Research on in-situ observation system of seabed boundary layer based on self-potential measurement

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Abstract. The submarine boundary layer is a dynamically changing strip located near the seabed interface. The dynamic change process involves the resuspension and redeposition of sediments, which has an important impact on the transportation of seafloor sediments and the transport of offshore chemical substances. Based on the self-developed self-potential monitoring device, the stability of the device and the characteristics of the seabed and the bottom layer of the sea floor with different textures were tested through laboratory experiments. The results show that the self-developed self-potential monitoring probe has high corrosion resistance, good electrode stability, and guaranteed measurement accuracy. The self-potential measurement can clearly identify the position of the seabed interface, and can judge seabed sediments by positive and negative anomalies. Nature, the sandy seabed is negative anomaly (about -8 mv), the clayey seabed is positive anomaly (about 10 mv). The concentration of solid suspended particles in the seawater and the self-potential difference between the seawater and the seabed appear relatively good linear relationship, the smaller the difference, the greater the concentration of solid suspended particles. The re-deposited sediment changes its self-potential under the influence of material composition and pore structure, but this effect gradually decreases as the consolidation time increases. Therefore, the spontaneous potential measurement can better reflect the dynamic changes of the seafloor sediments, and effectively monitor the dynamic changes of the seafloor boundary layer. It provides a new method for the in-situ observation of the dynamic changes of the submarine boundary layer.

1. Introduction
The seafloor boundary layer is a dynamically changing band located near the seabed interface, and its dynamic change process has an important impact on the seafloor dynamic process, especially in sediment transport and the transport of chemical substances near the seabed [1-3]. Currently research believes that high-concentration suspended sediment layers on the seabed, and transport of fine-grained sediments on the seafloor are all included in the study of the seafloor boundary layer [4,5]. That is, the
seafloor boundary layer contains both the overlying fluid in the range of 1-2 m above the seabed interface and the active sediments in the shallow surface of the seabed [6]. A large number of studies have shown that seabed sediments and high-concentration suspended sediment layers can undergo a series of changes under the action of ocean dynamics. Especially under extreme sea conditions, the changes of the seabed boundary layer are even more dramatic and complicated. These changes are mainly reflected in the concentration of solid suspended particles in the water and the porosity of the sediments. Therefore, the in-situ monitoring of the seabed boundary layer is also mainly focused on the measurement of the concentration of solid suspended particles in the water [7]. How to capture these changes in the first time and master the real-time data of the dynamic changes of the seabed boundary layer in order to obtain real observation data and predict the changes of seabed sediment erosion and deposition.

For the measurement of solid suspended particles in water, the following four methods are generally used: on-site conventional water sampling and filtration, optical backscattering technology, on-site laser particle size analyzer measurement and acoustic reflection technology [8-10]. For the measurement of sediment porosity, sampling, resistivity or acoustic parameter inversion are generally used. None of the above measurement methods can simultaneously measure the upper and lower parts of the seabed interface. Therefore, Jia Yonggang et al [11] proposed the method of measuring the seafloor boundary layer using resistivity, and developed a high-density resistivity probe. The functional relationship [12,13], which enables simultaneous measurement of the upper and lower parts of the seabed interface. However, this method based on resistivity test is greatly affected by the nature of its own electrode material and the chemical characteristics of seawater, the polarization phenomenon of the electrode is more obvious, and the measurement stability needs to be improved. The measurement of self-potential, which is also an electrical characteristic, can avoid this effect, and no power supply is needed during the measurement of self-potential [14,15]. The electrode has high stability and is more suitable for long-term in-situ observation of submarine sediments.

Therefore, in order to improve the stability and accuracy of the test, and can more effectively process the test results. In this paper, a system based on self-potential measurement of the seafloor boundary layer is developed. The barrel crosses the potential difference to identify the seabed interface. Based on the relationship between the self-potential and the suspended concentration of solid particles in seawater and the porosity of the bottom sediment, the Response model of dynamic changes of the seabed boundary layer.

2. Materials and methods

2.1 Probe for self-potential measurement

In order to achieve the goal of in situ observation of the seabed boundary layer based on spontaneous potential measurement, this paper independently developed spontaneous potential measurement probe, which consists of three parts: rod body, electrode sensor and acquisition system.

(1) The probe rod

The rod body is about 1.3m high and 7.5cm in diameter. It is mainly composed of metal bottom cone, tie rod, insulating gasket and sealing ring as shown in Figure 1. Insulate the gasket and the sealing ring on the pull rod in turn along the axis. The top and bottom of the insulating gasket are respectively provided with grooves to place the sealing ring. The top and bottom of the pull rod are respectively reserved with threads, the lower part is connected with the bottom cone, and the upper thread is used to compress the entire rod body so that the sealing ring can achieve the sealing effect. A total of 50 insulating gaskets are used, each with a height of 2 cm and 100 sealing rings.
Figure 1. The components of self-potential probe rod body.

(2) Electrode sensor

The electrode sensor is composed of 50 solid reference electrodes connected with a copper wire of equal length. The electrode ring used in this device is an all-solid, maintenance-free reference electrode independently developed by us. The electrode uses titanium alloy as the skeleton surface to be uniformly coated with a layer of graphene material about 0.1 mm thick, so as to achieve the effect of high stability and corrosion resistance. In order to reduce the resistance at the welding place, the reference electrode and the copper wire are connected by conductive silver glue, and then the connection place is coated with waterproof glue for double fixing and waterproof effect. The whole spontaneous potential probe is assembled as shown in Figure 2. Each wire corresponds to an electrode ring with a measurement height of 1 m and a resolution of 2 cm.

As shown in Figure 2, the top compartment is not sealed. However, during actual underwater use, the top of the cabin is sealed, so in this case only the electrode ring will be exposed to the water environment.

Figure 2. Physical picture of self-potential measurement probe.

(3) Collection System

In order to cooperate with the use of self-potential probes, we independently developed a multi-channel self-potential acquisition instrument. Figure 3 shows the circuit board of the collector. The collector has 48 channels, and the maximum number of electrodes can be up to 96. The operating power of the system is less than 7 w, the output current accuracy is less than 50 μA, and the voltage resolution is less than 2 μV, and the acquisition signal can be amplified by 5 times for easy processing. In addition, the electrode switching switch of the traditional electrical measuring instrument is generally controlled
by a relay, the volume and weight of the instrument are relatively large, and the switch contact has a certain service life and limit of the number of switches. With the advancement of technology and technology, the advantages of analog switch components such as small size, low internal resistance, and high switching frequency have become increasingly prominent. This subsystem uses analog switch group chips to control the switching of electrodes, reducing the volume and weight of the instrument, which is conducive to transportation and deep-sea deployment.

In addition, for the use of deep-sea environment, considering the problem of pressure resistance in deep-water environment, our design is to use integral injection molding to process the probe. First, make the mold for the rod body, then evenly arrange the electrode ring with the wires connected in the direction of the extension axis of the mold, and then place the main skeleton with the bottom cone on the lower part of the steel bar through all the electrode rings and place in the mold. Finally, the mold is combined and the ABS plastic is injected, the mold is opened after the pressure is maintained and cooled, and the rod is tested.

2.2 The test of Probe calibration
Due to the difference in electrode materials and wires, even if the process has been processed in accordance with the standardized process during the manufacturing process, it still cannot guarantee that the characteristics of each electrode ring are the same. Therefore, it is necessary to calibrate each electrode of the self-potential probe. In addition, the components of the analog switch in the collector will produce a small amplitude of current during the work process, which will affect the test results. Therefore, in the actual test process, the noise generated by this part of the test must be removed to calibrate the collector. So, a saturated calomel electrode is used as a fixed electrode to calibrate the system, and the potential difference between the fixed electrode and each electrode on the probe in tap water is measured in sequence. A total of 8 groups of tests were conducted, each group with a test interval of 24h, at room temperature, and each group of tests was averaged 3 times. Because the probe and the probe are not assembled together during the probe calibration test, the top of the probe is still hollow. In order to prevent water from entering the rod, the top 13 electrode rings were not immersed in the water body during the calibration test, so the number of electrode rings tested was 37. The electrode rings are numbered sequentially from the bottom cone upwards, respectively 1, 2, 3...37.

2.3 The self-potential test of difference sediment
Two different sediments are selected, one is the Yellow River Estuary sandy sediments, and the other is the South China Sea clay sediments, washed and dried for use. Put the self-potential probe into the water tank and fix it, and then install the sandy sediments of the Yellow River Mouth into the water tank until 10 electrode rings are buried. Then add seawater to the water tank until there are no more than 20 electrode rings, and let stand for 24 hours until the upper water body is clarified. This experimental design is mainly to obtain the position of the seabed interface more clearly. The electrode in the water body is used as a fixed electrode, and the potential difference between the fixed electrode and other electrode rings is measured respectively. The test results are averaged over 3 tests. In order to reduce the influence of the side wall effect, the No. 18 electrode was selected as the fixed electrode, and the above experimental steps were repeated after changing the clay sediment after the test.

3. Results and discussion

3.1 Calibration of self-potential probe
Figure 4. The results of calibration test.

Figure 4 shows the results of eight tests of self-potential probe calibration at room temperature. A-H represents the data of 8 groups of tests. Overall, the potential difference of each electrode ring fluctuates between 60-90 mv. Different electrode rings have the difference in potential difference within 20 mv in the same measurement, and more than half of the electrode ring values change within 10 mv. The same electrode ring has different test results in different measurements, and the change range is large, up to 40 mv, but most of the changes are within 10 mv. Among the test results of each group, obvious outliers appeared in group A. Group A is the first test result. The potential difference between each electrode ring varies greatly, and it is different from the test result change trend of other groups, especially in the electrode rings labeled 20-37. The main reason is that the group A test is the first test of the probe, and the test results are unstable. The electrode ring reacted abnormally in the water environment for the first time, or the analog switch in the collector had abnormality. Therefore, to eliminate the impact of the first test, the probe was immersed in water for 24 hours and the collector was used for 12 hours. The results show that this large-scale numerical anomaly disappears in future measurements. On the whole, except for the test results of group A, although the measurement results of the other groups have certain changes, the trend of change is the same, which also indirectly illustrates the stability of the self-potential measurement system. Therefore, the average value of multiple measurement results is used as the background self-potential of each electrode ring, and future measurement results need to subtract this background value to be the real measurement result.

3.2 Potential difference of sediment
Figure 5. The result of diffidence sediment.

Figure 5 shows the measurement results of the self-potentials of the two sediments. It can be found that when the electrode rings are in the water environment, the potential difference between the electrode rings is almost zero. When one electrode ring is located in the water body and the other electrode ring is located in the sediment, the potential difference will be abrupt. The points where the potential difference in Figure 5 occurs suddenly occur at the seabed interface, that is, the environment where the electrode ring is located changes. Therefore, the position of the seabed interface can be better identified by means of self-potential measurement. And the types of sediments can be distinguished according to positive and negative anomalies. Clay sediments show positive anomalies, and sandy sediments show negative anomalies. This is because the electrode ring is more sensitive to Cl\(^-\) in the solution during the test. When the relative concentration of Cl\(^-\) is higher, the anion predominates in a negative anomaly, and when the relative concentration of Cl\(^-\) is lower, the cation in the solution predominates that shows a positive abnormality. The reason for this difference in Cl\(^-\) concentrations is speculated to be due to the double electron layer of clay minerals. The outer ions of clay minerals attract Cl\(^-\) in the solution, thereby reducing the relative concentration of Cl\(^-\) in the solution, causing the self-potential to behave as a positive anomaly.

In addition, the potential difference in the sediment shown in Figure 5 has a certain change with the depth of the sediment. This change has a certain law, and whether the law of this change is affected by the way of measurement. Therefore, the electrode measurement method is changed, and the potential difference between adjacent electrode rings is measured in sequence from top to bottom. The result is shown in Figure 6. No matter in the water body or in the sediment, as long as the two electrode rings are in the same environment, the potential difference between the two electrode rings is zero. When the environmental conditions change, the potential difference appears abruptly, and different sediment potential differences show different differences. In Figure 5, the potential difference between the sediment and the electrode in the water body changes with the depth of the sediment. This change is directly related to the physical properties of the sediment. The classic Archie formula indicates the relationship between resistivity and sediment porosity and saturation. The seabed sediment as a saturated soil body, this relationship is only related to the pore structure, from which we can speculate the relationship between the self-potential and the porosity of the seabed sediment, so as to determine the dynamic changes of the seabed boundary layer.

In order to better verify the stability of the device and the accuracy of the measurement, we conducted an in-situ test of the self-potential of the sediment in the harbor basin, and the results are shown in Figure 7. We found that the natural potential transition is not as obvious as in the laboratory. The main reason is that when the probe was lowered, the bottom sediment was suspended in the sea during the period when the bottom sediment was disturbed, which affected the natural potential test results. However, the location of the seabed interface can still be identified as a whole.
4. Conclusion
This research focuses on the in-situ observation system of the seabed boundary layer. Through the development of an all-solid-state maintenance-free reference electrode, an in-situ observation system for dynamic changes of the seabed boundary layer based on spontaneous potential measurement was designed. Based on the difference in self-potential between the water body and the sediment, the position of the seabed interface can be clearly identified, and the potentials of different types of sediments vary greatly. Clay sediments exhibit positive anomalies and sandy sediments exhibit negative anomalies. The existence of such positive and negative anomalies may be related to the structure of the double electron layer of clay minerals. This paper validates the method of determining the seabed interface through self-potential measurement. Clarified that the self-potential value of the seabed sediments is related to the physical properties of the sediments, but what specific relationship there exists requires a lot of experimental data for further research.

Reference:
[1] Williams J J, Rose C P, Thorne P D et al 1999 Field observations and predictions of bed shear stress and vertical suspended sediment concentration profiles in wave-current conditions 
Continental Shelf Research 19 507-536.
[2] Jeng D S 2001 Mechanism of the wave-induced seabed instability in the vicinity of a breakwater: A review Ocean Engineering 28 537–570.
[3] Jia Y, Zhang L, Zheng J 2014 Effects of wave-induced seabed liquefaction on sediment re-suspension in the Yellow River Delta Ocean Engineering 89 146-156.
[4] Bedford K W, Libicki C, Wai O, Abdelrhman M, Iii R V E 1988 The structure of a bottom sediment boundary layer in central long island sound Springer Berlin Heidelberg 446-459.
[5] Agrawal Y C, Pottsmith H C 1994 Laser diffraction particle sizing in STRESS Continental Shelf Research 14 1101-1121.
[6] McKee B A, Aller R C, Allison M A 2004 Transport and transformation of dissolved and particulate materials on continental margins influenced by major rivers: benthic boundary layer and seabed processes Continental Shelf Research 24 899-926.
[7] Ramirez-Llodra E, Trannum H C, Evenset A 2015 Submarine and deep-sea mine tailing placements: A review of current practices, environmental issues, natural analogs and knowledge gaps in Norway and internationally Marine Pollution Bulletin 97 13-35.
[8] Eisma D 1993 Suspended matter in the aquatic environment Springer Berlin Heidelberg New York 315 pp.
[9] Hamilton L J, Zhang Z S Y 1998 Acoustic Backscatter Measurements of Estuarine Suspended Cohesive Sediment Concentration Profiles Journal of Coastal Research 14 1213-1224.

[10] Adams C E J, Wells J T, Park Y A 2013 Wave motions on a lutocline above a stably stratified bottom boundary layer Nearshore and Estuarine Cohesive Sediment Transport American Geophysical Union 393-410

[11] Jia Y G, Dai Q, Shan H X and Cui W L 2011 A laboratory study on the relationships between suspended sediment content and the conductivity and their influencing factors Acta Oceanologica Sinica 33 88-94 (in Chinese)

[12] Guo L 2012 Research on optimal design of improved multi-electrode resistivity probe Qingdao Ocean University of China

[13] Guo L, Wen M Z and Shan H X 2016 Study on Re-suspension process of seabed sediment induced by wave Marine Geology & Quaternary Geology 36 181-188.

[14] Liu J, Liu S D, Yang S L and Wang B 2013 Self-potential response characteristics to water seepage in wall rocks affected by mining Journal of China Coal Society 38 1031-1037 (in Chinese)

[15] Wang J J, Tao C H, Wang H J, Deng X M, Xiong W and Li Z 2018 Study of self-potential observation ways in the seafloor polymetallic sulfide deposits Haiyang Xuebao 40 57-67 (in Chinese)

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