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Study of Mechanical Properties of Different Hydrate Reservoirs

Cewen Bai, Jikai Jin, Xiuyan Fu, and Xin Wen

College of Architectural Engineering, North China University of Science and Technology,
Tangshan 063210, Hebei, China

Abstract

Based on the triaxial shear tests of mud sediments in the South China Sea, mud chalk-type sediments in the South China Sea, and sandy sediments in the Nankai Trough, Japan, at different hydrate saturation and enclosing pressures, the stress-strain relationships of hydrate-bearing clays, mud chalk-type soils, and sandy soils were analyzed. The test results show that:(1)The stress-strain curves of the South China Sea clay sediments show three stages of elasticity, plastic deformation and strain hardening, which are significantly different from those of the hydrate-free clays; the stress-strain relationships of the hydrate-containing clays before and after hydrate decomposition are significantly different, and the undrained strength of the clays decreases by up to 50% after hydrate decomposition compared with that before hydrate decomposition; the above results indicate that the presence of hydrate enhances the linkage or cementation between the clay particles. The above results indicate that the presence of hydrate enhances the linkage or cementation between the clay particles.(2)For the mechanical properties of the hydrate specimens of the muddy chalky sand type in the South China Sea, the hydrate endowment, effective stresses and pore pressures all have some influence on the strength and deformation properties. The inclusion of hydrate in the pore space enhances the shear expansion characteristics of the sediments. For the effect of effective stress on the mechanical properties of hydrate sediments, the increase of effective peritectic pressure reduces the strain softening properties of hydrate sediments. The destructive strength of the sediments increases with the increase of effective confining pressure.(3)For the hydrate specimens in the Nankai Trough of Japan under the same effective circumferential pressure conditions, with the increase of hydrate saturation, the stress-strain law of the sediments showed a tendency to transform from strain hardening to strain softening, and the morphology of sandy sediment axial strain-lateral strain curves was controlled by the factors of hydrate saturation, and the absolute value of the slope of the curves expressed the rule of change of the tangent Poisson's ratio.

Keywords

Hydrate-bearing Sediments; Triaxial Test; Stress-strain Curve.

1. Introduction

Natural gas hydrate resources have the advantages of wide distribution,large resources, high energy density, etc[1],which is an important alternative energy source. Accurately predicting the mechanical properties of hydrate-bearing reservoirs and revealing the deformation law of hydrate-bearing sediments can effectively avoid the occurrence of engineering disasters during the development of hydrate resources and provide a guarantee for the effective and safe development of natural gas hydrates.

The study of mechanical properties of hydrate-bearing sediments has been one of the hot research issues related to hydrate mining.Winters[2-4] and Waite[5] et al,Based on the test results of the in situ hydrate-bearing sand samples taken from Malik drilling and the indoor synthesized hydrate-bearing Ottawa sand samples, it was found that the strength of hydrate-bearing sands is related to the hydrate content, distribution, the nature of the sediments, the test conditions, the total amount of pore space, and the filled material, and that indoor synthesized hydrate-bearing sands are generally gelled because of the overfeeding of gas and have different physical and mechanical properties from the hydrate-bearing sand samples generated under sufficient water content conditions. The physical and mechanical properties of the sand samples are different.Hyodo et al[6,7] concluded that the mechanical properties of hydrate-bearing sands are related to temperature, backpressure, effective confining pressure, and hydrate saturation, and found that the strength of hydrate-bearing sands undergoes significant shear expansion with increasing hydrate saturation, and that the strength of hydrate-bearing sands is lower than that of hydrate-free sands after decomposition of the hydrates.Clayton[8] et al.found that the shear modulus,bulk modulus and damping ratio of hydrate-bearing sandy soils were all correlated with the degree of hydrate saturation and the degree of hydrate cementation.Masui[9,10]et al found that the stress-strain of in-situ and synthetic samples of hydrate-bearing sandy soils can be significantly different even when the strengths are the same, and the deformation characteristics of hydrate-bearing sandy soils are closely correlated with the initial pore ratio of the hydrate and the sediment particle gradation.Miyazaki[11,12]et al. obtained that the strength of hydrate-bearing sandy soils increases with increasing perimeter pressure and increasing shear rate.Priest[13]and Hyodo[7]et al. found that hydrate-bearing sands and soils generated by gas-saturated methods produce greater volumetric strains than water-saturated methods and have more pronounced strain softening properties, and that hydrate-bearing sands and soils generated in pore media with different gas and water saturations differed in terms of structural morphology and mechanical properties.Kneafsey[14]et al. investigated the effect of hydrate decomposition on the mechanical properties of hydrate sediments and inferred from this that it is more feasible to mine hydrates in sand or rock by depressurization and warming. On the domestic side, the research work on the mechanical properties of hydrate-containing sediments has been reported in the literature since 2010, e.g.,Zhang Xuhui[15] et al on the study of the mechanical properties of different hydrates as well as powdery and fine sands and the analysis of the influencing factors; Yan Rongtao[16] on the study of the effect of different synthesis methods on the strength of hydrated sandy soils;Yanghui Li[17]et al investigated the strength and modulus of hydrated kaolin containing ice after complete or incomplete decomposition of the hydrate; and Li Shi[18],Sun Zhongming[19],and Zhang Lei[20] studied triaxial tests of hydrated sandy soils and so on.

This paper carries out experimental research on the mechanical properties of mud hydrate, mud silt hydrate, and sand hydrate, which can not only meet the engineering needs of hydrate exploration and mining pre-study projects in the South China Sea and the Nankai Trough,but also has certain significance for academic exploration.

2. Mechanical Properties of Muddy Sediments in the South China Sea

Data from Shuyun Wang[21] et al, The clay used in the experiment was remodeled from several original soil samples taken from the seabed of a sea area in the South China Sea,and the basic physical parameters of the remodeled clay were:specific gravity of 2.70,liquid limit of 71%,plastic limit of 24%,plasticity index of 47,dry density of 1.3g/cm3,optimum water content of 30%,porosity of 0.25,coefficient of permeability of 1*10-9m/s,and the particlegrading curve shown in Fig. 1.

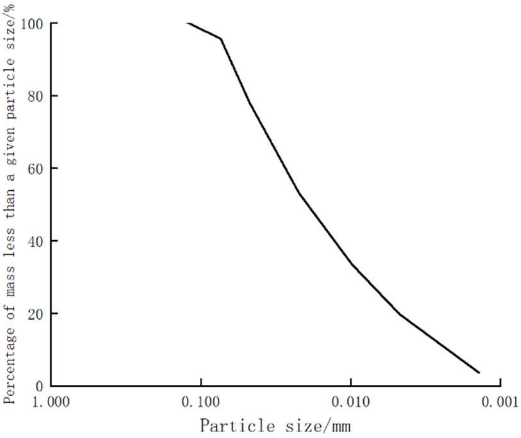

Fig. 1 Particle grading curves of muddy sediments in the South China Sea[21]

Fig. 2 shows the stress-strain relationship curves of the hydrate-free clay (at hydrate saturation=0%)under the conditions of peripheral pressure σ=2.5MPa,5 MPa and 7.5 MPa.From the figure,it can be seen that the stress-strain relationship of the hydrate-free clay sediment shows plastic damage,and the undrained shear strength reaches the peak when the strain reaches 2%,and the stress basically no longer increases or slightly decreases after the strain is greater than 2%.The average shear strength indexes of the undrained hydrate clay are:cohesive force C=0.04MPa and internal friction angle Φ=0.5°.

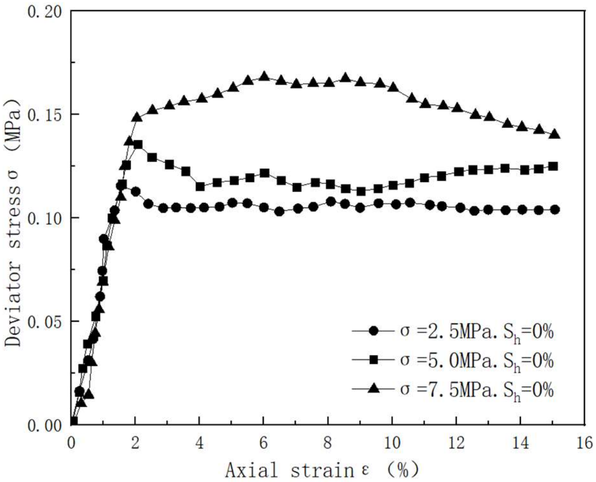

Fig. 2 Stress-strain curves of muddy sediments in the South China Sea
(without hydrate sediments)[21]

Fig. 3 shows the stress-strain curves of hydrate-bearing clay(at hydrate saturation=45%)under the conditions of peripheral pressure σ=2.5 MPa,5 MPa and 7.5 MPa.Compared with Fig. 3,the stress-strain relationship of hydrate-bearing clay in the range of strain 0-15% shows three distinctly different characteristics of elasticity,plastic deformation,and strain hardening.The hydrate-containing clay is approximately elastic behavior when the strain is lower than 1.5%;in the range of 2%-6% strain,it exhibits obvious plastic deformation,i.e.,a plateau period in which the stress is basically unchanged with the increase of strain; and it exhibits an obvious strain-hardening tendency after the strain is greater than 6%, and the stress increases significantly with the increase of strain.The average shear strength indexes of the clay with 40% hydrate content are:cohesive force C=0.15 MPa,and internal friction angle Φ=1.1°.

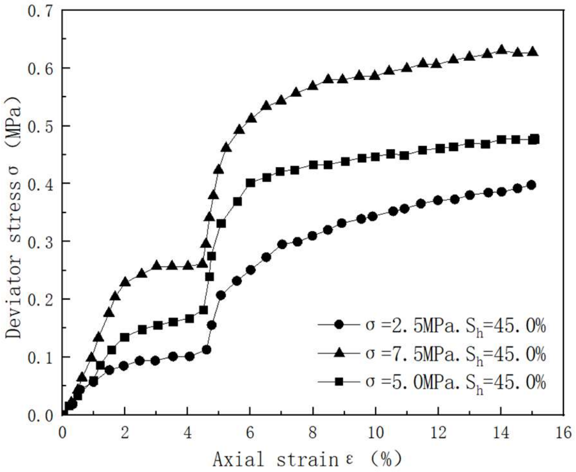

Fig. 3 Stress-strain curves of muddy sediments in the South China Sea (hydrate-bearing sediments)[21]

From the comparison of Fig. 3 and 4,especially when the hydrate-containing clay reaches 4.5% strain,a sudden step-type increase in the principal stress difference occurs.This is because,with the increase of strain,the particles of hydrate-containing clay are gradually compacted,and the internal pores are decreasing,and the filling degree of hydrate between the clay particles is getting bigger and bigger under the condition that the hydrate content in the samples is unchanged,and it keeps accumulating more than a certain critical value, and the supporting effect of hydrate on the whole soil skeleton becomes the most obvious, and thus there is a situation in which the change in the strain is small, but the stress grows by jumping,and after that,it shows a slightly slower strain hardening behavior.

3. Mechanical Properties of Muddy Chalk-type Sediments in the South China Sea

The data were obtained from Wang Lei[24],and the stress-strain curves of hydrate-free sediments and hydrate-bearing sediments in the South China Sea under different effective circumferential pressure conditions are shown in Fig. 4 and 5.For the stress-strain relationship of sediments in the South China Sea,the specimens of muddy chalk-type sediments in the South China Sea show elasticity and plasticity,which are greatly affected by hydrate and effective surrounding pressure.For the hydrate-free sediments,the stress-strain relationship maintains the strain-hardening property within the range of effective confining pressure.For hydrate-containing sediments,with the increase of the effective pressure,the stress-strain relationship changes from strain-softening characteristic to strain-hardening characteristic,which indicates that the increase of the effective pressure reduces the strain-softening characteristic of hydrate-containing sediments, which may be due to the fact that the greater the effective pressure,the greater the interaction and friction between particles,and the particles are not easy to be rearranged such as tumbling over other particles,which reduces the strain-softening characteristic of the hydrate-containing sediments. strain softening properties of hydrate sediments[22].At the same time,a higher effective confining pressure can inhibit the generation and development of fractures in the sediments[23],thus reducing the strain softening properties of hydrate sediments.

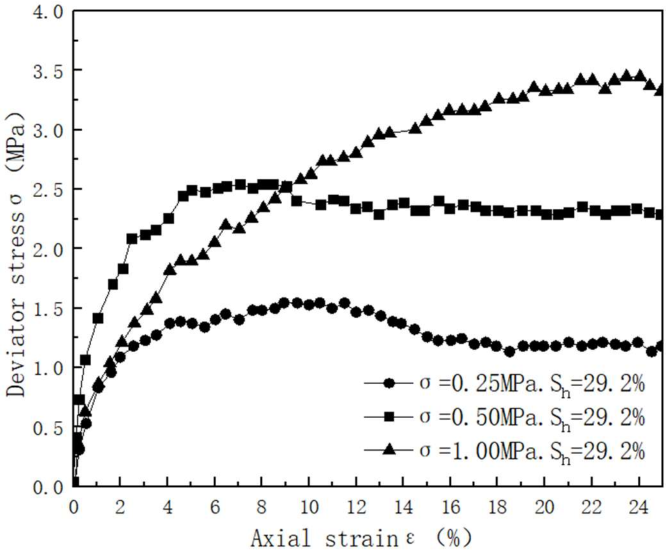

Fig. 4 Stress-strain curves of muddy chalk-type sediments in the South China Sea (hydrate-bearing sediments)[24]

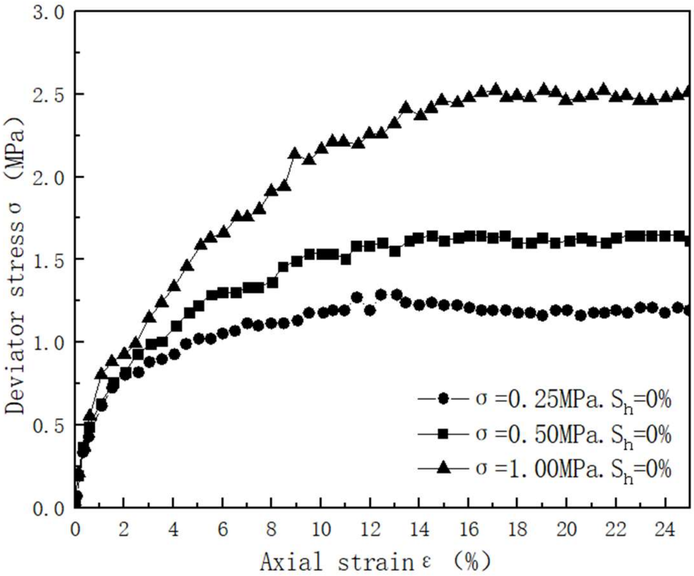

Fig. 5 Stress-strain curves of muddy chalk sediments in the South China Sea (excluding hydrate sediments)[24]

By comparing the stress-strain curves of the hydrate-free and hydrate-containing sediments at σ=0.25MPa,we find that: under this effective circumferential pressure,the hydrate-free sediments show strain-hardening characteristics,while the hydrate-containing sediments show strain-softening characteristics;the peak strength of the hydrate-containing sediments is higher than that of the hydrate-free sediments,but the residual strength of the hydrate-containing sediments is equal to the strength of the water-free sediments; and the peak strength of the hydrate-containing sediments is higher than that of the water-free sediments,but the residual strength of the water-free sediments is equal to the strength of the water-free sediments.The peak strength of hydrated sediments is higher than that of non-hydrated sediments,but the residual strength of hydrated sediments is equal to that of non-hydrated ones.This is because at the beginning of the shear process,the cementation structure formed by the hydrate controls the destructive behavior of the sediments, so that the hydrate-containing sediments maintain a higher strength than the non-hydrate-containing sediments.Thereafter, as the shear proceeds,the cemented structure of the hydrate-bearing sediments undergoes destruction, leaving the hydrate to make no contribution to the strength of the sediments, and thus the residual strength of the hydrate-bearing sediments is the same as that of the non-hydrate-bearing sediments[25].

4. Mechanical Properties of Sandy Sediments in the Nankai Trough, Japan

Data from this paper were tested under the conditions of hydrate saturation of 7.70%,9.38%,22.5% and 37.6%,and effective enclosure pressure of 1 MPa, respectively.The stress-strain relationship curves of natural hydrate-bearing sandy sediments in Nankai Trough under different hydrate saturation conditions are shown in Fig. 6.

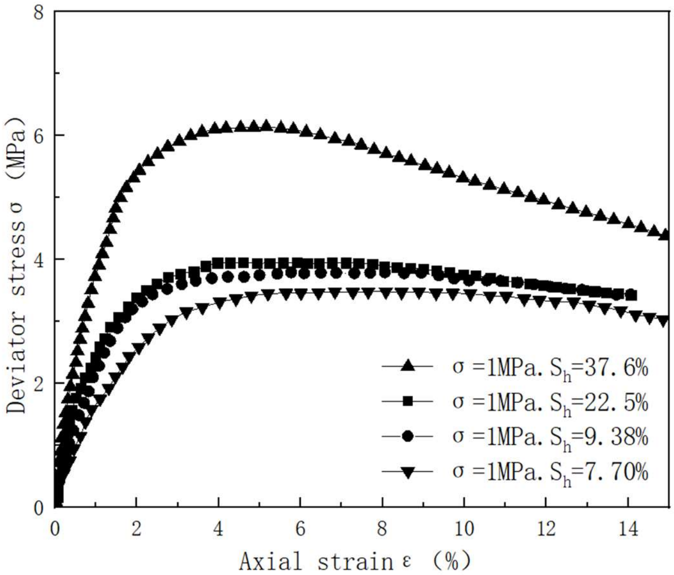

Fig. 6 Stress-strain curves of sandy sediments in the Nankai Trough,Japan

As can be seen from Fig. 6,under the same effective circumferential pressure conditions,with the increase of hydrate saturation,the stress-strain law of the sediments shows a trend from strain hardening to strain softening,the shape of the axial strain-lateral strain curve of the sandy sediments is under the common control of the hydrate saturation factors,and the absolute value of the slope of the curve indicates the change rule of the tangential Poisson's ratio;with the reduction of hydrate saturation,the tangential Poisson's ratio and initial Poisson's ratio are reduced under the same axial strain conditions.With the decrease of hydrate saturation,the tangent Poisson's ratio and initial Poisson's ratio under the same axial strain condition are reduced,and the initial Poisson's ratio of the hydrate-containing loose sediment is in the range of 0.19-0.48 as a whole.

5. Conclusion

By analyzing the number of triaxial tests of mud hydrate, mud chalk-type hydrate, and sand hydrate at different hydrate saturations and different enclosing pressures,the following conclusions can be drawn:

(1)The stress-strain curves of muddy hydrate sediments,which include three stages of elasticity,plastic deformation, and strain hardening (approximately elasticity at strains below 1.5%,plasticity in the range of 2%-6%,and obvious strain hardening characteristics after

6%),are significantly different compared to the stress-strain relationships of hydrate-free clays.Hydrate-containing clays show significantly different stress-strain relationships before and after hydrate decomposition,and their undrained shear strength values after hydrate decomposition show a maximum reduction of about 50% compared to those before hydrate decomposition.The undrained shear strength of hydrate-bearing clays increases with increasing hydrate saturation and peritectic pressure,and is 1-6 times higher than that of non-hydrate-bearing clays.(2)For the mechanical properties of muddy chalky hydrate specimens in the South China Sea, the hydrate endowment, effective stress and pore pressure all have some influence on their strength and deformation properties. For the effect of effective stress on the mechanical properties of hydrate sediments, the increase of effective peritectic pressure reduces the strain softening of hydrate sediments. The destructive strength of the sediments increased with the increase of effective peritectic pressure. Based on the above studies, it is shown that the influence of reservoir burial depth on mining safety should be fully considered in the hydrate mining process.(3)The shape of the axial strain-lateral strain curve of the hydrate-containing loose sediments is controlled by the effective pressure, hydrate saturation and other factors, and the absolute value of the slope of the curve indicates the rule of change of tangent Poisson's ratio; with the increase of the effective pressure and the reduction of hydrate saturation, the tangent Poisson's ratio and initial Poisson's ratio under the same axial strain conditions are reduced, and the starting Poisson's ratio of the hydrate-containing loose sediments is in the range between 0.19 and -0.48 as a whole. The initial Poisson's ratio of the hydrate-containing loose sediments is between 0.19 and 0.48.

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