A Model for the Elastic Modulus of Hydrate-Bearing Sediments

Xuhui Zhang*
Institute of Mechanics, Chinese Academy of Sciences
Beijing, China

Lele Liu
Qingdao Institute of Marine Geology
Qingdao, China

Junbing Zhou, Xiaobing Lu and Shuyun Wang
Institute of Mechanics, Chinese Academy of Sciences
Beijing, China

Changling Liu and Yuguang Ye
Qingdao Institute of Marine Geology
Qingdao, China

A model for the elastic modulus of hydrate-bearing sediment (HBS) is presented considering the variation of the hydrate saturation and hydrate occurrence mode. The model is based on the classical series and parallel modes, introducing a parameter of statistical force transfer paths among particles in HBS. Macro-triaxial compression tests and micro X-ray computed tomography (CT) observations of HBS in the gas-saturated formation mode were conducted. The applicability of the model was checked through the comparison between tests and theoretical results.

INTRODUCTION

Natural gas hydrate, a compound of methane molecules and water molecules, extensively exists in marine and permafrost sediments. Hydrate-bearing sediment (HBS) is a new kind of multiphase composite geotechnical material that consists of the gas hydrate, soil skeleton, and pore fluid of gas and water. The mechanical properties of HBS are the basic parameters for the analysis of soil deformation and failures during hydrate exploration and exploitation.

Many studies have been conducted in the laboratory by triaxial compression tests to obtain the mechanical data of HBS (Masui et al., 2008; Hyodo et al., 2007; Hyodo, 2013; Miyazaki et al., 2010; Miyazaki and Masui, 2011; Waite et al., 2008, 2009; Winters, 1999; Winters et al., 2004; Yun et al., 2007; Zhang et al., 2012a; Song et al., 2010). Different methodologies for sampling methane hydrate (dissolved gas method, partial water saturation method, ice-seeding method, hydrate premixing method) resulted in different hydrate occurrence modes in the pores of sediment (Ecker et al., 2000; Winters et al., 2004). By the most adopted dissolved gas method, heterogeneous nucleation occurs on the particle surface, subsequently grows into the pore space (pore-filling type), and goes to the final cementation with grains (grain-cementation type). The most pronounced increase in strength occurs when the hydrate saturation exceeds 40%. The explanation is that once hydrate saturation exceeds the critical value, the hydrate occurrence mode transfers from the pore-filling type to the grain-cementation type.

The elastic modulus of HBS is the main parameter for the evaluation of deformation. The relationship among the hydrate saturation, acoustic wave speed, and elastic modulus is required for both the resource assessment and the detection of dissociation front during the production of gas hydrate. The characteristics of the multiphase media (such as the hydrate saturation, sediment type, and hydrate formation mode) affect the acoustic wave speed and the elastic parameters of HBS. The theoretical relations were divided into two types (Lee et al., 1996; Lee and Collett, 2006; Wood, 1941): (a) the relation between the hydrate saturation and the acoustic wave speed of HBS and (b) the relation between the acoustic wave speed of HBS and the mechanical parameters (such as elastic modulus and shear modulus).

In the time-average model, the acoustic wave speed of HBS was taken as the weighted sum of that of each constituent. However, the effect of the cementation of hydrate was not considered in the model. Lee et al. (1996) combined the time-average method with the Wood equation (Wood, 1941). The weighted equation could predict well the elastic properties of HBS containing gas, but it was empirical. Lee and Collett (2006) presented a method to forecast the wave speed of underconsolidated HBS. The advantage of the model based on effective medium theory is that it can effectively predict the elastic properties of loose and gas-containing HBS. A linear relationship considering three phases (ice, hydrate, and soil matrix) was presented by Zhang et al. (2012a) to fit the elastic modulus of HBS. However, the predicted hydrate saturations by different models differ much from each other because of different hydrate occurrence modes in the pores of HBS.

This paper presents a model for the elastic modulus of HBS that is related to the hydrate saturation and hydrate occurrence mode. This model is based on the classical series and parallel modes and includes the force transfer path among particles in HBS. The model is validated by the triaxial test results, and its application is also discussed.

*ISOPE Member.
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