Soils and Foundations 2016;56(5):835–847

HOSTED BY

ELSEVIER

CrossMark

The Japanese Geotechnical Society

Soils and Foundations

www.sciencedirect.com
journal homepage: www.elsevier.com/locate/sandf

SOILS AND FOUNDATIONS

Technical Paper

# Macro and micro behaviour of methane hydrate-bearing sand subjected to plane strain compression

Akira Kato[a], Yukio Nakata[b,*], Masayuki Hyodo[b], Norimasa Yoshimoto[b]

[a]Department of Civil Engineering, Yamaguchi University, Tokiwadai 2-18-2, Ube, 755-0097, Japan
[b]Department of Civil Engineering, Yamaguchi University, Tokiwadai 2-16-1, Ube, 755-8611, Japan

Received 17 January 2015; received in revised form 16 May 2016; accepted 20 May 2016
Available online 28 September 2016

**Abstract**

For methane hydrate production, it is essential to understand the mechanical behaviour related to safety and efficiency. Plane strain compression tests were carried out to investigate the macro and micro behaviour of both the MH-bearing sand and the host sand. It was found that whilst there were no clear peak stress ratios in the TC results, the PSC results showed a marked increase in the peak stress ratios, regardless of whether or not MH was included. The peak strength increased due to MH, and the dilative behaviour of the MH-bearing sand occurred more markedly than that of the host sand. As the confining pressure increased, the peak strength decreased and the volume change became contractive. Deformation in the shear band was suppressed as the confining pressure increased for the host sand, whereas contractive and dilative behaviour occurred in the shear band for the MH-bearing sand regardless of the level of confining pressure. The thickness of the shear band for the MH-bearing sand appeared to be thinner than that for the host sand and there was no dependence on the confining pressure. As the confining pressure increased, the occurrence of particle crushing also increased. Coefficient of uniformity $U_c$, inside the shear band, was 1.7 times larger than the original $U_c$ of the host sand when $\sigma_3' = 5\ MPa$.


*Keywords:* Plane strain; Localisation; High pressure; Particle crushing

## 1. Introduction

Methane hydrates, referred to hereafter as "MHs", are metastable solid materials that consist of methane gas ($CH_4$) and water molecules. They are known to exist in a stable condition under certain temperature and pressure conditions. Their existence has been confirmed in permafrost layers and on deep ocean floors which satisfy the stability conditions of MHs (Kvenvolden et al., 1993). As an example, the amount of gas samples in the Nankai Trough is estimated to be about 7.4 trillion $m^3$ (which is equivalent to approximately 5.5 years of the natural gas consumption in Japan based on data from 2011). Therefore, MHs are expected to become one of the alternatives to the fossil fuels presently being imported from overseas countries. It is believed that MHs exist on the seafloor, and development is underway for MHs to become a future energy resource, replacing oil and coal (MH21 Research Consortium, 2001; Nagakubo, 2009).

Hyodo et al. (2002, 2005), of our laboratory, performed the first study on the mechanical behaviour of MH-bearing sediments using a triaxial compression test apparatus equipped with a high-pressure cell inside a freezer. The strength of MHs tends to increase with increasing confining pressure, a

*Corresponding author. Tel.: +81 836 85 9341; fax: +81 836 85 9301.
*E-mail addresses:* t002wc@yamaguchi-u.ac.jp (A. Kato), nakata@yamaguchi-u.ac.jp (Y. Nakata).
Peer review under responsibility of The Japanese Geotechnical Society.

http://dx.doi.org/10.1016/j.sandf.2016.08.008
0038-0806/

decreasing temperature, and an increasing strain rate. Since then, consolidated drained triaxial compression tests have been performed using a test apparatus that can simulate the temperature and pressure conditions of the deep seabed in order to investigate the mechanical properties of artificially prepared MH-bearing sand (Yoneda et al., 2007). In addition, the dissociation properties of MHs have been clearly shown by Yoneda et al. (2007) and Hyodo et al. (2008), who simulated the dissociation of MHs by heating and depressurisation. Likewise, Miyazaki et al. (2007) have shown that MH-bearing sand has a dependency on the loading rate; they performed consolidated drained compression tests with an alternating strain rate. Although it is not clear how MHs exist in sediments, it has been found that high MH saturation leads to increased strength in the sediments (e.g., Masui et al., 2008). Yun et al. (2007) have described the mechanical properties of gas hydrate-bearing sand, silt, and mud, using tetrahydrofuran (THF) instead of methane. The results indicated that the increase in shear strength was small for THF-hydrate saturation ratios less than 40%, but a marked increase in shear strength was observed when the saturation ratios exceeded 40%. The mechanisms at various concentrations are shown in Fig. 1. Similarly, in the case of MHs, it can be thought that the bonding between particles and hydrates, and the hydrate-occupied voids, govern the deformation and strength responses. Furthermore, it has been clarified that an increase in MHs in specimens of Toyoura sand leads to an increase in strength (Miyazaki et al., 2010, 2011).

A depressurisation method has been proposed for extracting methane gas from MH-bearing layers which exist in the seabed, as Kurihara et al. (2009) noted that this method was likely to be best for practical use. Using this method, however, it is predicted that there will be ground deformation and stress changes in the ground due to the dissociation of MHs with the possibility of increasing relative confining pressure due to decreasing pore pressure in the MH-bearing layer. In addition, in the Nankai Trough, the sediments are made up of alternative sand and mud layers, which are turbidities and hemipelagic mud, respectively (Suzuki et al., 2009). It is known that the existing MHs have been classified into four categories by Dvorkin et al. (2000), as shown in Fig. 2, and illustrated by Waite et al. (2004). The seismic velocity increases as the hydrate formation changes in order from A to D (Dvorkin et al., 2000), and as the hydrate saturation increases (Waite et al., 2004). In MH-rich layers composed of loose sediments, it can be assumed that when methane gas is produced by MH dissociation, fine soil particles, such as mud and silt, will move with the water or the gas around a production well. In addition,

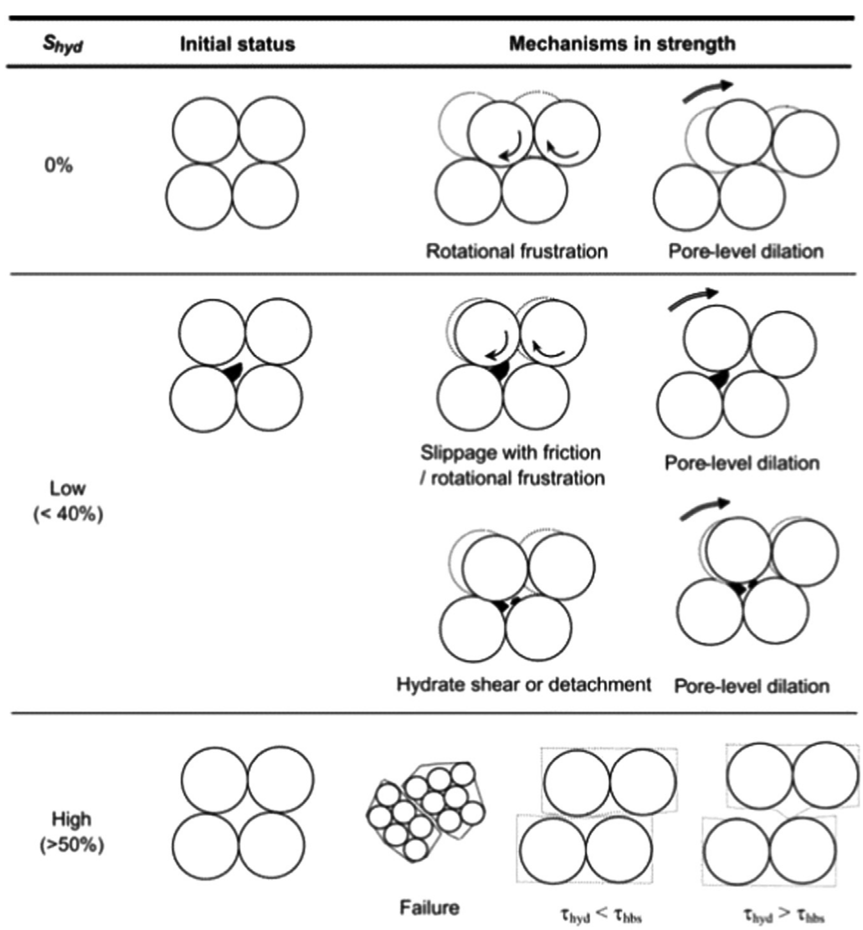


Fig. 1. Possible particle-level mechanisms controlling shear strength of hydrate-bearing sediments at various concentrations (Yun et al. 2009).