Improved Anderson–Hampton acoustic velocity model for marine sandy gas-bearing sediments

Y Wang¹, L Huang², Y L Wang³ and P Cheng⁴

¹ State Key Laboratory and Geotechnical Engineering, Institute of Rock and Soil Mechanics, the Chinese Academy of Science, Wuhan, Hubei 430071, China
² College of Civil Engineering and Architecture, Guilin University of Technology, Guilin, Guangxi 541004, China
³ Key Laboratory of Geotechnical Mechanics and Engineering of the Ministry of Water Resources, Yangtze River Scientific Research Institute, Wuhan, Hubei 430010, China
⁴ School of Civil Engineering and Architecture, Anhui University of Science and Technology, Huainan, Anhui 232001, China

Email: wang831yong@126.com

Abstract. Anderson & Hampton model is an important theoretical foundation for detection of marine shallow gas and identification of gas-bearing sediments. In the acoustic test of sandy gas-bearing sediments, it was found that if the excitation frequency is lower than the bubble resonance frequency, this model overestimates the attenuation of compressional wave velocity of the sediments, and it is difficult to accurately determine the original occurrence status of gas in the sediments by back analysis. The main reason is that the Gassmann equation in Anderson-Hampton model does not accurately describe the modulus parameters of sandy gassy sand sediments. Based on the occurrence characteristics of marine sandy gas-bearing sediments, an improved Anderson-Hampton acoustic velocity model was established by introducing saturation $S_r$ and an attenuation factor reflecting the decay speed of wave speed. The advantage of the new model was pointed out and the sensitivity of parameter was analyzed simultaneously.

1. Introduction
Shallow gas generally refers to the nature gas that accumulates in shallow seabed. The seabed buried shallow gas is regarded as an important marine geohazard. Marine shallow gas often exists in the form of gas-bearing sediments, while sometimes it forms over-pressurized gasbags that usually leaks gas bubbles into the sea. Shallow gas has been found in offshore areas, continental shelves, continental slopes, and deep-sea areas around the world (probably more widely spread in deep-sea). In China, it is commonly found in the offshore areas. Conducting research to investigate the impact of shallow gas presence in the seabed is of great significance to provide guidance for marine drilling, site selection...
and basic maritime planning operations, assessing the stability of submarine slopes, and evaluating natural gas resources under the seabed.

Acoustic detection method is widely used in marine detection. Because the acoustic wave has stronger propagation capability and smaller attenuation than other waves during propagating in water, many nondestructive detection techniques are based on the acoustic method in marine exploration. Hamilton [1] proposed two models for acoustic detection of saturated sediments; one model was developed for high-acoustic-velocity sediments and the other for low-acoustic-velocity sediments. Based on Hamilton models, Lu [2] used the acoustic velocity of seawater $C_0$ as a standard to determine the acoustic velocity of sediments and proposed three typical acoustic velocity structures of shallow sediments. Regarding the acoustic attenuation of saturated sediments, Hamilton [3] proposed an empirical formula for the characteristics of seabed sediments based on large amount of experimental data. Liang et al. [4] proposed a simple formula to calculate the acoustic attenuation of seabed sediments. In 1980, Anderson & Hampton systematically studied the acoustic properties of gas-bearing sediments for the first time using air capsules to simulate gas bubbles in marine muddy sediments. The acoustic model proposed by Anderson & Hampton [5-6] was regarded as an important theoretical foundation for detecting and identifying the shallow gas in marine seabed.

Biot [7-8] established the acoustic propagation theory for wave propagation in saturated rocks using the following methods: 1) considering the coupling effect of the solid and liquid phases; 2) assuming that the solid-phase framework is an elastomer and the liquid phase is compressible viscous fluid; 3) changing the viscosity coefficient of liquid phase to dynamic viscosity coefficient at high frequency [9]. Stoll applied Biot’s theory to submarine saturated sediments and developed the Biot-Stoll model [10]. Gassmann [11] proposed the acoustic propagation theory for rock media by following these steps: 1) considering the structure distribution of solid particles and pore fluids; 2) assuming that the rock shear modulus is not affected by pore fluids and the pores are spherical in shape; 3) ignoring the relative motions between fluids and solids; 4) deriving the corresponding expression for effective bulk modulus [12]. Wood [13] examined the acoustic propagation velocity in muddy sediments based on the following approach: 1) the shear force of suspension is ignored; 2) establishing relationships among volume density, volume compressibility, and volume concentration of suspension according to the suspension composition. And he developed an acoustic propagation equation for argillaceous suspensions. Based on the above-mentioned theoretical models for saturated sediments, Anderson–Hampton model was developed by extending the two-phase media to three-phase media. Using indoor simulation experiments, Anderson and Hampton found that the acoustic velocity, attenuation, reflection, and scattering in gas-bearing sediments are all influenced by the resonant frequency of gas bubbles in the sediments, which is directly affected by the size and shape of bubbles. When the excitation frequency is lower than the bubble resonant frequency, the acoustic velocity approaches a constant that is related to the material properties of sediments, i.e. low frequency stability. When the excitation frequency is higher than the bubble resonant frequency, acoustic velocity also approaches a fixed value related to the properties of the saturated sediments, i.e. high frequency stability. When the excitation frequency is close to the resonant frequency, the compression wave velocity of the gas-bearing sediments significantly changes, leading to complicated acoustic response characteristics.

Since the Anderson–Hampton acoustic model was proposed, significant progress has been reported in understanding the acoustic response characteristics of gas-bearing sediments in the seafloor. Based on the Biot-Stoll model, Bedfod [14] established relationships between the frequency and the wave velocity of gas-bearing sediments through distinguishing different types of soil. Considering different distribution types of bubbles, Hawkins [15-16] introduced an acoustic model for gas-bearing sediments based on the variation theory. Tegowski [17] estimated the bubble concentration in gas-bearing sediments through non-linear acoustic analysis and recognized the difference of scattering between the bubbles and other media, which allowed detecting the volume constant of gas bubbles and estimating their density in sediments. Mantouka [18] developed a linear bubble pulsation model to predict the effect of bubble pulsation on acoustic properties, and estimated the spatial bubble size
distribution. Wilkens [19] used the ASCS in-situ test system to detect the gas-bearing sediments in Baltic Sea and calculated the effective radius of bubbles using Anderson–Hampton acoustic model, and the reliability of the method was verified through laboratory computed tomography (CT) tests.

This paper introduced the experimental basis and theoretical foundation of Anderson–Hampton model, and discussed the potential application of the model in practice. The applicability of Anderson–Hampton model was investigated based on its assumption of gas-bearing sediments. An improved acoustic velocity model for sandy gas-bearing sediments was developed based on Anderson–Hampton model, meanwhile the sensitivity of the model parameters was analyzed.

2. Basic equations of Anderson–Hampton model

The Anderson–Hampton acoustic model relies on the elastic theory to describe acoustic velocity and acoustic attenuation. Based on the stress-strain relationship, when the acoustic wave propagates in the medium, it is primarily controlled by the bulk modulus $K$ and the shear modulus $G$ of the medium. To obtain the values of $K$ and $G$ for gas-bearing sediments, the Anderson–Hampton model considers the gas-bearing sediments as a mixture of particles, pore water, and gas. Wood equation is used to describe the acoustic velocity model for sediments with large gas content, which are regarded as gas-containing suspensions. However, when the gas content in gas-bearing sediments is small, the bulk modulus $K$ and shear stiffness $G$ of the sediments must be considered together. Anderson-Hampton model uses the Gassmann equation to describe it.

When the gas content in gas-bearing sediments is large, the Wood equation can be expressed as:

$$K = \frac{K_w K_m K_g}{n_g K_w K_m + (1 - n)K_w K_g + (n - n_g)K_m K_g}$$

(1)

where, $K$ is the bulk modulus of gas-bearing sediment; $K_w$ is the bulk modulus of pore water; $K_g$ is the bulk modulus of gas, $K_g = \gamma P_0$, $\gamma$ is the specific heat ratio of gas, and $P_0$ is the static confining pressure of sediment; $K_m$ is the bulk modulus of sediment particles; $n$ is the medium porosity; and $n_g$ is the medium porosity with gas.

The compressional wave velocity $V_p$ of gas-bearing sediments is obtained by:

$$V_p = \left(\frac{K}{\rho}\right)^{1/2}$$

(2)

Sediments with small gas content are considered by Anderson & Hampton as “closed system” being similar to the Gassmann model [24]. Meanwhile, the effect of the gas existing in the closed pores on the bulk modulus of pore water must be considered, and $K_w$ in the Gassmann equation should be substituted by $K'_w$:

$$K' = \frac{K_m (K_e + Q')}{K_m + Q'}$$

$$Q' = \frac{K'_w (K_m - K_e)}{n(K_m - K'_w)}$$

$$K'_w = \frac{K_w K_g}{n'_g K_w + (1 - n'_g)K_g}$$

(3)

where, $K_e$ is the bulk modulus of sediment framework; $K'_w$ is the bulk modulus of gas-water mixture in the sediment; and $n'_g$ is the ratio of gas to pores, $n'_g = n_g / n$.

The compression wave velocity of gas-bearing sediment when the gas content is small is expressed as:

$$V_p = \sqrt{\frac{(K+\frac{4}{3}G)}{\rho}}$$

(4)

According to the bubble dynamics theory, acoustic waves can cause bubbles existing in water to vibrate and may even generate strong resonance. Both the cross-sectional distribution of bubbles and the bubble surface attenuation can cause resonance to a great extent. Therefore, bubbles, which are regarded as highly dispersed propagation medium, will inevitably affect the propagation of acoustic waves in the vicinity of the resonance frequency. Anderson & Hampton summarized a large number of
resonant frequency equations, thereby proposing the following equation to determine the resonant frequency for gas-bearing sediments:

\[
f_0 = \frac{1}{2\pi r_0} \left( \frac{3\gamma P_0}{A\rho_s} + 4G \right)^{1/2}
\]

\[
A = (1 + B^2) \left[ 1 + \frac{3(\gamma - 1)}{X} \left( \sinh X - \sin X \right) \right]
\]

\[
B = 3(\gamma - 1) \left[ \frac{X^3(\cosh X - \cos X) + 3(\gamma - 1)(\sinh X - \sin X)}{x^2(\cosh X - \cos X) + 2(\cosh X - \cos X)} \right]
\]

\[X = \frac{r_0 \rho_s s_p}{C_g}\]

where, \(f_0\) is the free-field bubble resonant frequency; \(r_0\) is the equivalent bubble radius; \(A\) and \(B\) are both variable coefficients of pores; \(G\) is the shear modulus of sediment; \(\rho_s\) is the gas density; \(s_p\) is the specific heat of gas under certain pressure; \(C_g\) is the thermal conductivity of gas.

When the excitation frequency is much lower than the bubble resonant frequency, the compressional wave velocity in gas-bearing sediments can be calculated by using Equation (4). When the excitation frequency is close to or higher than the resonance frequency, the velocity ratio \(c_0 / c\) of the acoustic velocity in gas-bearing sediments was provided by Anderson & Hampton, where \(c_0\) is the acoustic velocity in gassy sediments, \(c\) is the acoustic velocity in saturated sediments.

\[
\left( \frac{c_0}{c} \right)^2 = \frac{1}{2} \left[ 1 + \frac{KX_i}{\gamma P_0 + 4G/3} \right] \left[ 1 \pm \frac{KX_i}{\gamma P_0 + 4G/3} \right]^{1/2}
\]

\[
X_i = \frac{\left[ n_s (1-f_i^2) \right]}{(1-f_i^2)^2 + d_i^2}, \quad Y_i = \frac{n_s d_i^2}{(1-f_i^2)^2 + d_i^2}, \quad f_i = \frac{f}{f_0}, \quad \delta_i = \delta_f, \quad \delta_r = \delta_r, \quad \delta' = \text{thermal damping}, \quad \delta_f = \text{radiation damping}, \quad \delta'_i = \text{viscous damping of framework}.
\]

As discussed above, the key to predicting the acoustic velocity of sediments using the Anderson–Hampton model is to obtain the bulk modulus \(K\), shear modulus \(G\), and the bubble resonance frequency \(f_0\) of sediments. The stress level, bubble radius, and gas volume fraction are the main factors affecting \(K\), \(G\), and \(f_0\). Owing to the relatively complex acoustic response of gas-bearing sediments in the stable high-frequency range and near the resonance frequency, the focus of this study is on the acoustic velocity characteristics of gas-bearing sediments in the stable low-frequency range.

3. Acoustic test and predictive analysis for sandy gas-bearing sediments

In order to discuss the suitability of applying the Anderson–Hampton model to sub-sea sandy gas-bearing sediments, the basic physical and mechanical parameters of the gas-bearing sandy sediments were applied to the Anderson–Hampton model (in Table 1). And the result was compared to the laboratory test results. In this study, silty fine sand used for the laboratory tests was taken from the
typical area of Hangzhou Bay, in China. The gas-bearing sand sample was prepared by replacing the water in the saturated sand with a saturated aqueous solution of CO2; and CO2 was released by depressurization to produce uniform gas bubbles in remoulded sand specimens [20]. The reformed sandy gas-bearing sediments specimens were determined the compressive wave velocity in the laboratory. The calculation parameters of the Anderson–Hampton model used to calculate the resonant frequency of bubbles and the compression wave velocity are listed in Table 1.

Table 1. The calculated parameters of Anderson–Hampton model.

| Parameter                             | Value           | Parameter                             | Value           |
|---------------------------------------|-----------------|---------------------------------------|-----------------|
| Water density ($\rho_w$)              | 1.0 kg/m$^3$    | Bulk modulus of pore water ($K_w$)     | 2.3×10$^9$ Pa   |
| Density of saturated sediment ($\rho_{sat}$) | 1804 kg/m$^3$  | Bulk modulus of particles ($K_m$)      | 50×10$^9$ Pa    |
| Specific gravity of sediment ($\rho_s$) | 2.68           | Specific heat ratio of gas ($\gamma$)  | 1.31            |
| Gas density ($\rho_g$)                | 1.83 kg/m$^3$   | Hydrostatic pressure ($P_0$)           | 1.013×10$^2$ kPa|
| Porosity of sediment ($n$)            | 0.52            | Bulk modulus of gas ($K_g$)             | 1.327×10$^5$ Pa |
| Shear modulus of sediment ($G$)       | 53×10$^9$ Pa    |                                        |                 |

Figure 1 shows a comparison between the prediction of Anderson–Hampton model and the laboratory test results.

As can be seen, the results calculated by Anderson–Hampton model are in good agreement with the measured values when the sediment is fully saturated. However, as the saturation decreases and the gas content increases, the measured results are quite different from those predicted by the model, mainly in terms of: 1) the acoustic velocity attenuation predicted by the model is larger than the measured results; 2) although the predicted results indicate that the acoustic velocity in the gas-bearing sediments rapidly attenuates and stabilizes around 640 m/s when the gas content is within 2%, the experimentally measured stabilized wave velocity is higher than that predicted by the model.

In fact, the Anderson–Hampton model does not provide a quantitative demarcation of gas content. Therefore, when applying the model, the corresponding formulation can only be empirically selected. Anderson–Hampton model for smaller gas content is used for sandy sediments, i.e. the Gassmann
However, there are several basic in the Gassmann equation: 1) the rock (solid and framework) is macroscopically uniform; 2) all the pores are interconnected; 3) the fluid (a mixture of liquid and gas) in the pores has no friction effect; 4) the rock-fluid composition system is closed; and 5) the pore fluid does not interact with the solid framework. Because of the large permeability coefficient of sandy sediments, all the pores are interconnected, and there are basically no closed and difficult-to-connect pores in the sand. And assumption 5) of Gassmann equation is violated because of the friction between the water and gas bubbles existing in the pore fluid that caused by their relative movement. In addition, all fluids have certain viscosity, including pore water. Movement between the pore fluid and solid particles will be affected by the viscosity. The viscosity will affect the propagation of acoustic waves, which is also inconsistent with the assumptions of Gassmann equation. In addition, when the relevant model was proposed by Anderson & Hampton, air capsules were used to simulate the air bubbles in muddy gas-bearing sediments for the laboratory test. Such material containing ‘big bubbles’ is only suitable for simulating fine-grained soils. For sandy sediments, the bubbles are mainly distributed in the pore fluid of the soil framework. The microscopic occurrence structure of gas bubbles is obviously different from the experimental basis of Anderson–Hampton model. For the above-mentioned reasons, the Anderson–Hampton model overestimates the attenuation of wave velocity with gas content in sandy gas-bearing sediments.

4. Improved Anderson–Hampton acoustic velocity model

For marine sediments, the physical parameters in fully saturated or fully dry status can be easily determined by laboratory tests. The compressional wave velocity of the gas-bearing sediment should range between the velocities in fully saturated and fully dry sediments. Therefore, by introducing the parameter of saturation, Anderson–Hampton model can be modified and a relationship between the acoustic velocity and saturation is established. Meanwhile, the modified model can also be used in situ wave velocity measurements for back analysis of the original occurrence status of the gas-bearing sandy sediments. Moreover, experiment results also revealed that there is an exponential decay between the compression wave velocity of sandy sediments and the increase of gas content. Therefore, an attenuation factor can be introduced to describe the attenuation law of compressional wave velocity.

The following relationships are workable in Anderson–Hampton model:

\[
K = \frac{K_m(K_f + Q')}{K_m + Q'} = K_f + \frac{Q'}{1 + \frac{Q'}{K_m}} < K_f + \frac{Q'}{K_m} < \frac{K_w}{n}
\]

and

\[
K = \frac{K_m(K_f + Q')}{K_m + Q'} = \frac{K_f + Q'}{1 + \frac{Q'}{K_m}} > K_f
\]

thus

\[
K_f < K < K_f + \frac{K_w}{n}
\]

Upon substitution of Equation (4), we obtain:

\[
V_{ps} \leq \sqrt{\left(\frac{K_f}{n} + \frac{K_w}{n} + \frac{4}{3}G\right)/\rho}
\]

\[
V_{pd} \geq \sqrt{\left(K_f + \frac{4}{3}G\right)/\rho}
\]
\[
\sqrt{\left(\frac{K_r + \frac{4}{3}G}{n}\right)} \leq V_p \leq \sqrt{\left(\frac{K_r + \frac{K_w}{n}}{n}\right) + \frac{4}{3}G} \rho
\]

Therefore,

\[
V_p = \sqrt{\left(\frac{K_r + \frac{K_w}{n}}{n}\right) + \frac{4}{3}G} \rho - S_r \left(\sqrt{\left(\frac{K_r + \frac{K_w}{n}}{n}\right) + \frac{4}{3}G} \rho - \sqrt{K_r + \frac{4}{3}G} \rho \right) (1 - e^{-\alpha(S_r - 1)})
\]

where, VPS is the compressional wave velocity of the fully saturated sediment; VPD is the compressional wave velocity of the completely dry sediment; Sr is the saturation of the gas-bearing sandy sediment; and \(\alpha\) is the attenuation factor, which reflects the speed of the wave attenuation.

Equation (14) is the improved Anderson–Hampton model proposed in this study. Figure 2 shows the experiment results compared to those calculated by the improved model. As can be seen, the wave velocity, the attenuation of wave velocity, and the stabilized wave velocity predicted by the model are in good agreement with the measured values. The improved model can quantitatively describe the relationship between the acoustic velocity and saturation degree for sandy gas-bearing sediments.

Equation (14) is suitable for the highly saturated gas-bearing sandy sediments, with the saturation degree ranging from 80% to 100%. Within this range, the gas bubbles mainly exist in the pore water of the sand framework. When the saturation is lower, the bubble occurrence will change. For example, when bubbles connect to form a “gasbag”, the applicability of the model must be verified. The modified model is based on the Anderson–Hampton theory, and it simplifies the bulk modulus calculation formula of soil framework and introduces an attenuation factor \(\alpha\) to control the attenuation rate of compressional wave velocity. Acoustic velocity experiment can be conducted to summarize the variation law of attenuation factor, \(\alpha\), according to different types of gas-bearing sediments.

In practical projects, the wave velocity of sediments below the seafloor can be easily obtained by the in-situ test; however, it can be difficult to obtain the bulk modulus of the sediment soil framework. Therefore, Equation (11) can be used to calculate the bulk modulus of the sediment, then substituted into equation (12). Finally, Equation (14) can be simplified as a function of compressional wave velocity, saturation degree, and attenuation factor for gas-bearing sandy sediments.

The magnitude of the attenuation factor \(\alpha\) determines the decay rate of the compressional wave velocity with the increase of gas content. However, it does not affect the wave velocity of saturated sediments and the stabilized wave velocity after decayed. The value of \(\alpha\) is affected by factors such as sediment type, degree of density, and roughness of soil particles. The attenuation characteristics of longitudinal waves in the sediment can be quantified by analyzing the change of \(\alpha\). Figure 3 shows a sensitivity analysis of the attenuation factor \(\alpha\).
5. Conclusions

In this study, the theoretical basis of Anderson–Hampton acoustic model was introduced to predict the acoustic wave velocity of sandy gas-bearing sediments. The deficiencies of the Anderson–Hampton model were analyzed and discussed. Furthermore, a modified Anderson–Hampton model was proposed to obtain more accurate predictions for sandy gas-bearing sediments, and the following conclusions were drawn:

1) Based on the theory of continuum medium, the Anderson–Hampton acoustic model regarded the sediment as a mixture of particles, water, and gas. The mixing density, bulk modulus, and shear modulus were calculated by the Wood equation and Gassmann equation. The acoustic response of marine gas-bearing sediments was jointly influenced by the effective radius of gas bubbles, the specific heat of bubbles, the pressure around bubbles, the sediment density, the bulk modulus of sediments, and the shear modulus of sediments.

2) The Anderson–Hampton acoustic model has certain flaws that are mainly manifested in the difficulty to acquire the sediment state parameters. Additionally, Gassmann equation used in this model cannot accurately describe the bulk modulus and shear modulus of sandy gas-bearing sediments, resulting in higher predicted acoustic velocity and acoustic attenuation than the experimentally measured results.

3) An improved Anderson–Hampton acoustic velocity model for sandy gas-bearing sediments was proposed by establishing the relationship between saturation degree and wave velocity. Owing to the limited number of acoustic experiments performed in this study, whether the acoustic velocity model can be applied to other types of sediments remains unknown, and further research should be conducted to verify the issue.

Acknowledgments

Authors gratefully acknowledge financial supports from the National Natural Science Foundations of China (51579237 and 51779017), and the foundation of Yangtze River Scientific Research Institute in China (CKSF2017023/YT & CKSF2016272/YT).

References

[1] Hamilton E L 1980 Geoacoustic modeling of the sea floor J. Acoust. Soc. Am. 68 1313-40
[2] Lu B 1995 Model of sound velocity structure in seawater-sediments B. Mar. Sci. 14 42-47
[3] Hamilton E L 1978 Sound velocity-density relations in sea-floor sediments and rocks J. Acoust. Soc. Am. 63 366-77
[4] Liang Y B, Li C Z and Lu B 1981 Physical and engineering properties of deep sea sediments (Beijing: Ocean Press) pp106-20
[5] Anderson A L and Hampton D L 1980 Acoustics of gas-bearing sediments I. Background J.
[6] Anderson A L and Hampton D L 1980 Acoustics of gas-bearing sediments II. Measurements and models J. Acoust. Soc. Am. 67 1890-903

[7] Biot M A 1956 Theory of elastic waves in a fluid-saturated porous solid I. Low-frequency range J. Acoust. Soc. Am. 28 1768-84

[8] Biot M A 1956 Theory of elastic waves in a fluid-saturated porous solid II. High-frequency range J. Acoust. Soc. Am. 28 179-91

[9] Zou D P, Yan P and Lu B 2012 A geoacoustic model based on sound speed characteristic of seafloor surface sediments of the South China Sea ACTA Oceanol. Sin. 34 80-86

[10] Stoll R D and Kan T K 1981 Reflection of acoustic waves at a water-sediment interface J. Acoust. Soc. Am. 67 131-62

[11] Gassmann F 1951 Elastic waves through a packing of spheres Geophysics 16 673-85

[12] Zhang Z Y, Fan T and Wang X L 2015 Pore structure parameters influences on various types of seismic wave propagation Advances in Earth Science 30 1306-25

[13] Wood A B 1955 A textbook of sound: The low-frequency sound speed of fluid-like gas-bearing sediments (London: G. Bell) p 578

[14] Bedford A and Stern M 1983 A model for wave propagation in gassy sediments J. Acoust. Soc. Am. 73 149-56

[15] Hawkins J A and Bedford A 1992 Variational theory of bubbly media with a distribution of bubble size-I Liquids Int. J. Eng. Sci. 30 1161-76

[16] Hawkins J A and Bedford A 1992 Variational theory of bubbly media with a distribution of bubble sizes-II. Porous solids Int. J. Eng. Sci. 30 1177-86

[17] Tegowski J, Klusek Z and Jakacki J 2006 Nonlinear acoustical methods in the detection of gassy sediments Acoustic Sensing Techniques for the Shallow Water Environment ed Caiti A and Chapman N R et al (Netherlands: Springer) pp 125-36

[18] Mantouka A, Dogan H, White P R, and Leighton T G 2016 Modelling acoustic scattering, sound speed, and attenuation in gassy soft marine sediments J. Acoust. Soc. Am. 140 274-82

[19] Wilkens R H and Richardson M D 1998 The influence of gas bubbles on sediments acoustic properties: in suit, laboratory, and theoretical results from Eckernförde Bay, Baltic sea Cont. Shelf Res. 18 1859-92

[20] Cheng P 2017 Experimental study on acoustic properties of seabed gas charged sand sediments (Huainan: Anhui University of Science and Technology) p 22