Study on shear wave attenuation characteristics of shallow sediments in gas hydrate pilot production area of South China Sea

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Abstract. Shear wave attenuation of sediment is an important acoustic feature of seafloor sediment, which reflects the ability of sediment to absorb and dissipate shear wave energy, which is closely related to sediment structure. In order to explore the change rule and influencing factors of shear wave attenuation in sediments, the absorption coefficient was selected as the characterization of shear wave attenuation characteristics, and unconsolidated undrained triaxial shear tests were carried out with two typical sediment silty sand and fine sand in Shenhu sea area of South China Sea as samples. Through comparative analysis, the experimental results show that the shear wave absorption coefficient of sediment is in the process of shear failure at first, it fluctuated slightly, then gradually stabilized, and finally continued to rise in the fluctuation. The shear wave absorption coefficient increases with the increase of porosity and decreases with the increase of confining pressure. In addition, the relationship between the shear wave absorption coefficient and the undrained shear strength of sediment presents a quadratic function. The smaller the shear wave absorption coefficient is, the higher the undrained shear strength of sediment is.

1. Introduction
The South China Sea is rich in natural gas hydrate. Since the 21st century, China has carried out a lot of work on the exploitation of natural gas hydrate [1] [2]. The exploitation of hydrate is accompanied with great environmental risk, and the process of temperature rise or pressure relief caused by external disturbance may induce hydrate decomposition [3] [4]. In order to ensure the safety of engineering activities, it is necessary to monitor the stability of seabed sediments. Shear wave attenuation characteristics of sediments are important acoustic characteristics of seafloor sediments, reflecting the ability of sediment to absorb and dissipate shear wave energy, which is closely related to sediment structure [5] [6]. In the acoustic monitoring of sediment, the attenuation characteristics of shear wave is an important supplement to the shear wave velocity data.
The study of shear wave attenuation characteristics of seafloor sediments is still in the initial stage, and the change of attenuation characteristics and its main control factors, and the relationship with the physical and mechanical properties of sediments need further systematic work [5]. The parameters characterizing shear wave attenuation include quality factor $Q$, absorption coefficient $\alpha$, logarithmic attenuation $\delta$ and attenuation coefficient $\beta$ expressed in decibels. There is a certain relationship between these parameters and can be converted to each other by formula.

In this paper, based on the previous research results and understanding, taking the shallow sediments of the natural gas hydrate pilot production area in Shenhu sea area of the South China Sea as the research object, the variation of the absorption coefficient of the sediments in the process of shear failure is studied by using the bending element equipment through triaxial experiments, so as to explore the variation rules and influencing factors of the shear wave absorption coefficient of the sediments. The research results will be used as a supplement to the study of acoustic characteristics of seafloor sediments and promote the application of shear wave characteristics survey and monitoring in marine areas.

2. Materials and methods

2.1. experimental soil
In this paper, two kinds of typical sediment silt and fine sand in Shenhu sea area of South China Sea are selected to carry out the experiment [7]. The soil samples used in the experiment are prepared by artificial soil mixing. The grading table of experimental soil is shown in Table 1.

| Particle size (mm) | >0.5 | 0.25–0.5 | 0.075–0.25 | 0.005–0.075 | <0.005 |
|--------------------|------|----------|------------|-------------|--------|
| Fine sand          | 5%   | 10%      | 50%        | 25%         | 10%    |
| Silt               | 2%   | 3%       | 20%        | 50%         | 25%    |

2.2. experimental device
In this study, the triaxial test system (model: dynttmaxdyn) produced by GDS company and the supporting bending element system (model: BES) were used. The experimental setup is shown in Fig. 1.
2.3. design of experimental parameters
In order to restore the situation of the in-situ environment of the sediment as much as possible, the unconsolidated undrained shear (Uu) method was used to conduct the experiment. In order to simulate the stress state of sediments with buried depth less than 20m, the soil samples were designed to shear under three effective confining pressures of 50kPa, 100KPA and 200KPa. In the experiment, the loading rate was 0.5%/min, and the compression was continued until the strain reached 15%. The porosity of silt and fine sand samples were 0.41, 0.43, 0.45, 0.47 and 0.49, respectively. A total of 30 groups of experiments were carried out, and all the experiments were conducted at normal temperature (20 ± 2) °C.

2.4. data processing method
In order to study the attenuation characteristics of sediment, the absorption coefficient α is selected as the parameter to characterize the attenuation characteristics of shear wave, which is defined as the attenuation of shear wave amplitude per unit distance. In the actual experiment, the shear wave absorption coefficient of sediment samples is calculated according to formula (1) according to the peak changes of the transmitted wave and the received wave in the shear wave waveform curve, as shown in Fig 2.

\[
\alpha = \frac{(A_1 - A_2)}{L}
\]  

(1)

Where α is shear wave absorption coefficient (mV / M); A1 is emission wave amplitude (MV); A2 is receiving wave amplitude (MV); L is sediment sample length (m).

![Shear wave waveform](image)

**Figure 2.** Shear wave waveform
3. Results and discussion

3.1. Variation tendency of sediments shear wave absorption coefficient during shear failure

In order to study the change law of the shear wave absorption coefficient of sediments during the shear failure process, the stress-strain curve and the absorption coefficient-strain curve obtained are plotted in the same coordinate system, as shown in Figure 3.

At the beginning of shear failure process, the absorption coefficients of each experimental samples has little difference, while the absorption coefficients of the fine sand and silt samples with a porosity of 0.49 are slightly higher than others. The absorption coefficient changes little in the front half part of the experiment, while it fluctuates greatly which shows a wavelike rising trend in the bottom half part. According to the different trends of shear wave absorption coefficient, we divide the shear failure process into three stages.

Stage I: In this stage, the absorption coefficient of the shear wave has a small fluctuation. The internal structure begins to change and sediments have a certain degree of compaction as a result of loading, which might be the cause of the absorption coefficient fluctuations.

Stage II: In this stage, the absorption coefficient of the shear wave is relatively stable and does not change basically. During this stage, the shear band within sediments has begun to develop, but experiments data show that the effect of the change on the absorption of shear wave energy by sediments is weak, and it has not obvious effect on the shear wave absorption factor of sediments.

Stage III: In this stage, the absorption coefficient of shear waves shows a wavelike rising trend in fluctuations. At this time, sediments are completely destroyed, and the shear band inside sediments continues to expand during the subsequent compression process, meanwhile secondary fissures appear which makes sediments structure more and looser than before. This change in sediments accelerates the energy attenuation during shear wave propagation. During this stage, the absorption factor of fine sand and silt samples with high-porosity shows a faster increase rate, which shows internal cracks in loose sediments are more likely to occur and develop faster in a certain extent.
3.2. Influencing factors of sediments shear wave absorption coefficient

The influencing factors of the shear wave absorption coefficient are researched by changing the experimental conditions. The particle size composition of sediments and the experimental equipment in the experiments do not change, sediments porosity varies between 0.41 and 0.49, and the effective confining pressure changes within the range of 0 to 200 kPa. Above experimental conditions set to explore the effects of sediments porosity and effective confining pressure on shear wave absorption coefficient.

Figure 4 shows the relationship between the shear wave absorption coefficient and porosity of sediments. It can be seen that the absorption coefficient of shear waves increases with increasing porosity. This trend is particularly obvious at high porosity which varies from 0.45 to 0.49, and the absorption coefficient of shear waves increases rapidly. Meanwhile this trend is not obvious at low porosity. Previous studies have suggested that the attenuation of shear waves is related to the "viscous" effect between particles and pore water [8][9]. High-porosity sediments have more internal pores, and particles have more contact with pore water, which may cause more attenuation during the propagation of shear waves. For dense sediments with low porosity, the sediments have formed a dense skeleton, and the porosity continues to decline that the pores between the skeletons are filled, and that may have a small effect on the absorption coefficient, which might be the result of the experiment. However, for shallow sediments on the seafloor, the structure is loose and the porosity is...
low, leading to that the shear wave attenuation characteristics will have a sensitive reflection on the change of porosity.

![Figure 4. Effect of sediments porosity (n) on shear wave absorption coefficient (α)](image)

Figure 5 shows the relationship between the shear wave absorption coefficient and the effective confining pressure of sediments. It can be seen in the figure that with the increase of the effective confining pressure, the absorption coefficient of the shear wave exhibits a characteristic of fluctuating decline whose downward trend is close to linear. For the whole process, the shear wave absorption coefficient of samples with high porosity is almost higher than that of samples with low porosity under the conditions of same effective confining pressure. Due to the relative motion between sediments particles during shear wave propagation, the friction force between particles is one of the reasons for the attenuation of the shear wave propagating inside sediments. The rigidity of sediments increases with the increase of the effective confining pressure that makes the contact closer between particles, reduces the relative motion of particles during shear wave propagation, thus reduces the loss of shear wave energy [10]. Therefore, the increase in effective confining pressure decreases the absorption coefficient of shear waves.
3.3. Relationship between sediments attenuation characteristics of shear wave and undrained shear strength

The influence factors of the shear wave absorption coefficient were analyzed above. The shear wave absorption coefficient presented an upward trend with the decrease of the porosity of the sediment and the increase of the effective confining pressure. The undrained shear strength has the same influence factor as the shear wave absorption coefficient. Therefore, we directly fitted the sediment's undrained shear strength with the shear wave absorption coefficient, and the results are as follows.

![Figure 5](image1.png)

*Figure 5. The correlation between the shear wave absorption coefficient $(\alpha)$ of sediments and the effective confining pressure $(\sigma_3)$*

![Figure 6](image2.png)

*Figure 6. Relationship between attenuation coefficient of sediment shear wave and undrained shear strength*
It can be seen from the figure that the shear wave absorption coefficient of the silt and fine sand samples shows a good quadratic function relationship with the undrained shear strength, and the undrained shear strength of the soil decreases with the increase of the shear wave absorption coefficient. Compared with silt samples, when the shear wave absorption coefficient is less than 49 mV/m, the corresponding undrained shear strength of fine sand samples shows a trend higher than the undrained shear strength of silt samples with the same absorption coefficient, and the difference between the two with smaller absorption coefficient is greater. On the contrary, when the shear wave absorption coefficient is greater than 49 mV/m, the undrained shear strength of silt samples with the same shear wave absorption coefficient is slightly higher than that of fine sand samples.

In conclusion, the shear wave absorption coefficient of sediment has a good correlation with the undrained shear strength. The undrained shear strength of sediments can be estimated simply by using the data of the sediment shear wave absorption coefficient.

4. Conclusion
Due to the complexity of shear wave absorption attenuation characteristics, the mechanism of acoustic attenuation characteristics of Marine sediments has not been fully clarified so far. Therefore, it is still a complex problem worthy of attention in the follow-up research. In this paper, the sediment shear wave absorption factor change rule in the sediments of the shear process, the influence factors of shear wave absorption factor and its relationship with the undrained shear strength are studied, based on the results of the experiments of sediment characteristics of shear wave absorption factor has carried on the preliminary analysis, within the scope of the study got the following conclusions:

1) In the process of shear failure, the shear wave absorption coefficient of sediments will successively show different trends: small fluctuations first, then gradual stability, and finally continuous rise in the fluctuation. The rising trend of shear wave absorption coefficient indicates that the sediment has been completely destroyed.

2) The shear wave absorption coefficient of sediments is related to porosity and confining pressure environment of sediments. The absorption coefficient increases with the increase of porosity, especially in the loose sediments with high porosity. Absorption coefficient decreases with the increase of confining pressure.

3) The shear wave absorption coefficient of sediment has a strong correlation with the undrained shear strength of sediment. Within the research scope of this experiment, the relationship between the two shows a quadratic function. The smaller the shear wave absorption coefficient is, the higher the undrained shear strength of the sediment will be. The data of the shear wave absorption coefficient of the sediment can be used to make a rough estimate of the undrained shear strength.

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References
[1] Yu Xinghe, Wang Jianzhong, Liang Jinqiang, et al. Depositional accumulation characteristics of gas hydrate in the northern continental slope of South China Sea [J]. Acta Petrolei Sinica, 2014, 35 (2).
[2] WU Neng-you, ZHANG Guang-xue, LIANG Jin-qiang, et al. Progress of Gas Hydrate Research in Northern South China Sea [J]. Advances in New and Renewable Energy, 2013, 1(1):80-94.
[3] Nagakubo S, Arata N, Yabe I, et al, Environmental impact assessment study on Japan's Methane Hydrate R & D Program [J], Fire in the Ice: Methane Hydrate Newsletter, 2011,10 ( 3 ) : 4–11,
[4] LIU Feng. Hazards in marine hydrocarbon exploitation engineering due to gas hydrate [J]. International Petroleum Economics, 2010 (9):63-67.
[5] Shear waves in marine sediments[M]. Springer Science & Business Media, 2012.
[6] PAN Guo-fu, WU He-jin, WANG Xiao-Yan, et al. Seabed sediment shear wave laboratory measurements by using resonant column test [C]. Symposium on acoustics in Western China: Technical Acoustic, 2015:86-88.
[7] CHEN Fang, Zhou Yang, SU Xin, et al. Gas Hydrate Saturation and its relation with grain size of the hydrate-bearing sediments in the shenhu Area of Northern South China Sea [D]. Marine Geology & Quaternary Geology, 2011.
[8] Biot M A. 1956. Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low frequency range. J. Acoust. Soc. Am., 28, 168-178.
[9] Biot M A. 1956. Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher frequency range. J. Acoust. Soc. Am., 28, 179-191.
[10] LIU Bin, Kern H, Popp T. Velocity and attenuation of P-wave and S-wave in dry and water saturated rock samples with different porosity under different confining pressures. J. Chinese Journal of Geophysics, 1998, 41 (4): 537-546.