Image analysis of natural gas hydrate-bearing sand during shear with different plane strain shear rate

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ABSTRACT

Natural gas hydrate is an important resource in the future. To get this resource safely and sustainably, the shear rate-dependent behaviors of Toyoura sand with and without hydrate have been studied with a plane strain shear test. By analysis of picture information and PTV technology, it was found that: increasing the shear rate did not significantly change the angle of the hydrate-bearing sediment samples, but it delayed the appearance of the shear band. The large local maximum shear strain of the Toyoura sand with hydrate was more concentrated in the shear band and local volume expansion was more significant with the increase of the shear rate.

Keywords: natural gas hydrate, plane strain, shear rate-dependence, particle tracking velocimetry

1 INTRODUCTION

As a promising energy resource, natural gas hydrate (NGH) has been studied widely. The stable existence of NGH requires low-temperature and high-pressure conditions. To obtain this resource from reservoirs safely and ensure the possibility of long-term sustainable exploitation, the study on the time-dependent behaviors of the mechanical and deformation characteristics for natural gas hydrate-bearing sediment is important. Miyazaki, et al., 2017 studied the Toyoura sand samples with and without methane hydrate by three different kinds of experiments: constant-strain-rate, constant-stress-rate, and constant-stress (creep) test under triaxial loading conditions. It was found that methane hydrate-bearing sediment samples’ strength showed clearly shear rate dependence. In addition, it is suggested that loading rate dependence of mechanical properties study was a more efficient method to investigate the time-dependent behaviors of hydrate-bearing sediments. Carbon dioxide hydrate-bearing sediment samples’ shear rate dependence of the mechanical properties has also been reported (Iwai, et al., 2018). Current studies on the shear rate dependence and local deformation characteristics of methane hydrate-bearing sediments under plane strain conditions are still vacancy.

In this study, Toyoura sand with and without methane hydrate samples have been used to study the shear rate-dependent behavior of deformation properties with plane strain shear test apparatus. The development and characteristics of shear bands were studied. Through PTV (Particle Tracking Velocimetry) technology, the local maximum shear strain and volume strain of the specimen have been studied. Finally, the compression and expansion characteristics of the volumetric strain were studied separately firstly, making it possible to gain a deep understanding of the local volumetric strain of the specimen during the shearing process.

2 EXPERIMENTAL INSTRUMENTS AND CONDITIONS

Temperature-controlled and high-pressure plane strain testing apparatus with an observation window was used in this study. A schematic diagram of the observation system is shown in Fig. 1. The supplementary explanation of each part is presented below. A more detailed introduction to this instrument can be found in previous reports (Yoneda, et al., 2013). The observation grid was attached between the sample and membrane on the sigma-2 plane. Fig. 2 shows the grid size (2 mm * 2 mm), PTV area, and the analysis element unit of PTV. In this study, the middle part of the grid (60 mm * 140 mm) was chosen as the PTV analysis area to avoid serious edge lens effects. The pictures of local deformation were recorded by a digital camera. Toyoura sand was selected as host sand to artificially

Fig. 1. The schematic diagram of the observation system (a: Sample; b: Confining plate; c: Observation window; d: Top cap; e: Pedestal; f: Camera; g: Light; h: Mesh; i: Load cell).
produce methane hydrate-bearing sediments. The particle density of the Toyoura sand was 2.64 g/cm³ in this study. The pore pressure was 10 MPa and effective confining pressure was 3 MPa during the drained shearing test. The temperature was controlled at 278.15 K all the time. Hydrate saturation is controlled at about 40% and calculated based on the amount of decomposed gas collected after the shearing test. The specific conditions of the experiment are shown in the Table. 1.

3 RESULTS AND DISCUSSION

3.1 Stress-strain relationship

Both initial shear stiffness and peak shear strength, the shear-rate dependence behaviors of hydrate-bearing sediment samples are more significant than that of pure sand samples, see Fig. 3. The volumetric strain of samples with hydrate changed from compression to expansion with increasing shear rate. For samples without hydrate, the volumetric compressive strain effect of the specimen gradually decreases with increasing shear rate.

3.2 Characteristics of the shear band

In this study, after the sample has experienced peak shear strength, the location where the strength decreases fastest was used to study the characteristics of the shear band. Similar research methods can also be found in previous reports (Kajiyama et al., 2017). And, for easy observation, the shear bands are unified in the same direction. See Fig. 4, the shear band angle of Toyoura sand with hydrate is around 57.7°. The increase in the shear rate did not significantly affect the angle of the shear band of the hydrate-bearing samples. Besides, the
the angle of the shear band of the pure sand samples is higher at high shear rates (from 52.3° to 56.2°).

In this study, after the sample reaches the peak shear strength, the local strain concentration is aggravated, and an obvious shear band can be observed. Therefore, the time of the peak shear strength appears can reflect the time when the local shear strain concentration or the shear band appears. Fig. 5 shows the axial strain corresponding to the peak shear strength of the samples under different experimental conditions. From that, the opposite effect of shear rate on the occurrence time when peak strength of hydrate-bearing sediment samples and pure sand samples can be found. Namely, the peak shear strength of the pure sand samples appears later, compared to the hydrate-bearing sediment samples. As the shear rate increases, this difference becomes smaller and smaller.

3.3 PTV analysis

Fig. 6 shows the contours of the maximum shear strain of Toyoura sand with and without hydrate during the shear process. The distribution of maximum shear strain contours gradually developed from approximately uniform to the local concentration during the shearing process, forming an obvious shear band (the red zone in Fig. 6). As for the hydrate-bearing sediment samples, under relatively high shear rate conditions (0.5 %/min), the significant strain concentration occurs at the axial strain of 8%, as shown in Fig. 6. Interestingly, in the case of lower shear rate (0.05 %/min), obvious shear strain localization can be observed when the axial strain is smaller (ε_a=6%). Conversely, in the case of pure sand samples, the increase of the shear rate makes the localized strain concentration appear earlier. See Fig. 6 corresponding axial strain is about 12% when the local shear strain concentration occurs at a shear rate of 0.05
Fig. 7. PTV analysis results of the volumetric strain of the different specimen types during the shearing process.
%/min and corresponding axial strain is 8% of that at a shear rate of 0.5 %/min.

Another interesting finding is that the shear rate has different effects on the large maximum shear strain contour distribution of the two types of specimens. As for the samples with hydrate, under low shear rate (0.05 %/min), the large maximum shear strain contours appeared not only in the interior of the shear band but also around the shear band. As the shear rate increased to 0.5 %/min, larger local maximum shear strain contours are more concentrated inside the shear band. Instead, in the case of pure sand samples, at two different shear rates, the large local maximum shear strain contours can be observed around the shear band.

Due to the local strain, the local volume strain of the sample is also different from the overall volume strain in the plane strain shear tests. When the overall volumetric strain of the specimen has been exhibiting compression characteristics to varying degrees, significant volume expansion may occur near the shear band zone. Kato et al., 2015 reported that volume compression and expansion simultaneously exist at the shear band area under plane strain shear tests. Yoneda et al., 2016 analyzed the plane strain shear process at microscales. By the microfocus X-ray computed tomography technology, it was observed that the particle structure was significantly changed in the shear band, while the outside of the shear band has only a small structural change. In summary, study the local volume strain of the sample during the plane strain shear process is also necessary.

Fig. 7 shows PTV analysis results of the volumetric strain of the different specimen types during the shearing process. In this study, the local volume expansion and compression of the specimen during shearing were analyzed separately by the PTV technique. For hydrate-bearing sediment samples, whether it is a low or high shear rate, the local swelling effect gradually dominates with increasing loading. And at a high shear rate (0.5 %/min), the expansion behavior is more significant. This is consistent with the total volumetric strain results. Furthermore, when the shear rate is 0.05 %/min, in addition to the expansion effect in the shear band, there are also significant compression effects that can be observed, and the distribution of the larger expansion strain contours is more dispersed. In contrast, when the shear rate is 0.5 %/min, there is only a significant expansion volumetric strain effect in and around the shear band. The compressive volumetric strain effect is hardly found. And the larger volumetric expansion strain is concentrated in the interior of the shear band.

For pure sand samples, although the overall volumetric strain of samples is mainly volumetric compression, within the shear rate range in this study, and the volumetric compressive strain gradually decreases with the increase of shear rate. From the results of PTV analysis, under low shear rate (0.05 %/min), with the increase of loading, the local volumetric compression effect gradually dominates, and only a small volume expansion effect can be observed near the shear band. At a high shear rate (0.5 %/min), the local volumetric expansion effect is obvious and concentrated. Only the lower part of the sample can find the significant local volumetric compression effect. Although the overall volume strain of the sample is always dominated by volumetric compression, see Fig. 5.

4 CONCLUSIONS

Based on the image analysis of the plane strain shear tests of Toyoura sand with and without hydrate samples, the shear rate-dependent characteristics of the shear band and local volumetric strain have been studied. The conclusions are as follows:

1) The shear band angle of hydrate-bearing sediment samples did not change significantly with increasing shear rate.

2) Compared to the Toyoura sand without hydrate sample, the shear band of Toyoura sand with hydrate appeared earlier, and increased shear rate would delay the appearance of shear bands of the hydrate-bearing sediment samples.

3) With the increase of shear rate, the large local maximum shear strain of Toyoura sand with hydrate was more concentrated in the shear band, and the local volume expansion phenomenon increased significantly. In addition, pure sand specimens show significant local volume expansion strain only at high shear rates.

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