Shallow gas detection and data transmission in the formation

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Abstract. In recent years, with the proposal and implementation of national marine strategy, more and more marine engineering facilities are being developed. All marine engineering construction is bound to be inseparable from marine geological survey, and the existence of shallow gas in the stratum is also a big invisible danger in the engineering. Therefore, this study used waterproof and breathable film to separate the shallow layer of gas, then measured the methane concentration with infrared methane gas sensor and sent the formation information measured by CPTU probe the data acquisition module through the electromagnetic wave wireless module. Finally, all measured values are transmitted to the ground via a cable.

1. Introduction
Shallow gas refers to various types of natural gas resources with relatively shallow burial depth and relatively small reserves [1]. It mainly includes biogas, oil gas, coalbed methane and water soluble gas, etc. It is mainly composed of methane, a small amount of carbon dioxide and nitrogen. On the one hand, shallow gas can be used as a new energy utilization development, on the other hand, the leakage and eruption of shallow gas will cause great harm to the construction of marine engineering. During the development, serious disasters were caused due to insufficient investigation of shallow gas. With the continuous development of China’s economy, people are paying more and more attention to the development of marine resources and the construction of marine engineering. But the construction of various ports and sea-crossing bridges and the implementation of engineering projects need to understand the seabed conditions. Therefore, it is necessary to design a detection device capable of detecting the methane concentration and the location layer information in the shallow gas.

At present, the main methane detection method used in China is mainly the exploration drilling method [2], which is used to press the probe into the sediment by hydraulic device, and then collect the shallow gas by the drainage gas collection method, and use the gas chromatograph in the laboratory. The concentration of each gas in the shallow gas was measured by infrared absorption spectroscopy. Although the method has high precision, it cannot measure in real time, the detection period is long, the cost is high, and the physical and mechanical characteristics of the formation cannot be known, which cannot meet the engineering needs. Therefore, this paper designs a real-time and fully functional detection device to meet engineering requirements.

2. Shallow gas detection system design
Firstly, the probe is pressed down by the penetration device, and the CPTU probe at the lowermost part of the probe measures the cone resistance, the side wall friction force and the pore water pressure, and
outputs corresponding signals. At the same time, the porous ceramic and the permeable stone part of the gas separation probe are used for solid-liquid separation, the gas-liquid separation is realized by the polymer waterproof and gas permeable membrane in the probe. Finally, when there is shallow gas outside the probe, the methane sensor inside the probe senses the concentration of methane and output the corresponding signal, as shown in Figure 1.

Due to the presence of the polymer waterproof gas permeable membrane and the structural problems of the probe, the signal amount of the CPTU output cannot be transmitted by the cable. Therefore, two wireless signal transmission modules are used to transmit the signal to the probe in which the methane sensor is located, and then the semaphore of the CPTU probe and the methane sensor are converted into corresponding specific values, and the data are transmitted to the mother ship through the cable wrapped by PVC transparent hose inside the probe pole, and the changes of each value are displayed by the upper computer. The overall scheme design is shown in Figure 2.

Porous ceramics for solid-liquid separation in design are porous ceramic sheets with small pore size and high open porosity prepared by high-quality raw materials such as corundum sand, silicon carbide and cordierite, and formed by special high-temperature sintering process. The material has more uniform and controllable pores, and the filter material is in full contact with the ceramic material, which can well block the mud outside. In order to achieve better solid-liquid separation, a permeable rock with a smaller pore size is added inside the probe.

The waterproof breathable membrane used in the design is a kind of polymer multi-microporous membrane made of PTFE. The ePTFE film is prepared by biaxial stretching process and has a micro-network structure of "micro-fiber—node" (as shown in Figure 1). The minimum pore size of this network structure is 0.1 micron, and the number of micropores per square centimeter is as high as billions. These micropore diameters are one percent of the smallest water droplets (light fog) diameter (about 20 microns), and thousands of times larger than water molecules. Because of the existence of surface tension, they can block the passage of liquid water or solid particles, while allowing air or steam to pass through, so they have good water-proof, dust-proof and air-permeable functions.

The function of the gas separation probe is to separate the shallow gas from the seawater and the mud. The main part is mud water separation device, pressing device, compression gasket, gas-liquid separation chamber, sensor placement room. The main function of the CPTU probe is to determine the basic physical and mechanical properties of the seabed soil and the bearing capacity of the foundation to facilitate the construction of the engineering facilities. The main test parameters are cone head resistance, sidewall friction and pore water pressure. Since the gas separation probe and the CPTU probe have different outer diameters, a diameter reduction is required to combine the two. Its overall structure is shown in Figure 3.
The probe can be regarded as an ideal circular waveguide. The surface current inside the waveguide is the main cause of the attenuation of the electromagnetic wave power \[4\]. The attenuation coefficients of the electromagnetic waves of different waveforms are different. According to the waveguide theory, there are only two waveforms in the ideal waveguide: TM wave and TE wave \[5\]. The attenuation coefficient can be calculated by the following equation formula:

\[
\alpha_{\text{TM}} = \frac{R_s}{a Z_0} \frac{1}{\sqrt{1 - \left(\frac{\lambda}{\lambda_{\text{TM},mn}}\right)^2}}
\]

(1)

\[
\alpha_{\text{TE}} = \frac{R_s}{a Z_0} \frac{1}{\sqrt{1 - \left(\frac{\lambda}{\lambda_{\text{TE},mn}}\right)^2}} \left[\left(\frac{\lambda}{\lambda_{\text{TM},mn}}\right)^2 + \frac{n^2}{(\rho_{\text{mn}})^2 - n^2}\right]
\]

(2)

\[
\frac{\lambda_{\text{TM},mn}}{a} = \frac{2\pi}{\rho_{\text{mn}}} \quad \frac{\lambda_{\text{TE},mn}}{a} = \frac{2\pi}{\rho'_{\text{mn}}}
\]

(3)

The values of \(\rho_{\text{mn}}\) and \(\rho'_{\text{mn}}\) are determined (can be checked the table is obtained), so the cutoff wavelength of each waveform is only related to the radius of the circular waveguide, and the larger the radius of the circular waveguide, the larger the cutoff wavelength of each waveform. Table 1 and Table 2 give the partial zeros of the first type of Bessel function and its derivatives, respectively.

| \(m\) | \(n\) | 1    | 2    | 3    | 4    |
|-------|-------|------|------|------|------|
| 0     |       | 2.405| 5.520| 8.654| 11.792|
| 1     | 0     | 3.832| 7.016| 10.173| 13.324|
| 2     | 1     | 5.136| 8.417| 11.620| 14.796|
| 3     | 2     | 6.380| 9.761| 13.015| 16.796|
| 4     | 3     | 7.588| 11.065| 14.372| 17.616|
Table 2. Zeros of the first class Bessel function derivative

| m | n  | 1     | 2     | 3     | 4     |
|---|----|-------|-------|-------|-------|
| 0 | 0  | 0     | 3.832 | 7.016 | 10.173|
| 1 | 1  | 1.841 | 5.331 | 8.536 | 11.706|
| 2 | 2  | 3.054 | 6.706 | 9.969 | 13.170|
| 3 | 3  | 4.201 | 8.015 | 11.346| 14.586|
| 4 | 4  | 5.317 | 9.282 | 12.682| 15.964|

Substituting the values of $\rho_{nm}$ and $\rho_{nm}'$ into equation (3) gives the value of $\frac{\lambda_{TE,cm}}{a}$ and $\frac{\lambda_{TM,cm}}{a}$ as shown in Table 3.

Table 3. The value of $\frac{\lambda_{TE,cm}}{a}$ and $\frac{\lambda_{TM,cm}}{a}$

| m  | n=0 | n=1 | n=2 |
|----|-----|-----|-----|
|    | $\lambda_{TM,cm}/a$ | $\lambda_{TE,cm}/a$ | $\lambda_{TM,cm}/a$ | $\lambda_{TE,cm}/a$ | $\lambda_{TM,cm}/a$ | $\lambda_{TE,cm}/a$ |
| m=1 | 2.6127 | 1.6398 | 1.6398 | 3.4126 | 1.2235 | 2.0572 |
| m=2 | 1.1382 | 0.8956 | 0.8956 | 1.1785 | 0.7465 | 0.9369 |

Assuming that the wavelength of the electromagnetic wave in this design is $\lambda$, the radius of the drill pipe is $a$, the concept of the cutoff wavelength shows that only electromagnetic waves with a wavelength smaller than the cutoff wavelength can propagate in the waveguide. Therefore, only the waveforms satisfying $\lambda_{c,cm} > \lambda$ in Table 3 can be propagated in the drill pipe.

This design selects a commonly used wireless signal transmission module with a frequency band of 2.4 GHz. According to the wavelength calculation formula, the frequency is 2.4 GHz, the corresponding wavelength $\lambda = 125$ mm, the drill rod radius is 46 mm, and the ratio of the wavelength to the radius is approximately equal to 2.7173. Only the $TE_{11}$ wave can be propagated in the drill pipe according to Table 3. Substituting the wavelength and radius into equation (2) can obtain the minimum attenuation coefficient of $TE_{11}$ in the drill pipe, which is more suitable for signal transmission and meet the requirements of this experiment.

3. Experimental results

In order to ensure that the signal is transmitted in the drill pipe, the receiving and transmitting module are placed in a galvanized pipe. Then a two-meter long galvanized pipe is respectively connected at both ends of the galvanized pipe, so that it can be guaranteed that the electromagnetic wave signal is propagated in the tube. Through experimental tests, the 2.4GHz wireless signal transmission module can transmit up to 30cm, meeting the experimental requirements, the data measured by the CPTU probe can be communicated to the sensor chamber across the intermediate barrier.

In order to further verify that the electromagnetic wave signal can be transmitted in the probe, it is necessary to completely enclose the wireless module in the probe, but because it cannot be powered by the power supply in a fully enclosed environment, it is powered by a small enough 5V lithium battery. The wireless module requires a 3.3V power, and a step-down circuit is needed to convert the 5V to 3.3V, specifically as shown in Figure 4.
Because the probe is made of stainless steel, the board needs to be protected with electrical tape to prevent short circuits. The connected wireless module is shown in Figure 9. According to the principle of the transmission line, when the length of the antenna is one quarter of the wavelength of the electromagnetic wave, the optimum gain is obtained, and the loss is the smallest. Therefore, a copper wire having a length of one quarter of the wavelength is selected as the antenna, and finally the wireless module is enclosed in the probe. The wireless module in the sensor placement room can receive the signal from another wireless module placed at the bottom of the probe, therefore the method is feasible. By introducing different concentrations of methane into the probe, the infrared methane sensor can measure the methane concentration of the gas, and the device is reliable by comparing with the actual value, as shown in Figure 5.

4. Conclusion
In this paper, a set of experimental devices combining methane detection and pore pressure static penetration are designed. Methane concentration in shallow gas and basic physical and mechanical properties of soil were measured by infrared methane sensor and CPTU probe. In the future, this device will be improved by using better data processing methods to reduce errors. The device is only tested in the laboratory, in-situ field testing is required to obtain more accurate experimental data. It can be widely used in developing shallow gas resources at sea bottom and guiding Marine engineering construction.

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