Effects of fines on triaxial shear behavior of methane hydrate bearing sands

A.Nishimura i), N. Yoshimoto ii) and S. Kajiyama iii)

i) Master student, Department of Civil & Environmental Engineering, Yamaguchi University, Ube,755-8611 Japan.
ii) Director, Department of Civil & Environmental Engineering, Yamaguchi University, Ube,755-8611 Japan.
iii) Ph.D Student, Department of Civil & Environmental Engineering, Yamaguchi University, Ube,755-8611 Japan.

ABSTRACT

Recently there has been much research into Methane Hydrate (referred to as MH hereafter) as a developable material in the deep seabed in Nankai Trough. In this study, specimens were prepared to simulate the sediments in Nankai Trough, and a series of triaxial tests were performed on samples with varying density and fines content $F_c$ of 0%, 8.9% and 25%. MH was produced with almost 30 and 50% MH saturation in the specimens. The apparatus can simulate the deep sea-bed environment. From the results of only the host sands, it was found that as the fines content increased, stiffness decreased and the volumetric strain increased. In the case of MH bearing sand however, an increase in fines content tended to lead to an increase in stiffness and maximum axial deviator stress, with positive dilative behavior occurring during shearing.

Keywords: triaxial test, fines content, shear strength, cementation

1 INTRODUCTION

Methane hydrate is expected to become a new natural gas resource which can improve the self-sufficiency ratio of the energy supply in Japan. Research and development of MH has been carried out in the deep sea-bed of the Nankai Trough for the economical and safe production of natural gas from MH reservoirs. The natural core sampling data of Nankai Trough is shown in Fig.1. Grain size distribution tests were performed as well as density, and conductivity and porosity tests of core samples. The MH bearing layers consist of layers of sand and mud made from turbidites. The grain size distribution of the MH bearing layers is varied, and it is therefore expected that the mechanical properties will also vary. In this study, triaxial tests have been carried out in order to evaluate the shear characteristics of MH bearing sediments with varying density and fines content $F_c$ of 0%, 8.9% and 25%; simulating sediments in the reservoir created from the data obtained from test core borings. In this study, $F_c=8.9\%$ taken as the base grain size distribution referred to as Turbidite b (Tb).

2 EXPERIMENTAL CONDITIONS

MH bearing sediments were prepared and tested using special triaxial apparatus. The apparatus can duplicate the high pressure, low temperature environment of the deep sea-bed. A simple diagram...
of the test apparatus is shown in Fig. 2. The grain size distribution of the imitation sample is shown in Fig. 3. Samples with degrees of MH saturation 0, 30 and 50% were prepared for the shear tests. The mineral content and grain size distributions of this soil layer were approximated; No. 8, No. 7, and R5.5 Silica sand, kaolin, and mica were mixed, and the simulation host sands were produced. The fines content was adjusted to 0%, 8.9%, 25% using a 75μm sieve for No. 8 and No. 7 silica sand. The density of the simulation host sand was adjusted to $e=0.67-0.82$ by using three levels of tamping energy $E_c=40,120,360$kJ/m$^3$. The experimental procedure is as follows: An unsaturated specimen 30mm in diameter and 60 mm in height was prepared using tamping. Next, the specimen was installed in the triaxial apparatus and MH was generated over a span of 24 hours under a prescribed pressure and temperature. After MH generation, the specimen was saturated with water and the effective confining pressure, temperature and pore pressure were controlled. After consolidation, drained shear tests were performed at a strain rate of 0.1%/min. Figure 4 shows state paths for pressure and temperature.

3 TEST RESULTS

3.1 Effects of fines

Figure 5 shows the relationship between void ratio and fines content of the host sand and MH bearing sand. Here, solid lines depict void ratio before consolidation and dashed lines are the void ratio after consolidation. From the figure it can be understood that at the same $E_c$ there is little difference in void ratio for $F_c=0$ and 8.9%, while there is a clear decrease at a $F_c$ of 25%. Further, it can be seen that the void ratio only decreases slightly due to consolidation.

Figure 6 shows the results of triaxial shear tests on host sands and MH bearing sands prepared with $E_c=120$ kJ/m$^3$. In host sands, an increase in fines content leads to an increase in peak strength, the volumetric and axial strain at peak strength increases, and rigidity decreases. In MH bearing sands, the rigidity and peak strength increase as the fines content increases. Also, expansive dilation increases with increasing fines content. This is due to cementation of soil particles by MH$^3)$. The same behavior was also observed for $E_c=40,360$ kJ/m$^3$.

Figure 7 shows the relationship between the maximum deviator stress and void ratio in host sand and MH bearing sand. For $F_c=0$% and 8.9%, the strength of the host sand and MH bearing sand increases with increasing density. This tendency is more apparent for the MH bearing sand than the host sand. However, this correlation between void ratio and strength is not apparent for MH bearing sand at $F_c=25%$. The peak strength and residual strength of the host sand and MH bearing sand are shown in Fig. 8. The figure shows that the axial strain required to reach peak strength is relatively small and both the peak strength and residual strength are higher in the MH bearing sand compared with the host sand. For the host sand, both the peak and residual strength
are almost the same value. On the other hand, there is a big difference between the peak and residual strength in the MH bearing sand. This is due to cementation of MH. It is assumed that the secant angle $\phi_{res}$ is the same as at the point where peak strength occurs in MH bearing sand, with the increase in strength due to cementation of MH. In Fig. 9, the tangent is drawn to the Mohr's circle at peak strength to obtain the cohesion $c$, which represents the cementation of MH. Figure 10 shows relationships between cohesion $c$, secant angle $\phi_{res}$, and fines content. The level of cohesion increases as the fines content gets higher for specimens prepared with tamping energies $E_c$ of 40 and 120kJ/m³. It is presumed that MH cements the fines which previously did not contribute to the strength or rigidity of the specimen. Thus, MH bearing sand including fines has higher cohesion than simply sand. However, the cohesion at $E_c=360kJ/m³$ for $F_c=25\%$ shows a lower value than the other specimens. It is believed that the cementation of MH decreases once the amount of fines passes a certain amount and the residual secant angle $\phi_{res}$ increases with increasing tamping energy and fines content as shown Fig.10.

3.2 Effects of effective confining pressure

It is thought that the level of MH saturation in the sea bed is not constant, and varies with depth. Therefore, triaxial tests were carried out under various conditions of MH saturation and effective confining pressures in an attempt to reproduce actual conditions. Figure 11 shows the effects of MH saturation on the stress ratio and volumetric strain relationships with an effective confining pressure $\sigma'_c=1MPa$ and degree of MH saturation=0, 30 and 50%. From this figure, it can be seen that the initial rigidity and peak strength increase, whilst the volumetric strain decreases as the MH saturation gets higher. Figure 12 shows the influence of effective confining pressure on the stress ratio and volumetric strain relationships at an MH saturation of almost 50%. From this figure, it can be seen that initial rigidity, peak strength and residual strength decreased at higher confining pressure. Volumetric strain decreased along with decreasing confining pressure. It is thought that flocculation of the cemented soil particles by MH are destroyed with the increase in effective confining pressure. An equation for estimating strength based on the above phenomena is proposed including parameters for the influence of MH saturation and effective confining pressure.

4 EVALUATION OF PEAK STRENGTH

In order to evaluate the influence of MH saturation and effective confining pressure on the peak strength of MH bearing sands, an adaptation of Gutierrez's equation (1) for the peak strength of soils will be used. Here, the critical stress ratio $\eta_c$ is replaced with the residual stress ratio $\eta_{res}$, and the mean stress $p$ with effective confining pressure $\sigma'_c$. The relative density is taken as $Dr=1$ since all tests are carried out with a fixed density. A rearrangement of the equation (2) gives:
\[ \eta_{\text{peak}} = \eta_{\text{cr}} + CD \ln \left( \frac{P_c'}{P_c} \right) \]  
\[ \eta_{\text{peak}} - \eta_{\text{cr}} = C \ln \left( \frac{P_{c'}}{\sigma_c} \right) \]  

With \( C \) as a material constant, this equation shows that when \( \sigma_c' \) exceeds the critical pressure \( P_{c'} \), effective confining pressure no longer influences the peak stress ratio \( \eta_{\text{peak}} \), and the peak strength becomes equal to the residual stress ratio \( \eta_{\text{res}} \). From this, if the residual stress ratio \( \eta_{\text{res}} \), material constant \( C \) and breakdown pressure \( P_{c'} \) are known, then it is possible to estimate the peak stress ratio \( \eta_{\text{peak}} \).

Figure 13 shows the relationship between \( \eta_{\text{peak}} \) and \( \eta_{\text{res}} \) and effective confining pressure \( \sigma_c' \). The critical pressure \( P_{c'} \) is defined as the confining pressure under which the peak stress ratio \( \eta_{\text{peak}} \) equals the residual stress ratio \( \eta_{\text{res}} \). Figure 14 shows the relationship between \( \eta_{\text{peak}}, \eta_{\text{res}} \) and \( P_{c'}/\sigma_c' \). From this figure, a material constant \( C \) is obtained from the angle of each line of approximation. Figure 15 shows the relationship between the material constant \( C \) and MH saturations. It is clear that the material constant \( C \) and MH saturations have a linear relationship as shown in equation (3).

\[ C = 0.001 \times S_{\text{MH}} + 0.02 \]  

The relationship between residual stress ratio \( \eta_{\text{res}} \) and effective confining pressure \( \sigma_c \) is shown in Fig.16. From this figure, it can be seen that the residual stress ratio \( \eta_{\text{res}} \) decreases as effective confining pressure \( \sigma_c' \) increases.

\[ \eta_{\text{res}} = 1.33 - 0.02 \times \sigma_c' \]  

The peak stress ratio \( \eta_{\text{peak}} \) can then be calculated from the above equations (2), (3), (4). A comparison of the estimated values and experimental values for the peak stress ratio is shown in Fig.17. From this figure, it is confirmed that both of values are very close.

5 CONCLUSIONS

The results of this research are as follows:

Triaxial tests on MH bearing sands show that peak deviator stress increases and volumetric strain decreases as fines content \( F_c \) gets higher. This tendency is more prominent at lower densities. The difference of peak strength and residual strength is taken as cementation of MH expressed by cohesion \( c \). This effect increases as fines content \( F_c \) gets higher.

MH bearing sand’s peak strength, residual strength and initial rigidity decrease as effective confining pressure increases. This tendency is more apparent at higher saturations of MH. Based on these characteristics, it can be estimated that the peak strength does not depend on effective confining pressure and MH saturations as referenced Gutierrez’s equation.

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