INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2017) 1–9

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Mechanical experiments and constitutive model of natural gas hydrate reservoirs

Chuanliang Yan [a,*], Yuanfang Cheng [a,**], Menglai Li [b], Zhongying Han [a], Huaiwen Zhang [a], Qingchao Li [a], Fei Teng [a], Jiping Ding [a]

[a] School of Petroleum Engineering, China University of Petroleum (East China), PR China
[b] Key Laboratory of Shale Gas Exploration, Ministry of Land and Resources, Chongqing Institute of Geology and Mineral Resources, PR China

ARTICLE INFO

Article history:
Received 24 April 2017
Received in revised form 27 May 2017
Accepted 17 June 2017
Available online xxx

Keywords:
Natural gas hydrate
Constitutive model
Experiment
Hydrate saturation

ABSTRACT

Natural gas hydrate is a new type of green energy resources and has great development prospects, and it has attracted worldwide attentions. The exploitation of natural gas hydrate may result in a series of geological disasters. Therefore, the constitutive model of natural gas hydrate bearing sediments needs to be established to reveal deformation laws of the reservoir sediments and accurately evaluate mechanical properties of hydrate reservoirs. This is the basic guarantees for the effective exploitation of natural gas hydrate resources. The triaxial compressive tests were conducted on samples of natural gas hydrate sediment. Furthermore, the Duncan-Chang hyperbolic model was modified by considering the influences of hydrate saturation based on the test results to obtain the constitutive model according with the deformation characteristics of natural gas hydrate reservoirs. The results show that the stress-strain curves of natural gas hydrate reservoirs show unobvious compaction stage and peak strength, short elastic stage, long yield stage, and significant strain hardening characteristics. After applying loads on natural gas hydrate bearing sediments, the internal solid particles were dislocated and slid. When the loads were small, the sediments demonstrated elastic deformation. With the increase of loads, plastic flows appeared in the interior, and the hydrate crystals were re-orientated, thus the sediments showing plastic deformation. Initial tangent elastic modulus increased with the effective confining pressures, which had little correlations with hydrate saturation. Furthermore, the damage ratio increases with the increase of effective confining pressures, while slightly decreases with the increase of natural gas hydrate saturation. The predicted results of stress-strain curves of sediments with different hydrate saturations well coincide with the results of triaxial compressive tests, indicting the feasibility and rationality of this model.

Introduction

Energy consumption and the standard of living are closely correlated and thus humanity needs abundant energy supplies [1]. The global energy consumption has reached more than 500 EJ in year 2014 [2]. But the traditional energy resources are getting less and less. As a kind of new energy, natural gas hydrate has advantages including a large amount

* Corresponding author.
** Corresponding author.
E-mail addresses: yanchuanliang@163.com (C. Yan), yfcheng@126.com (Y. Cheng).
http://dx.doi.org/10.1016/j.ijhydene.2017.06.135

of resources, high energy density and low pollution [3]. The carbon reserves of natural gas hydrate in the world is two times that of the total carbon reserves of conventional fossil energies, such as the proven oil, coal and natural gas [4]. Therefore, it is recognized as the most important follow-up clean energy, showing broad development prospects [5].

Natural gas hydrate is a clathrate crystalline compound formed by water and natural gases at a certain temperature and pressure, mainly found in the continental permafrost zones or shallow sedimentary layers in deep seas, and about 164 m^3 of natural gas can be stored in just 1 m^3 of hydrates [6]. However, the unreasonable exploitation of hydrate may threaten the safety of offshore platforms and subsea engineering and cause a series of serious natural disasters and engineering accidents, like submarine landslide, sand production and submarine pipeline rupture, and so on [7,8].

Since the vast majority of natural gas hydrates are methane hydrates, existing studies have focused on the characteristics of methane hydrates and their sediments. As a new type of rock and soil materials, the material compositions of methane hydrate bearing sediments (MHBS) are more complex than those of traditional materials and MHBS generally consists of soil particles, water, gas and methane hydrate. Moreover, the mechanical properties of MHBS are closely related to the properties and states of each component and the interaction between components determines the mechanical characteristics [9]. The constitutive model is a basis for describing deformation characteristics of materials under external loads and a theoretical basis for analyzing numerical simulation of material deformation [10–12]. Therefore, the constitutive model shows important significances for the construction design and calculation of mining of methane hydrate. In order to well understand the mechanical properties of MHBS to safely exploit methane hydrate resources, many scholars have studied the mechanical responses of MHBS by carrying out experiments [13–15] and numerical simulations [16,17], and have achieved a lot of beneficial results.

In the triaxial compressive process, with the increase of strain, hydrate crystals are damaged and crushed [18]. Moreover, the cementation is gradually damaged under the effects of forces and the influences of hydrate on mechanical properties of MHBS are gradually reduced. Therefore, the stress-strain curves of MHBS show very strong non-linear characteristics [19].

Masui et al. [20] conducted the triaxial compressive experiments on the sand samples with different hydrate contents formed in ice-sand mixture and water-sand mixture. They found that with the increase of hydrate contents, shear strength, secant modulus and cohesion increase, along with insignificant changes of internal friction angles while obvious changes of the strain softening trends. Miyazaki et al. [21] carried out the triaxial compression tests for loading and unloading of artificial hydrate samples at a constant strain rate. On this basis, they studied the deformation mechanisms of hydrate samples, and found the first contraction and then expansion properties of samples due to the existence of hydrate between particles and the elastic strain gradually developing to plastic. By introducing hydrate saturation into the yield and plastic potential functions of MHBS, Klar et al. [22] established the elastic-plastic constitutive model of MHBS. This model with a few parameters can well reflect the change laws of peak strength and Young's modulus of MHBS with different hydrate saturations. However, due to the assumption that yield and plastic potential functions only correspond to hydrate saturation, this model is an ideal elastic-plastic model that cannot reveal the strain softening properties of MHBS in loading process. Furthermore, by changing the size of overconsolidated boundary surfaces and initial yield surfaces and considering the influences of suction and hydrate saturation, Kimito et al. [23] built a complex viscoelastic-plastic constitutive model. Although this model can reflect the strain softening properties of MHBS, it involves many parameters that difficult to be determined. Moreover, its reasonability has not been verified. To reveal the mechanical effects of hydrate, Uchida et al. [24] put forward the mechanical concept of hydrate saturation to modify the yield surfaces, and finally established the critical state model of MHBS. This model can well show the mechanical properties of MHBS, but the model parameters are hard to be determined, and the physical quantity and change law of hydrate saturation are difficult to be measured and verified through tests. Therefore, the application of this model is greatly limited. Li et al. assumed MHBS as elastic materials and established the constitutive model based on the damage theories [19,25]. However, this model can only present the strain softening laws of MHBS. The test results demonstrate that with the decrease of hydrate saturation and increase of effective confining pressures, the strain-stress curves of MHBS show an obvious change from the strain softening to strain hardening [26].

At present, the triaxial tests on MHBS are rare and the relevant data are lacking. The currently proposed constitutive model can only be used in a certain range or cannot be effectively verified by test data. Therefore, it is necessary to deeply research the strength and deformation properties of MHBS. The Duncan-Chang (D-C) model, as a hyperbolic constitutive model, can describe the stress-strain curves of sand and clay materials [27]. In this study, the triaxial compressive test of MHBS with clay and sand mixed by a mass ratio of 1:3 was conducted, and the D-C model was modified by using the test data to establish a constitutive model conforming to the deformation properties of MHBS. The purpose is to provide basic data and theoretical supports for safely mining of methane hydrate and evaluating the stability of reservoirs.

Experimental methods

Experimental equipments

The experiment was carried out by using the physical and mechanical simulation test system of methane hydrate independently developed by the Rock Mechanics Laboratory of China University of Petroleum. This system (Fig. 1) mainly included an *in-situ* formation system of hydrate, a low-temperature triaxial rock mechanics test system, and devices for preparing rock cores and measuring physical properties. The system integrated the hydrate formation system with the triaxial mechanical test system, which can

Please cite this article in press as: Yan C, et al., Mechanical experiments and constitutive model of natural gas hydrate reservoirs, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.06.135