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Discrete element analysis of uplift and lateral capacity of a single pile in methane hydrate bearing sediments

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ABSTRACT

Methane hydrate (MH) is extensively found in outer continental margins where offshore infrastructures with pile foundations are also common. The presence of MHs significantly alters the mechanical properties of the host marine sediments, and therefore affects the behavior of piles inside. This paper presents an attempt to investigate the performance of a single pile in methane hydrate bearing sands in seabed using the distinct element method. A novel bond contact model was employed for sandy grains cemented by MHs at contacts, and calibrated from the triaxial compression tests on synthetic specimens of methane hydrate bearing sands. The response of the pile subjected to axial pullout loads and lateral loads was simulated under different subsurface conditions characterized by different saturation levels of MHs. The results show that the presence of MHs increases the uplift capacity of the pile by changing the failure mode of the soils from the perimeter failure to the conical failure. The uplift capacity of the pile significantly deteriorates as a result of de-bonding, while the onset of the rapid de-bonding triggers the softening of the uplift load. In addition, the lateral capacity of the pile largely increases due to the presence of MHs. The pile in methane hydrate bearing sands is considered flexible rather than rigid as a result of the increased deformation modulus of soils due to MH cementation between particles. The lateral load–displacement diagram of the pile in methane hydrate bearing sands is not as smooth as that in clean sands with an abrupt drop associated with the onset of de-bonding.

1. Introduction

Methane can be trapped and caged in water molecules under specific temperature–pressure conditions, forming an ice-like solid known as methane hydrate (MH). Being recognized as a new type of energy resources, MH has received increasing research interests in Japan, the United States, China, and India among others. In addition to the permafrost regions, the outer continental margins below water depth of 300 m are vast reservoirs sequestering most of MHs on the Earth, where at least 100 worldwide sites have been confirmed based on the data compiled in [1]. Samples of MH bearing sediment (MHBS) have been collected within 6.5 m below the seabed of the Black Sea [2] and the Gulf of Mexico [3], and also at much greater depth. The presence of MHBS in seabed brings new challenges to geotechnical engineers and others. Due to growing development in continental margins associated with oil production, offshore infrastructures have been constructed using pile foundations to resist pullout and lateral loads due to wind and wave actions. These piles very likely penetrate existing MHBS layers or are surrounded by newly created MHBS, provided that MHs are found along most continental shelf and slope regions [1]. Engineering behavior of piles embedded in MHBS becomes an interesting puzzle in addition to others associated with MHBS exploitation, such as wellbore instability (e.g., [4,5]) and submarine landslides (e.g., [6,7]) as a result of MHBS dissociation.

The behavior of a pile is ruled by the properties of soil-pile interface and soils. As a result, piles embedded in MHBS could behave differently from those embedded in other types of soils, since MHBS exhibits several peculiar properties according to experimental observations [8–14]. It is worthwhile to assess the capacity of piles in MHBS to attain a rational design method for piles in MHBS from both geotechnical and economical point of view. The behavior of piles surrounded by sands [15–21] and clays

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[22,23] has been intensively studied by means of numerical analyses and experiments considering many factors, such as soil properties, pile properties, load properties, and/or installation methods. Additionally, a few studies, although much less, have been conducted on piles in some other peculiar soils such as cemented sands [24], oil-contaminated sands [25], jet grout layers [26], and weathered rocks [27]. However, the investigation on behavior of piles in MHBS is hindered by incomplete knowledge on MHBS.

Although the study on mechanical properties of MHBS remains in the early stage, important advancements have been achieved as a result of experimental efforts [8–14], all of which confirm that the presence of MHs alter mechanical properties of the host sediments in terms of stiffness, strength and dilation. In addition to other factors (e.g., grain properties of host soils, temperature, confining pressures, water pressure and hydrate saturation level), the formation habit of the MHs (i.e., distribution of MHs at the pore scale) plays a significance role in controlling the macroscopic behavior of MHBS [28]. Waite et al. [29] summarized three main formation habits of MHs: (1) pore-filling, with MHs floating in the pore fluid without bridging any particles; (2) load-bearing, with hydrate particles taking part in the strong force chains of the granular assembly; and (3) cementation, with MHs cementing sand grains and acting as bridges between grains. Particularly, the last case is common where unconsolidated sediments are percolated by abundant gas phase of methane, and the cemented MHs have been recognized in the Black Ridge off the southeast coast of the United States [14].

The finite element method, though extensively used for analyzing pile–soil interaction [16,19,30], will be a rigorous tool only if a reasonable constitutive relation of soils is used. Unfortunately, no such relation for MHBS has received universal acceptance, although several constitutive models of MHBS were proposed in the framework of the non-linear elastic model [31–34] or the critical state model [35,36]. Alternatively, the distinct element method (DEM) [37] has shown potential to capture the major mechanical behavior of MHBS from both microscopic and macroscopic perspectives by using relatively simple contact laws between particles [38–42]. In contrast to modeling pore-filling MHs [38,39], Jiang et al. [40–42] aimed at a novel bond contact model of MHBS where MHs are present as cementation at interparticle contacts, because this type of MHs plays a more significant role in affecting bulk strength and stiffness of the host sediments than the pore-filling MHs according to [8,10,12].

The potential of DEM in modeling pile–MHBS interaction has been illustrated in [43] by using a simplified model of MHBS given in [41]. This study continues the work by applying the latest bond contact model of MHBS [42] to pile–MHBS interaction in response to axial pullout loads and lateral loads in two-dimensional (2D) context. Apparently 2D model cannot well capture the volumetric strain behavior of geomaterials because particles will not move spatially into adjacent voids as accurately as in three-dimensional (3D) simulations. However, 2D DEM is still useful from the geotechnical engineering viewpoint due to its ability in featuring the strength properties, failure and instability of geomaterials with carefully-calibrated contact models. Compared with 3D modeling, 2D DEM is better in terms of easy interpolation and visualization. Most importantly, 2D DEM is the only possible choice using current PCs to investigate large boundary-value problems, in which an extremely large number of particles are necessary for minimizing size effect and boundary effect. Hence, this paper is considered as the first-phase effort to provide insight into the fundamental micro-mechanism giving rise to the unique pile–MHBS interaction, which will not significantly change once a 3D model is used. Another challenge of this study is the experimental validation using a rigorous procedure in view of extreme difficulty in stabilizing MHBS in laboratory [8–14] and quantifying grain characteristic and motions at the particle level [44]. Nevertheless, this study is intended to approach the realistic problem in a hierarchical fashion in every aspect of DEM simulations, including code implementation, model calibration and validation of results obtained from 'clean' ground without MHs.

2. DEM simulation of MHBS

2.1. The bond contact model of MHBS

The formulation of the latest bond contact model for MHBS has been given in details in [42], and only salient features of this model are recapped here for readability.

Fig. 1 schematically shows an analogy to two sandy grains cemented by MH. The grains are represented by two disks in two dimensions with radii R_1 and R_2, and MH forms a symmetric bond in between with a finite width (B) and the minimum thickness (t_0). The bond will break in an irreversible manner as a result of excessive contact forces including the normal force (F_n), shear force (F_s), and moment (M).

Fig. 2 illustrates the mechanical response of the contact force components: F_n, F_s and M. Every component linearly increases with the increase of the related displacement until any component reaches the load limits, i.e., bond tensile resistance (R_{tb}), bond compressive resistance (R_{cb}), bond shear resistance (R_{sb}), and bond rolling resistance (R_{rb}).

For an intact bond, the contact forces can be computed as follows:

$$F_n = K_n(u_n + t_0), \tag{1a}$$

$$F_s = \sum K_s \Delta u_s, \tag{1b}$$

$$M = K_r \theta, \tag{1c}$$

where u_n, Δu_s, and θ is the overlap, the relative tangential displacement increment, and the relative rotation angle of particles, respectively; and K_n, K_s and K_r are normal, tangential, and rolling stiffnesses, respectively. Note that the compressive normal contact force is defined as positive, and the shear contact force is computed in an incremental fashion.

For a broken bond, the contact behavior is reduced to the interparticle rolling resistance model formulated in [45], of which the contact laws are written as:

$$F_n = \begin{cases} K'_n u_n, & u_n \geqslant 0 \\ 0, & u_n < 0 \end{cases}, \tag{2a}$$

$$F_s = \min\left[\sum K'_s \Delta u_s, \quad \mu F_n\right], \tag{2b}$$

$$M = \min\left[K'_r \theta, \frac{F_n \cdot \delta_r \cdot \bar{R}}{6}\right], \tag{2c}$$

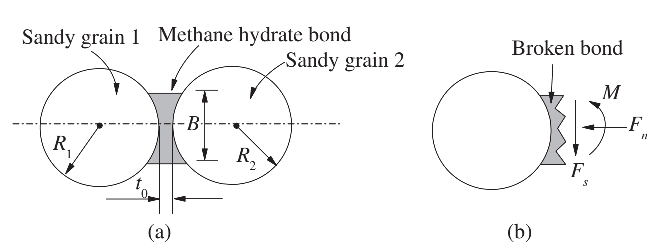

Fig. 1. Schematic illustration of: (a) two sandy grains bonded by methane hydrate in between; and (b) broken hydrate bond due to excessive contact forces.