Investigation on the bearing capacity characteristics of methane hydrate bearing sediments by FEM with a new constitutive model

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ABSTRACT: The mechanical behaviors of methane-hydrate-bearing-sediment (MHBS) exhibit greater secant stiffness, shear strength and dilatancy under shearing when comparing with soils without hydrate and the strain-softing and dilation behavior is enhanced by increasing saturation degree of methane hydrate. However, the bond weakening induced during hydrate dissociation or dissolution may lead to excessive ground settlement, which may cause serious damage to artificial structures such as the fixed offshore drilling platform anchored to the seafloor. In this paper, a novel constitutive model for MHBS is proposed and implemented in the commercial FEM software ABAQUS to analyze the influence of MH saturations on the bearing capacity characteristics of MHBS. The constitutive model adopted is based on the structured soil constitutive model and the initial yield parameter in the model is inversely proportional to MH saturations. The results show that :1) The failure mode of the foundation tends to exemplify a "punching failure" mode under high stress conditions and no obvious inflection point is observed in the p-s curve. 2) The bearing capacity of MHBS increases with increasing of MH saturations, while the effect of lateral earth pressure ratio K_0 appears to be limited.

KEYWORDS: Methane hydrate sediment; Constitutive model; Bearing capacity.

1 INTRODUCTION

Methane hydrate (MH), which is viewed as one of the most promising energy resource, has been found to exist under a condition of high pressure and low temperature.Previous researches showed that MH in the subsurface holds more than 10 trillion tons of carbon, which is twice as much as that of fossil fuel (Kvenvolden, 1999; Collett et al., 2000). MH is crystalline clathrate composed of methane and water molecules. The sediment containing MH is usually referred to as methane-hydrate-bearing sediment (MHBS) and its properties can be greatly affected by the existence of MH. For example, the strength of MHBS can be enhanced by the bonding effects of MH between particles. However, once the hydrate dissocaites, the bond weakening may change the mechanical properties of MBHS and lead to serious engineering problems, such as the reduction of the bearing capacity of pile foundations.

The general bearing capacity problems have been extensively investigated through analytical, experimental, and numerical studies(Terzaghi, 1943; Chen and McCarron, 1991; Manoharan and Dasgupta, 1995; Frydman and Burd, 1997; Lee et al., 2005). However, few researchers have made investigation on the bearing capacity relevant to the MBHS, though the bearing capacity characteristics of MHBS plays an important role in exploring the methane gas safely. This is mainly due to the special existence condition of methane hydrate, which makes it quite difficult to perform bearing capacity experiments or other laborary tests on MHBS. Finite Element Method (FEM), which has been widely employed in geotechnical community, may be an effective tool to achieve this goal, in which a proper consititive model for MHBS is necessary to provide a reliable simulation.

For this purpose, a novel constitutive model for MHBS is adopted and implemented in the commercial FEM software ABAQUS in this paper. The constitutive model adopted is developed based on the structured soil constitutive model and the initial yield parameter in the model is inversely proportional to MH saturation. The qualitative relationship between the MH saturation and the initial yield parameter is established by selecting a proper initial yield parameter, which can mimic the stress-strain relationship of MH in experimental tests well. The FEM simulated results were analyzed with emphasis on the influences of MH saturation on the bearing capacity characteristics of MHBS. The influence of lateral earth pressure ratio was also discussed.

2 CONSTITUTIVE MODEL FOR MHBS

The mechanical behaviors of the cementation-type MHBS are similar to those of structured soil because the methane hydrates can make the soil grains bonded together as well. This is confirmed by the results of drained triaxial tests on artificially-created hydrate-bearing soils (e.g., Yun et al., 2007; Miyazaki et al., 2010; Hyodo et al., 2013). So in the paper, a novel constitutive model for MHBS developed from the structured soil constitutive model was adopted. As the details of the structured soil constitutive model have been reported in the previous paper (Jiang et al., 2016), only a brief outline is given below.

The structured soil constitutive model is developed within a classical elasto-plastic framework. The yield function in the *p'*-*q* space is expressed as:

$$f = \ln(\frac{p}{\overline{p}}) + \ln[1 + \frac{q^2}{(Mp)^2}] = 0 \tag{1}$$

where q is the deviatoric stress, p is the mean effective stress, M is the slope of the critical state line in q-p space, and $\overline{p}$ is the hardening parameter. The hardening parameter controls the size of the yield surface and can be expressed as:

$$\overline{p} = \frac{p^*}{1 - \exp(-c_a \cdot \varepsilon_d^p - c_b)} \tag{2}$$

where p^* is the hardening parameter for the reconstituted soil, ε_d^p is the equivalent plastic strain defined as $\varepsilon_d^p = \sqrt{(\varepsilon_s^p)^2 + (\varepsilon_v^p)^2}$, in which ε_s^p and ε_v^p are plastic shear strain and plastic volumetric strain, respectively; c_a characterizes the bond breakage ratio , and c_b is the initial yield parameter which describes the degree of initial structure.

Based on the work by Li and Dafalias (2000) and Yao et al. (2008), the hardening parameter p^* is defined as follows:

$$p^* = p_0 \exp(\frac{1}{C_p}\frac{M_d^2-\eta^2}{M_d^2-\eta^2}\varepsilon_v^p) \quad (3)$$

where p_0 is the initial mean effective stress, η is the current stress ratio, $C_P=(\lambda-\kappa)/(1+e_0)$, in which λ and κ are the slopes of the isotropic normal compression line and swelling line of reconstituted soil, respectively; e_0 is the void ratio corresponding to p=1kPa, $M_d = Me^{m\psi}$ and $M_b = Me^{-m\psi}$ are the dilatancy and peak stress ratios, respectively, in which m and n are two model parameters, and ψ is the state parameter defined as $\psi = e_0 - (\lambda-\kappa)ln2 - \lambda lnp$.

Based on the work by Li and Dafalias (2000), the dilatancy relation is expressed as follows:

$$d = \frac{d\varepsilon_v^p}{d\varepsilon_s^p} = \frac{M_d^2-\eta^2}{2\eta} \quad (4)$$

The plastic potential function g can be obtained by integrating equation (4):

$$g = p(1+\frac{q^2}{M_d^2 p^2}) \quad (5)$$

Based on the structured soil constitutive model presented above, the constitutive model for the MHBS can be developed by establishing a qualitative relationship between the MH saturation and the initial yield parameter through adjusting the initial yield parameter till a consistency of simulated stress-strain relationship and that of experiments can be obtained. The relationship can be expressed as the following form:

$$c_b = a\exp(-bS_r^{MH}) \quad (6)$$

where a and b are two fitting parameters, and S_r^{MH} is the methane hydrate saturation.

The experimental results used for the constitutive model parameters calibration came from the drained triaxial tests for MHBS conducted by Masui et al. (2008). The initial conditions and model parameters used in this paper are listed in Table 1.The two fitting parameters, a and b in Eq. (6), are chosen to be 4 and -5.53, respectively. More details for the model validation can be found in Jiang et al. (2017).

Figure 1 shows the comparison of variation of friction angle and cohesion with hydrate saturation between the laboratory tests and FEM simulations for MHBS. The model predicts a result close to the experimental data. In both experimental and numerical cases, the internal friction angle is insensitive to the hydrate saturation, while the cohesion has a considerable increase due to the presence of methane hydrate.

Table 1. Selected physical parameters for MHBS

λ		0.1357
κ		0.01
M		1.5
v		0.3
m		1
n		1
e_0		1.79
c_a		2
c_b	S_r^{MH}=0%	4
	S_r^{MH}=25.7%	0.9808
	S_r^{MH}=35.4%	0.6061
	S_r^{MH}=40.7%	0.539
	S_r^{MH}=55.1%	0.28768

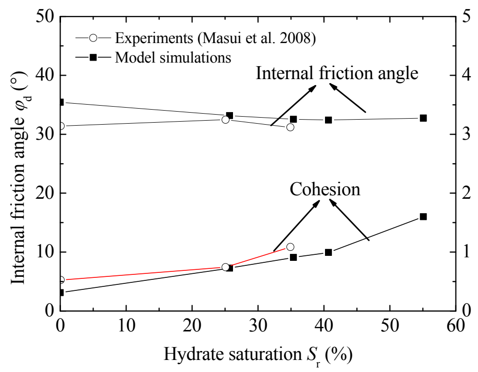

Figure 1. Variation of friction angle and cohesion with S_r^{MH}

3 FEM MODEL

The bearing capacity analyses were carried out using the commercial FEM software ABAQUS. The constitutive model for MHBS was implemented in ABAQUS with UMAT subroutine. MHBS simulated was under plane strain condition. The footing load, which was assumed vertical and central without any rotation, was applied on a rigid footing with a rough base. In ABAQUS, this rough base condition can be realized by applying incremental vertical velocities and zero lateral velocities of the nodal points, which were in contact with the footing base. The overlaying soil above the MHBS was assumed to be 50 m depth and its buoyant gravity density was chosen to be 10 kN/m^3. So the overburden pressure p_0 was approximately equal to 0.5 MPa.

The FEM mesh and boundary conditions used in the analyses are shown in Figure 2. Because of the symmetric geometry of the model, only a half domain of the model was analyzed for simplicity. The MHBS ground was discretized into the four-node quadrilateral axial-symmetric elements (CAX4) and the mesh size was finer near the footing edge. The total number of elements is 2500.

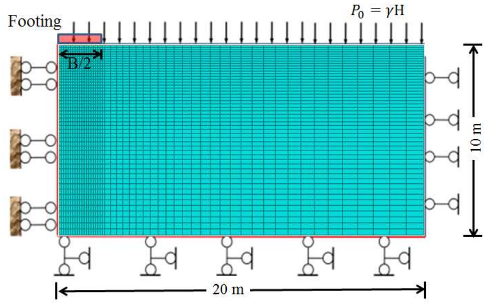

Figure 2. FEM mesh and boundary conditions

Table 2. Summary of the test program

Tests	S_r^{MH}	K_0	B (m)
1	0%	1	2
2	25.7%	1	2
3	35.4%	1	2
4	40.7%	1	2
5	55.1%	1	2
6	55.1%	1	4
7	55.1%	0.9	4
8	55.1%	0.8	4
9	55.1%	0.7	4
10	55.1%	0.6	4
11	55.1%	0.5	4

In this paper, the effects of methane hydrate saturation and the lateral earth pressure ratio K0 on the bearing capacity were mainly investigated. The conditions of simulation tests are summarized in Table 2.

4 SIMULATION RESULTS

4.1 *Effects of hydrate saturation*

Figure 3 shows the relationships between the average footing pressure p and the relative settlement of footing S/B with different hydrate saturation. The average footing pressure $p=p_s-p_0$. p_s was obtained by dividing the sum of the vertical forces at the Gauss points in the soil elements beneath the footing base by half of the width of the footing. p_0 refers to the initial overburden pressure. As shown in Figure 3, all the load–displacement curves with different hydrate saturation show no obvious inflection points, which indicate a punching failure type. It may due to the large buried depth of MHBS. The results also show a general increasing tendency in the bearing capacity with the increasing hydrate saturation.

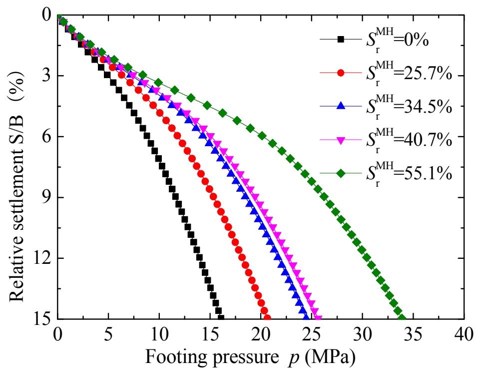

Figure 3. Load-settlement curves with different hydrate saturation S_r^{MH}

In order to quantitatively study the influence of hydrate saturation on the load capability, a strengthened coefficient F_{OS} is defined as:

$$F_{OS} = \frac{p_r}{p_{3\%}} \tag{5}$$

where p_r is the normalized footing pressure when the relative settlement equal to r (3%, 6%, 9%, 12%, 15%) and $p_{3\%}$ refers to the normalized footing pressure when the relative settlement equal to 3% with the hydrate saturation is 0%.

As shown in Figure 4, the methane hydrate saturation can significantly influence the bearing capacity, especially when the S/B is large. The relationship between F_{OS} and hydrate saturation changes from a linear one to a nonlinear one as the S/B increases. The nonlinear relationship is quite similar to the relationship between the cohesion and hydrate saturation. As the internal friction angle is independent of hydrate saturation, the hydrate contribution to the bearing capacity of MHBS is of a cohesive nature, rather than a frictional natural.

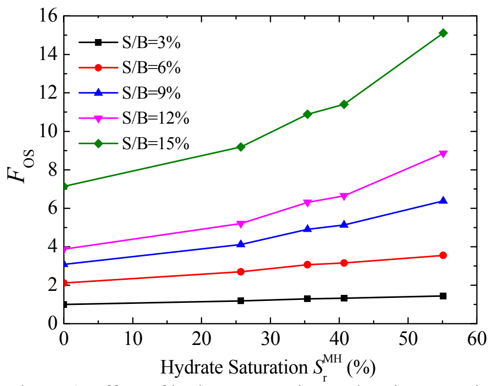

Figure 4. Effect of hydrate saturation on bearing capacity

4.2 *Effects of lateral earth pressure ratio*

Figure 5 and Figure 6 show the effects of lateral pressure ratio K_0 on the bearing capacity characteristics of methane hydrate bearing sediments. The results show that the bearing capacity increases with increasing K_0. The relationship between F_{OS} and K_0 is approximately linear at a given *S*/*B*. However the effects of K_0 appear to be limited. Because when S/B=15%, the F_{OS} in the initial condition of K_0=1 increases by approximately 9% compared with the initial condition of K_0=0.5. Similar simulation results can also been found in Lee et al. (2013).

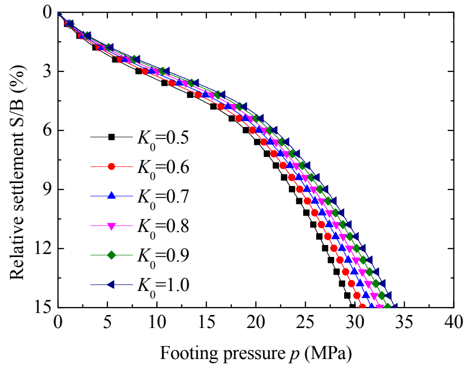

Figure 5. Load-settlement curves with different lateral pressure ratio K_0

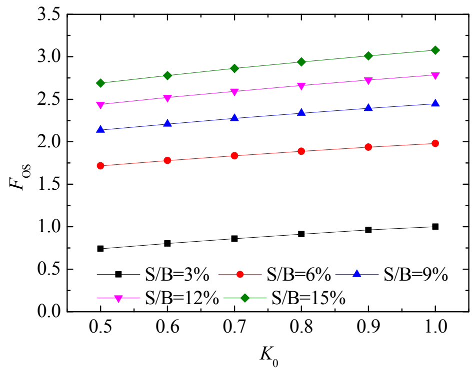

Figure 6. Effect of lateral earth pressure ratio K_0 on bearing capacity

5 CONCLUSION

The study on the bearing capacity characteristics of methane hydrate bearing sediments is of great significance for the safe exploration of methane gas. For this purpose, FEM simulations were carried out with a novel constitutive model for MHBS, which is developed from the structured soil constitutive model by establishing a qualitative relationship between the MH saturation and the initial yield parameter. The effects of methane hydrate and lateral pressure ratio on the bearing capacity were mainly investigated. The following conclusions can be made:

(1) The failure mode of the foundation tends to exemplify a "punching failure" mode under high stress conditions.

(2) The bearing capacity of MHBS increases with increasing hydrate saturation and the hydrate contribution to the bearing capacity is of a cohesive nature, rather than a frictional nature.

(3) The bearing capacity of MHBS increases with increasing of lateral pressure ratio, while the effects of lateral earth pressure ratio K0 appear to be limited.

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