Table 2 (Sánchez et al., 2017).

Table 2. Soil parameters adopted in the modeling of HBS.

Properties	Core 7	Core 9
M	1.26	1.26
λ	0.16	0.16
κ	0.014	0.014
p_c (MPa)	12	12
a	3	3
N	0.98	0.98
γ	-0.14	-0.14
C_h (initial)	0.1675	0.311
α	6	21
β	1	1
r_1	1.1	1.3
r_0	1e-5	1.25e-4
η	3	48
χ_0	1	1
K_h (MPa)	9600	9600
G_h (MPa)	4300	4300

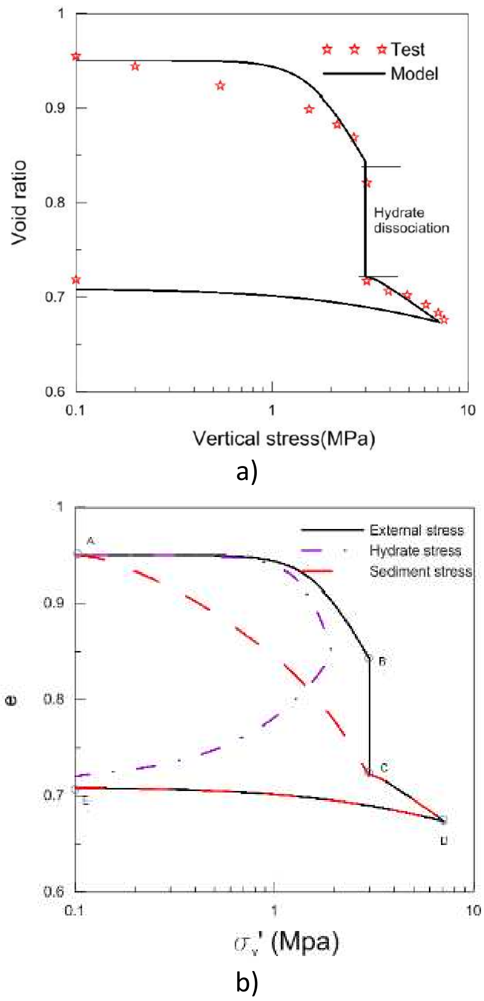

Figure 3: Behavior during dissociation of natural GHBS specimens under oedometric conditions: (experimental data from (Santamarina et al., 2015)).

4 CONCLUSIONS

A constitutive model for hydrate bearing sediments is presented in this paper. The concept of stress partition was incorporated into the model to estimate the mechanical contribution associated with hydrates and soil skeleton at different stages of loading and hydrate dissociation. Information from several mechanical tests recently published is selected to study the model's capabilities. The proposed geomechanical model can capture not only the main trends and features of sediment observed in the different tests, but also to reproduce very closely the experimental observations in these analyzed cases. A contribution of this work is the modeling of GHBS during dissociation and providing different part of the stress contribution.

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