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Investigation into the effect of backpressure on the mechanical behavior of methane-hydrate-bearing sediments via DEM analyses

MINGJING JIANG ⁱ⁾, FANGYUAN ZHU ⁱⁱ⁾, STEFANO UTILI ⁱⁱⁱ⁾

i) Professor, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China; Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai, China; Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 200092, China (mingjing.jiang@tongji.edu.cn)

ii) Former Graduate student, Department of Geotechnical Engineering, Tongji University, Shanghai, China (fangyuan623@sina.com)

iii) Associate Professor, Department of Engineering, University of Warwick, Coventry, UK (S.utili@warwick.ac.uk)

Corresponding author:

Dr. Mingjing Jiang,

Professor of Geotechnical Engineering,

Professor of Exceptional Rank of Tongji University,

Department of Geotechnical Engineering, College of Civil Engineering

Tongji University, Shanghai, 200092, China.

E-mail: mingjing.jiang@tongji.edu.cn; Tel: +0086-21-65980238

Abstract:

Backpressure has been extensively applied in experimental tests to improve the water saturation of samples, and its effect on the strength of saturated soils has been traditionally regarded as trivial in Soil Mechanics. However, a non-negligible influence of backpressure on the macro mechanical properties of methane-hydrate-bearing-sediments (MHBS) has been surprisingly observed in several recent experiments reported in the literature. This paper aims to shed light on this phenomenon. A theoretical analysis on the microscopic interaction between soil grains and inter-particle methane hydrate (MH) was carried out to highlight how backpressure affects the mechanical properties of the inter-particle MH which in turn affect the macroscopic mechanical behavior of MHBS. The influence of backpressure is accounted for in a new bond contact model implemented into the Distinct Element Method (DEM). Then, a series of DEM biaxial compression tests were run to investigate the link between mechanical properties of MHBS and backpressure. The DEM numerical results show that shear strength, small strain stiffness and shear dilation of MHBS increase with the level of backpressure. As the critical state is approached, the influence of backpressure ceases. Moreover, the elastic modulus and cohesion of MHBS increase linearly while the internal friction angle decreases at a decreasing rate as the backpressure increases. Simple analytical relationships were achieved so that the effect of backpressure on the mechanical properties of MHBS can be accounted in the design of laboratory tests to characterize the mechanical behavior of MHBS.

Keywords:

Backpressure, macro mechanical properties, methane hydrate, methane hydrate bearing sediments;

1 Introduction

Gas hydrates are ice-like solids composed of water and gas, in which the gas molecules, mainly methane, are trapped within a lattice formed by water molecules [1,2,3]. Hydrates, especially methane hydrates (MHs), have attracted increasing global interest in the past two decades due to their potential use as a future energy resource [4-9]. They are highly concentrated: for instance one cubic foot of hydrate normally produces 150-170 cubic feet of natural gas when dissociated [5,10]. It is estimated that the amount of gas in hydrate reservoirs worldwide exceeds the volume of known conventional gas resources [4,11]. Besides, the estimated amount of organic carbon in hydrates is twice as much as that in all conventional fossil fuel resources, including natural gas, coal and oil [12].

MHs are widely found in marine continental margin sediments and permafrost regions where temperature and pressure conditions are appropriate for the stability of MHs [13,14]. In particular, over 90% of natural MHs are found in marine sediments [1]. It has been observed that the presence of MHs changes the mechanical behavior of the bearing sediments, for instance by greatly enhancing the strength of the host sediments [15-17], especially when the MH content is high. However, MHs may dissociate as a result of changes of temperature/pressure conditions, or human interventions (e.g., installation of platforms, cables or pipelines), which in turn may change the microstructure of methane-hydrate-bearing sediments (MHBS) and deteriorate their mechanical properties. This may then compromise the stability of wellbores, pipelines, rig supports and other equipment involved in oil and gas production and in the worst case scenario lead to submarine landslides [10,18]. In order to investigate the triggering mechanisms of these geo-hazards and to establish suitable macroscopic constitutive models to solve boundary-value problems related to the production of MH from MHBS (e.g., potential instability of the walls of the drilling wells), a comprehensive investigation is needed to understand the fundamental mechanical properties of MHBS.

To date, various geo-laboratory tests have been performed on artificial or natural MHBS samples to investigate their mechanical behavior. To replicate the pore-water pressure condition beneath the ocean floor and to stabilize MHs in the soils, MHBS samples are usually tested with some backpressure applied. The effect of backpressure is often neglected since, according to the principle of effective stresses [19], it is the effective confining pressure that controls the mechanical behavior of MHBS. However, experimental results recently obtained by Miyazaki et al. [20] and Hyodo et al. [21] surprisingly indicate that backpressure does influence the mechanical properties of MHBS, e.g., shear strength and stiffness of MHBS increase with the level of backpressure. The mechanisms at the root of this phenomenon remain largely unknown. It is authors' opinion that the root causes of the backpressure-dependent mechanical behavior of MHBS manifested at the macroscopic scale have to be sought in the interaction between MHs and soil grains at the microscopic scale. To this end, the paper aims to investigate this interaction by performing a campaign of biaxial tests via the Distinct Element Method (DEM). The choice of the DEM is supported by the fact that biaxial DEM tests have already demonstrated to be successful at establishing quantitative correlations between bond properties and the mechanical behaviour observed at the macroscopic scale for other bonded granulates [22-25].

Although experimental tests performed for different values of backpressure are reported in the literature (e.g., backpressures of 5MPa, 10MPa and 15MPa in [26-28]; backpressures of 6MPa, 7MPa, 8MPa and 8.5MPa in [20]; a backpressure of 8MPa in [28], backpressures of 15MPa and 20MPa in [29]), no systematic study, to the best of authors' knowledge, has been carried out until now. So the campaign of tests here reported is the first systematic investigation into the effect of backpressure on the mechanical behavior of MHBS.

The paper has the following structure. Firstly, the available experimental evidence about the influence of backpressure on the mechanical properties of MHBS, [20,21], is briefly recalled. Secondly, a bond contact model capturing the interaction between

soil particles and MH bonds under different levels of backpressure is introduced, [30].
Thirdly, the results obtained via DEM biaxial tests performed for various levels of
backpressure are illustrated. The numerical results are compared with experimental
tests to assess the predictive capability of the DEM. The influence of backpressure on
the macroscopic mechanical properties of MHBS in terms of elastic modulus,
apparent cohesion and internal friction angle, and their dependency on the level of
MH saturation and on the effective confining pressure is also investigated.

2 Backpressure-dependent behavior of MHBS

In geotechnical laboratory tests, backpressure is widely used to fully saturate soil
samples [31-37]: the samples are saturated by increasing at the same time the internal
pore-water pressure, σ_w (also called backpressure), and the cell pressure, σ_3 , of the
same amount. According to the principle of effective stresses [19], the amount of
backpressure should not affect the mechanical behavior of fully saturated samples.
However, several recent experiments [20,21] unequivocally point to a non negligible
influence of the applied backpressure on the mechanical properties of MHBS. For
instance, tests reported by Miyazaki and Hyodo (see Figure 1) run for various levels
of backpressures with all the other variables (e.g., effective confining pressure, void
ratio, and temperature) being constant except for a small variation of MH saturation,
show that both the peak deviator stress and the secant elastic modulus of MHBS
increase for increasing backpressure. The small variation of MH saturation, S_{MH} ,
between the tested samples is unavoidable due to the current experimental limitations
in controlling the amount of MH flowing into the samples. However, the influence of
backpressure is evident observing that (see Fig 1a) samples with lower MH saturation
($S_{MH}=17\%$) subject to a higher backpressure ($\sigma_w = 8$ MPa) exhibit a higher shear
strength than samples with higher saturation ($S_{MH}=19\%$) subject to a lower
backpressure ($\sigma_w = 6$ MPa) .

Several authors showed that MH plays an important role in the mechanical behavior of MHBS [14,17,39,40], e.g., they tend to increase strength, stiffness, strain softening and shear dilation of the host sand. MHs are found in the pores of MH bearing sediments. Brugada et al. [14] and Waite et al. [17] identified three main formation habits at the pore scale, plotted in Figure 2: (1) pore-filling, with methane hydrates floating in the pore fluid without bridging any particles; (2) load-bearing, with hydrate particles being part of the strong force chains of the granular assembly; and (3) cementation, with methane hydrates cementing sand grains (acting as bridges between grains). As suggested by Waite et al. [41] and confirmed by experimental data from different sources [42,43], the bulk properties of MH bearing sediments strongly depend on the formation habits of the hydrates. For instance, hydrates acting as cementation agents at inter-particle contacts cause a larger increase in strength and stiffness than pore-filling hydrates. This implies that hydrate morphology has to be accounted for into any realistic constitutive model. In this respect, only an investigation at the scale of the pores can shed light on the link between pore habit and macroscopic properties [44]. Brugada et al. [14] made the first attempt to simulate the pore-filling habit by 3D DEM simulations. In their simulations, soil grains and MH particles get into contact and exchange forces, however without exhibiting any cementation at contacts. Jung et al. [40] improved previous numerical research work by characterizing the mechanical behaviour of MHBS for two cases of hydrate pore habits: distributed hydrates and patchy saturation. In this paper instead, habit 3 is considered (see Figure 2). This habit is of common occurrence especially in unconsolidated sediments containing an abundant gas phase: for instance significant deposits of cementing MHs have been discovered in the Blake Ridge, off the southeast coast of the United States [45] and in the Cascadia margin [46]. In this habit, hydrates form mainly at grain contacts generating interparticle bonds [41]. With regard to laboratory tests, this habit is induced by percolating methane gas through samples of sands partially saturated with water in the pendular regime. The formation of MH generates the onset of bonds between nearby sand grains whose stiffness remains unchanged since the grains are not coated by the hydrate. [21-23,30,39,41,47]

showed that this pore habit plays an important role in the macro-mechanical behaviors of MHBS and contributes substantially to the bulk properties of MHBS. For instance in case of a MH saturation of 50%, the strength of the MHBS can be twice as much as that of the host sand [20-24].

Figure 3 presents a schematic view of a pair of soil grains immersed in water and cemented by a MH inter-particle bond. MH can be envisaged as a solid block surrounded by water at a pressure equal to the backpressure acting on the MHBS sample. For the range of water backpressure employed in the experiments of [20] and [21], the sand grains can be assumed unbreakable and of negligible deformability. MHs instead are crystalline compounds whose deformability and strength are affected by the level of surrounding pressure. In fact, tests on blocks of pure solid MH, i.e., without sand grains [42,48-52], show that both the strength and elastic modulus of MHs increase with the level of surrounding pressure. In the next section, the bond contact model incorporating the main mechanical features of the MH bonds and employed in all the DEM biaxial tests presented in the paper, is illustrated.

3 MH bond contact model incorporating the effect of backpressure

The bond model for MH cementing pairs of sand grains was first formulated in Jiang et al. [30]. The contact law here employed for the bond, experimentally derived in [53,54], is presented in Figure 4. The mechanical response of the bond is featured by elastic behavior until breakage followed by brittle failure. For an intact bond, the normal force F_n , the shear force F_s , and the moment M are computed, respectively, by:

$$F_n = K_n(u_n - u_0) \quad (1a)$$

$$F_s \leftarrow K_s \Delta u_s + F_s \quad (1b)$$

$$M \leftarrow K_r \Delta \theta + M \quad (1c)$$

where u_n is the overlap of two particles; Δu_s and $\Delta \theta$ are the increments of relative shear displacement and relative rotation angle, respectively; u_0 is the initial overlap

between two adjacent particles, indicating the distance between the two particles at the time of formation of the MH bond. K_n , K_s and K_r in Equation (1) are the normal, tangential and rolling bond contact stiffnesses, respectively. They are given by:

$$K_n = \frac{BE_{MH}}{t} \quad (2a)$$

$$K_s = \frac{2}{3} K_n \quad (2b)$$

$$K_r = \frac{1}{12} K_n B^2 \quad (2c)$$

where E_{MH} is the Young's modulus of MH; t is the average thickness of the MH bond defined as the area of MH bond divided by its width. The bond width, B (see Figure 3), was prescribed for all bonds as a fraction of the equivalent radius of the two bonded particles, $\bar{R} = 2R_1R_2 / (R_1 + R_2)$, so that $B = \beta\bar{R}$.

Contact interaction between non-bonded particles (e.g. contacts formed by particles moving around after their MH bonds have broken) is linearly elastic – perfectly plastic, i.e. linear springs in both normal and tangential directions plus a frictional slider in the tangential direction only (see [30, 55]).

With regard to the strength of the bonds, in Figure 5 the bond strength envelope employed in the DEM simulations is plotted in the F_s - M - F_n space. The strength of a bond subject to pure tensile, compressive, shear or rolling actions is denoted by R_{tb} , R_{cb} , R_{sb} and R_{rb} respectively. The strength envelope in the F_s - M plane assumes an elliptical shape:

$$\frac{M^2}{R_{rb0}^2} + \frac{F_s^2}{R_{sb0}^2} = 1 \quad (3)$$

with R_{sb0} being the tangential strength of the bonds in the absence of any moment, and R_{rb0} the rolling strength in the absence of any shear force. R_{sb0} and R_{rb0} are both a function of the applied normal force F_n and of the tensile and compressive bond strengths, R_{tb} and R_{sb} , respectively. They were determined on the basis of the

experimental data available on bonding MH [20,21] according to the procedure outlined in [53]:

$$R_{sb0} = 1.38 \cdot 0.38 \cdot (F_n + R_{tb}) \cdot \left(\ln \frac{R_{cb} + R_{tb}}{F_n + R_{tb}} \right)^{0.59} \quad (4a)$$

$$R_{rb0} = 1.366 \cdot 0.741 \cdot (F_n + R_{tb}) \cdot \left(\ln \frac{R_{cb} + R_{tb}}{F_n + R_{tb}} \right)^{0.59} \quad (4b)$$

$$R_{tb} = B \times \sigma_{tMH} \quad (4c)$$

$$R_{cb} = B \times \sigma_{cMH} \quad (4d)$$

where σ_{tMH} and σ_{cMH} are the tensile and compressive strengths of pure MH, respectively. The Young's modulus and the tensile and compressive strengths of MH are a function of pore-water pressure temperature and MH density. Tests performed on pure MH samples [30] provide the following expressions:

$$\frac{E_{MH}}{p_a} = 3 \left(\frac{\sigma_w}{p_a} \right) - 1.98 \left(\frac{T}{T_0} \right) + 4950.50 \left(\frac{\rho}{\rho_w} \right) - 1821.78, \quad (5a)$$

$$\frac{\sigma_{cMH}}{p_a} = 0.81 \left(\frac{\sigma_w}{p_a} \right) - 2.08 \left(\frac{T}{T_0} \right) + 184.16 \left(\frac{\rho}{\rho_w} \right) - 134.65, \quad (5b)$$

$$\frac{\sigma_{tMH}}{p_a} = 0.45 \left(\frac{\sigma_w}{p_a} \right) - 1.15 \left(\frac{T}{T_0} \right) + 101.75 \left(\frac{\rho}{\rho_w} \right) - 74.39, \quad (5c)$$

where $\sigma_w = \gamma_w h$ as shown in Figure 5, with h being the depth of the water table; T the ambient temperature; ρ the MH density; p_a the standard atmospheric pressure ($1.01 \times 10^5 \text{ Pa}$); T_0 a reference temperature of 1°C and ρ_w the density of water at 4°C .

Concerning the level of MH saturation, it is convenient to introduce a dimensionless parameter S_{MH} , expressing the ratio of the methane hydrate area, A_{MH} , over the total void area, A_V , *i.e.*, $S_{MH} = A_{MH} / A_V$. This parameter is a 2D measure of the level of MH saturation equivalent to the 3D ratio of methane volume over the

void volume. S_{MH} can be calculated from the geometry of all the bonds in the sample (see [30]) according to the following formula:

$$S_{MH} = \frac{A_b}{A_v} + S_{MH_0} = \frac{(1+e_p)}{e_p A} \sum_{i=1}^m A_{b,i} + S_{MH_0}$$

$$= \frac{(1+e_p)}{e_p A} \sum_{i=1}^m \bar{R}_i^2 \left[2\beta - \beta \sqrt{1 - \frac{\beta^2}{4}} - 2 \arcsin\left(\frac{\beta}{2}\right) + \frac{t_{0,i} \beta}{\bar{R}_i} \right] + S_{MH_0} \quad (6)$$

where A is the total area of the sample, e_p the sample planar void ratio, m the total number of MH bonds in the sample, $A_{b,i}$ the area of each bond, $t_{0,i}$ the minimum thickness of each bond (see Figure 3) and $\bar{R}_i$ the equivalent radius for each bonded pair of particles (the width of each bond being $B_i = \beta \bar{R}_i$). In Equation (6), S_{MH_0} is the threshold value of hydrate saturation at which methane hydrates start to bond sand grains which in turn is a function of the hydrate growth history. In [30] an in-depth explanation of Eq (6) is provided.

The input parameters of the adopted bond model are four (listed in Table 1): the pore-water pressure surrounding the bond, σ_w , temperature, T , the density of MH, ρ , and the bond width parameter β . However, for the range of backpressures considered in this study (5~20MPa), the maximum possible variation of MH density is only 0.02g/cm³ [59], hence a constant MH density of 0.9 g/cm³ was assumed in all DEM simulations. Then, the Young's modulus (E_{MH}), tensile strength (σ_{tMH}) and compressive strength (σ_{cMH}) of the bonds can be obtained via Equations (5). Finally, the stiffness (i.e., K_n , K_s , K_r) and strength parameters (i.e., R_{tb} , R_{cb} , R_{sb0} and R_{rb0}) of the bonds can be calculated via Equations (2) and (4), respectively. It is important to note that the density of MH is affected by the amount of backpressure applied.

4 DEM tests on MHBS

The presented bond contact model was implemented into a C++ subroutine and run

in the PFC-2D code [56].

4.1 Simulation procedure

In the DEM numerical tests, we set out to mimic the methane hydrate generation process as reported in the experimental tests of [21] (see Figure 1). In their tests, first, methane gas was pumped into the host specimens to form MHs under a backpressure of 4MPa, 1°C temperature and an effective confining pressure of 0.2MPa. After the generation of MHs was completed, water was injected to fully saturate the samples and backpressure was increased to the prescribed value of interest. Then, the samples were consolidated under the prescribed confining pressure with both backpressure and temperature kept constant. Finally, the samples were sheared in drained conditions at a strain rate of 0.1%/min and constant backpressure and temperature.

To mimic these experiments in the DEM, first homogenous samples without any cementation were generated via the ‘multi-layer under-compaction method’ [56], then they were isotropically consolidated to an effective confining pressure of 0.2 MPa. Second, bonds of various thicknesses were activated between pairs of adjacent particles either in contact or having a distance between their edges of less than a prescribed threshold and the bond parameters being chosen to reflect the presence of 4 MPa of backpressure at 1°C. Then, the bond parameters were changed to reflect the application of various levels of backpressure (*i.e.* 5MPa, 10MPa, 15MPa or 20MPa), which remained constant during the subsequent part of the tests. Thereafter, the effective confining pressure of the samples was gradually increased to a prescribed value (isotropic consolidation). Lastly, the samples were axially loaded by moving the top and bottom platens at a constant strain rate of 5%/min maintaining the backpressure constant.

4.2 Sample parameters

Figure 6 presents the grain size distribution of Toyoura sand employed by Hyodo et al. [21] and the distribution employed in our DEM simulations. The DEM material is made up of disks of 10 diameter sizes ranging from 6.0mm to 9.0mm. The median diameter, d_{50} , is 7.6 mm, with the uniformity coefficient of the particle size distribution being 1.3. The particle size distribution of the DEM material is obtained by an almost uniform upscale of the experimental particle size distribution. Particle scaling is necessary to perform the simulations within an affordable runtime. Table 2 lists the values of the DEM parameters used in the simulations. In Figure 7, a DEM MHBS sample is plotted before compression is applied. It can be observed that the initial MH bonds (plotted as black solid lines in the figure), are homogenously distributed in the sample.

Close examination of SEM images of MHBS samples shows that MH bonds are limited in size, i.e., they are formed only between particles lying within a certain distance (t_0^{th}) whose value depends on various factors, e.g. relative density of the granular sample, level of MH saturation, etc. According to the experimental observations available [30], this distance was assumed as 5% of the median particle diameter, i.e. $t_0^{th}/d_{50}=0.05$. The relationship between β and $S_{MH} - S_{MH_0}$ obtained from Eq (6) for $S_{MH_0}=20\%$ (value taken according to [43, 58]) and an initial planar void ratio, e_p , of 0.25 is plotted in Figure 8. The value of β employed in each DEM test to reproduce a prescribed S_{MH} , was selected using the relationship in Figure 8.

5 DEM numerical results

5.1 Stress-strain relationships obtained at different backpressures

In the description of the state of stress, the following 2D invariant variables have been used: $s = (\sigma_y + \sigma_x) / 2$ (mean effective pressure) and $t = (\sigma_y - \sigma_x) / 2$ (deviator stress).

In Figure 9 both the stress-strain and volumetric behaviors of MHBS from experimental triaxial tests of Hyodo et al. [21] and our DEM simulations are plotted.

In the figure, positive and negative values of volumetric strain means dilation and contraction, respectively. For each case, results for two different levels of backpressure (5MPa and 10MPa) are presented. It can be observed that although the numerical results do not quantitatively reproduce the experimental data, they capture the essential features of the observed influence of backpressure on the stress-strain response of the MHBS. These features can be listed as follows: 1) the peak deviator stress manifested for a backpressure of 10MPa is higher than the peak deviator stress manifested for 5MPa of backpressure although the MH saturation in the former test is (slightly) lower than in the latter one; 2) the initial slope of the stress-strain relationship for the test run at 10MPa of backpressure is higher than the test run at 5MPa; 3) the difference between the deviator stress of the two samples (5MPa and 10MPa backpressure) becomes much smaller at large strains; (4) shear dilation increases with the level of backpressure.

To explain these findings, the stress-strain and the volumetric responses obtained from DEM biaxial tests run for various level of confinement (σ_3') and backpressures (σ_w) are plotted in Figure 10. It emerges that the peak deviator stress increases for increasing levels of backpressure; however the deviator stress at large axial strains tend to reach a unique value independently of the level of backpressure applied. So the influence of backpressure on the stress-strain response of MHBS at large strains is much less significant than at small strains. This is in agreement with the available experimental data (see Figure 9b).

In order to investigate the mechanisms taking place at the microscale responsible for the influence of back-pressure on the observed MHBS mechanical response, we examined the pattern of bond breakages and the distribution of contact force chains throughout the tests. In Figure 11 the percentage of intact MH bonds is plotted against the applied axial strain. Obviously the percentage of MH bonds decreases as the axial strain increases. It is evident that the percent of intact MH bonds at large strains (e.g., 15%) is heavily affected by the level of applied backpressure: the higher the level of

backpressure, the larger the number of intact bonds. This result appears to be at odds with the observation that the deviator stresses relative to these tests are very close at large strains (see Figure 10). The distribution of the intact MH bonds in the sample holds the key to unveil this apparent contradiction. The intact bonds of a sample subject to a large level of backpressure and a sample subject to a small level, 20MPa and 5MPa respectively, are plotted in Figure 12. It can be observed that in the case of large backpressure (20MPa) most bonds are broken and the intact ones are roughly uniformly distributed. Instead in case of low backpressure (5MPa), most bonds are still intact but their distribution in the sample is highly inhomogeneous. In particular a diagonal narrow band with only a few disconnected MH bonds appears running from the upper to the bottom boundary of the sample. This band forms a weak zone which determines the maximum vertical stress that the sample can sustain. This is confirmed by observing that the contact force chains in the weak zone of the sample subject to low backpressure are significantly thinner than in the other zones of the sample (see Figure 12). In the two samples the maximum stress that can be sustained is similar since in both cases it is governed by zones where there are no networks of interconnected bonds. These observations at the microscale explain why the deviator stresses of the two samples at large strains are close to each other and to the value observed for samples without any MH bond.

So it can be concluded that the peak deviator stress in MHBS samples increases with the level of backpressure due to the fact that larger applied backpressures increase the strength of MH bonds; however, this strength increment progressively reduces with the progression of sample shearing which causes more and more bonds to break until a full diagonal band of broken bonds running from the upper to the bottom boundaries of the sample is formed. This band rules the maximum vertical stress that can be sustained by the sample so that the deviator stress tends to reach a unique value at large strains independent of the level of backpressure applied.

5.2 Effect of backpressure on the mechanical properties of MHBS

In Figure 13 the secant elastic modulus calculated at 50% of the measured deviator stress (E_{50}) is plotted against the level of backpressure applied for tests run at various levels of MH saturations and effective confinement. From the figure emerges that the elastic modulus increases almost linearly with the level of backpressure σ_w whatever the value of effective confining pressure, σ_3' , and MH saturation, S_{MH} , are. Also it can be observed that the elastic modulus is higher at larger effective confinement (σ_3') and MH saturation (S_{MH}) as can be expected. So the elastic modulus of MHBS can be determined as a function of σ_w , σ_3' and S_{MH} :

$$E_{50} = E(\sigma_w, \sigma_3', S_{MH}) \quad (7)$$

For sake of generality, it is convenient to use an expression for Eq. (7) in dimensionless form:

$$\frac{E_{50}}{p_a} = A_1 \frac{\sigma_3'}{p_a} + (A_2 \frac{\sigma_w}{p_a} + A_3) \cdot (S_{MH} - S_{MH0})^{A_4} \quad (8)$$

with $A_1, A_2, \dots A_4$ being constant values to be determined by biaxial tests. In our case, the constants assume the following values: $A_1=6.46$, $A_2=1.36$, $A_3=1470$, and $A_4 = 0.30$. The curves obtained according to Eq. (8) were reported in Figure 13 as well: it is apparent that they well interpolate the data. In the figure a vertical dash line signals the critical pressure for the dissociation of MH at 1 °C, $\sigma_{w(cr)}=2.9$ MPa, [60]. Since MH cannot exist at a backpressure lower than the critical pressure, Equation (8) no longer applies for $\sigma_w < \sigma_{w(cr)}$.

The peaks of the deviator stress obtained from all the tests performed are plotted in the $t-s$ plane (see Figure 14) together with their linear interpolations. The slope and the intercept of the linear interpolations provide the internal friction angle (ϕ) and the apparent cohesion (c) of the MHBS. From the figure it emerges that ϕ and c depend on both backpressure and MH saturation:

$$c = c(\sigma_w, S_{MH}) \quad (9a)$$

$$\phi = \phi(\sigma_w, S_{MH}) \quad (9b)$$

The values of apparent cohesion were plotted against backpressure in Figure 15. It emerges that c increases almost linearly with the level of backpressure and the slope of the line is dictated by the level of MH saturation. Therefore a convenient dimensionless expression for Equation (9a) is:

$$\frac{c}{p_a} = (B_1 \frac{\sigma_w}{p_a} + B_2) \cdot (S_{MH} - S_{MH0})^{B_3} \quad (10a)$$

with $B_1, \dots B_3$ being constant values. In our case $B_1=0.115$, $B_2=-0.10$ and $B_3=0.43$.

The lines obtained according to Eq. (10a) were reported in Figure 15: it is apparent they interpolate the data very well.

The relationship between internal friction angle and backpressure obtained from the DEM tests (Eq (9b)) is plotted in Figure 16. It can be observed that the internal friction angle decreases with the level of backpressure and the rate of decrease is roughly insensitive to the amount of MH saturation applied. Hence, a suitable expression for Equation (9b) is:

$$\phi = C_0 - C_1 \left(\frac{\sigma_w}{p_a} \right)^{C_2}, \quad (10b)$$

with $C_0, \dots C_2$ being constant values that in our case are: $C_0 = 23.2^\circ$, $C_1 = -0.14$ and $C_2 = 0.72$. The linear relationship obtained on the basis of Equation (10b) is reported in Figure 16 (solid black line).

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364 5.3 Other factors affecting the mechanical properties of MHBS

In addition to backpressure, both surrounding temperature and the density of inter-particle methane hydrate influence deformability and strength of the inter-particle methane hydrate (see Eqs. (5)) which in turn affect the mechanical properties

of MHBS. In the following, new equations will be proposed to account for the influence of temperature (T) and methane hydrate density (ρ) on the secant elastic modulus at 50% of the deviator stress (E_{50}), apparent cohesion (c), and internal friction angle (ϕ) of the MHBS.

The values of E_{50} , calculated from the DEM tests, are plotted against temperature and methane hydrate density in Figures 17 and 18 respectively. From the figures emerges that the elastic modulus linearly increases with temperature decreasing and methane hydrate density increasing. This indicates the dependence of E_{50} on temperature and methane hydrate density may be accounted for by the following expression:

$$\frac{E_{50}}{p_a} = A_1 \frac{\sigma_3'}{p_a} + (A_2 \frac{\sigma_w}{p_a} + A_3 \frac{T}{T_0} + A_4 \frac{\rho}{\rho_w} + A_5) \cdot (S_{MH} - S_{MH0})^{A_6} \quad (11)$$

Comparison between Equation (11) and Equation (5a) shows that both the elastic modulus of MHBS (E_{50}) and of pure MH (E_{MH}) hold linear relationships with backpressure (σ_w), temperature (T) and MH density (ρ). Assuming that E_{50} can be expressed as a function of the elastic modulus of pure MH, a simple dimensional expression to determine E_{50} can be derived from Equations (11) and (5a):

$$E_{50} = a_1 \sigma_3' + a_2 E_{MH} \cdot (S_{MH} - S_{MH0})^{a_3} \quad (12)$$

with a_1 , a_2 and a_3 being constant parameters, and E_{MH} given in Equation (5a). In our case, the constants assume the following values: $a_1 = 6.92$, $a_2 = 0.55$ and $a_3 = 0.30$. The linear relationships obtained by using Equation (12) are reported as dashed lines in Figures 17 and 18. It emerges that Equation (12) effectively captures the dependence of E_{50} on backpressure (σ_w), temperature (T), density of pure methane hydrate (ρ), methane hydrate saturation (S_{MH}) and effective confining pressure (σ_3').

The values of apparent cohesion (c), calculated from the DEM tests, are plotted against temperature and methane hydrate density in Figures 19a and 19b respectively.

Similarly to the secant elastic modulus E_{50} , also cohesion linearly increases with temperature decreasing and methane hydrate density increasing. Hence, the dependence of cohesion on temperature and methane hydrate density may be accounted for by the following expression:

$$\frac{c}{p_a} = (B_1 \frac{\sigma_w}{p_a} + B_2 \frac{T}{T_0} + B_3 \frac{\rho}{\rho_w} + B_4) \cdot (S_{MH} - S_{MH_0})^{B_5} \quad (13)$$

Assuming that the apparent cohesion can be expressed as a function of the tensile strength of pure MH (σ_{tMH}), a simple dimensional expression to determine c can be derived from Equations (13) and (5c):

$$c = b_1 \sigma_{tMH} \cdot (S_{MH} - S_{MH_0})^{b_2} \quad (14)$$

where b_1 and b_2 are constant parameters (here $b_1 = 0.20$ and $b_2 = 0.42$), and σ_{tMH} is given in Equation 5(c). The relationships obtained by using Equation (14) are plotted as dashed lines in Figures 15 and 19. Looking at the two figures emerges that Equation (14) is effective at capturing the dependence of cohesion on backpressure (σ_w), temperature (T), density of pure methane hydrate (ρ) and methane hydrate saturation (S_{MH}).

The values of internal friction angle (ϕ), calculated from the DEM tests, are plotted against temperature and methane hydrate density in Figures 20a and 20b respectively. Analogously to apparent cohesion, the internal frictional angle linearly increases with temperature decreasing and methane hydrate density increasing whereas no significant change is found associated with the variation of MH saturation. Therefore, the dependence of the internal friction angle on temperature and methane hydrate density may be accounted for by the following expression:

$$\phi = C_0 - (C_1 \frac{\sigma_w}{p_a} + C_2 \frac{T}{T_0} + C_3 \frac{\rho}{\rho_w} + C_4)^{C_5} \quad (15)$$

with $C_1, C_2, \dots, C_4$ being constants. This indicates that the internal friction angle can

be expressed as a function of the tensile strength of methane hydrate (σ_{tMH}) in a way similar to that of cohesion (see Equation (14)). Hence, a simple dimensional expression to determine ϕ can be derived from Equations (15) and (5c):

$$\phi = \phi_{host} - c_1 \left(\frac{\sigma_{tMH}}{p_a} \right)^{c_2} \quad (16)$$

where c_1 and c_2 are constant parameters, and ϕ_{host} is the internal friction angle of the host sand (i.e., the sample without MH bonds). In our case, $\phi_{host} = 23.8^\circ$, and c_1 , c_2 are equal to 0.21 and 0.77, respectively. The relationships obtained by using Equation (16) are plotted in Figures 16 and 20. Looking at the two figures emerges that Equation (16) is effective at capturing the dependence of the internal friction angle on backpressure (σ_w), temperature (T), density of pure methane hydrate (ρ) and methane hydrate saturation (S_{MH}).

6 Conclusions

This paper investigates the mechanisms taking place at the microscopic level at the origin of the experimentally observed influence of backpressure on the mechanical properties of methane hydrate bearing sediments (MHBS) via a theoretical mechanical analysis at the grain scale and a campaign of Distinct Element Method tests. DEM biaxial compression tests was performed under different levels of backpressure to validate the proposed bond model accounting for the influence of backpressure on the MH bonds cementing the grains of the bearing sediment and to investigate the relations between mechanical properties of MHBS and backpressure. The main conclusions are as follows:

(1) in agreement with experimental tests reported in the literature, backpressure is found to increase the shear strength and elastic modulus of MHBS samples in tests run at constant effective confining pressure.

(2) DEM biaxial tests incorporating the proposed contact bond can effectively capture the main features of the influence of backpressure on stress-strain and volumetric behaviors of MHBS. High levels of backpressure increase shear strength, elastic modulus and shear dilation of MHBS. The contribution of the backpressure to the deviator stress decreases as the axial strain increases. At large axial strains, the values of the deviator stress of MHBS samples with different backpressures are nearly identical. This is due to the fact that weak areas without MH bonds control the deviator stresses of MHBS samples at such a state.

(3) The DEM simulations show that the apparent cohesion and elastic modulus linearly increase while the internal friction angle decreases at a decreasing rate as the backpressure increases. These backpressure effects depend on the effective confining pressure and MH saturation. Such dependency is formulated in Equations (8) and (10).

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