Stability of submarine landslides by in situ observation

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Abstract. With the continuous expansion of human activities to the ocean and the development of marine engineering, the stability of submarine landslides has attracted increasing attention. Monitoring data of the stability of submarine landslides under the action of strong wind and waves remain lacking because of limited observation technology and complex real sea conditions. This paper reports the long-term and continuous stability monitoring of submarine landslides under the action of wind and waves in the seabed of the Zhujiajian landslide area of Zhoushan by using a self-developed observation equipment. Effective data were collected, and variations in the pore pressure and displacement of seabed under the action of wind and waves were analyzed. Then, problems related to the change of displacement of seabed under the action of waves were explored. A typhoon event occurred during the observation period, and the significant wave height increased significantly from about 0.1 m under calm sea conditions to 0.5 m. The excess pore pressure in the sediment of 1 m under the seabed fluctuated obviously under the action of waves, with an amplitude of 2–4 kPa. By contrast, the amplitude of excess pore pressure oscillation was about 0.5 kPa under calm sea conditions, and the wave enhancement significantly increased the excess pore pressure oscillation in shallow sediments. The displacement of 0.5 mm occurred from 12 m to 13.5 m under the seabed, and the rapid accumulation or large fluctuation of lateral displacement occurred at different depths during the three periods when the significant wave height peaked.

1. Introduction

Seabed sediments under the action of extreme wave loads are prone to instability, which leads to geological disasters, such as submarine landslide and collapse depression. Based on geophysical survey and laboratory tests, some scholars have proposed various seabed deformation and sliding modes, such as circular shear sliding [1], rotary sliding [2], plane shear sliding and flow sliding [3], which pose a serious threat to the safety of submarine pipelines, platforms, and other engineering structures.

The deformation and sliding of seabed are the most intuitive index to reflect seabed stability. On the one hand, observation data can be used to analyze the deformation characteristics of geological disasters in the early stage of seabed and provide strong evidence for the study of disaster mechanism. On the other hand, it can provide early warning for marine engineering and ensure the safety of engineering and personnel. The implementation of in situ observation is difficult because of the complex engineering dynamic geological process of the seabed and the high technical requirements for the observation equipment. As a result, research on the...
deformation and sliding of the seabed, especially the in situ observation method of large-scale long-distance sliding migration, is still in the exploration stage at home and abroad. The deformation of sea floor caused by submarine tectonics and subduction can be classified into ocean floor deformation, submarine tectonic deformation, and submarine gas hydrate deformation. The high requirements of equipment, technology, and cost and the randomness of seabed deformation and sliding events complicate the collection of relevant data and cause a low rate of return. Few observation methods are currently available for seabed deformation at home and abroad. Therefore, the development of seabed deformation observation technology means we should learn from the methods of other research fields and chose appropriate development and application processes.

As early as the 1980s, in the Sino US Canada joint investigation, Prior et al. used the seabed sediment dynamic recording system to record the dynamic characteristics of seabed soil in the Yellow River Estuary during storm surges [4]. Results showed that some original landslides would “resurrect” and that their locations would hardly change. The reactivation of silt flow landslides is caused by the disturbance and reduction of sediment strength. The system consists of a triaxial acceleration sensor and an inclinometer. The dynamic characteristics of seabed soil can be reflected by recording the acceleration value and the change in inclination angle. Similar to Prior et al., Saito et al. [5] also designed a seabed displacement monitoring system by using an observation device that can monitor seabed stability during the exploitation of natural gas hydrate on the seabed. Seabed displacement was calculated using the acceleration waveform recorded by a three-component acceleration sensor placed on the seabed. This method was also applied to observe seabed deformation in a deep-sea hot spring area [6,7]. A remote-control underwater robot was used to place a Bremen ocean bottom tiltmeter equipped with a triaxial acceleration sensor and an inclinometer for long-term in situ observation. The monitoring device developed by OYO and JOGMEC was used for deep-water test in the MH21 project for exploitation of marine gas hydrate in Japan [8]. In the North Sea, Stenvold et al. used a high-precision water pressure measurement technology to monitor seabed subsidence [9]. This method is also commonly used to study tectonic movement. Chadwick et al. employed this method to monitor seabed uplift and predict the eruption time of submarine volcanoes [10]. Using this method, Wallace et al. monitored the uplift of the seabed through an absolute pressure gauge network distributed at the edge of the Hikulangi subduction off the coast of New Zealand and successfully captured a subduction tectonic movement in the coastal subduction zone - slow slip from September to October 2014 [11]. In 2006, the Scripps Institute of Oceanography at the University of California conducted a long-term observation of submarine instability slopes by using acoustic ranging [12]. In 1996, the Scripps Institute of Oceanography, University of California, USA, used optical fiber sensors to observe the tectonic strain of the seabed [13].

The environmental factors include marine dynamic factors and dynamic change factors of seabed boundary layer sediments. The marine dynamic effect mainly includes wave, current, tide, and other dynamic parameters. The indexes of in situ observation mainly include wave height, wave period, velocity, direction, and tide level. The submarine-based observation platform provides an effective means to observe the dynamic process of the ocean bottom boundary layer [14]. The seafloor-based observation platform was first designed by Sternberg and Creager and used to observe marine dynamics and sediment transport in the bottom boundary layer of Puget Gulf tidal channel [15]. This platform was then improved and used in different sea areas and experiments. Since the mid-1970s, the National Geological Survey, the Virginia Institute of Oceanography, and the National Oceanic and Atmospheric Administration of the United States have constructed similar observation systems [16]. These systems have been widely used in the observation and study of marine dynamic processes in estuaries, coasts, continental shelves, and deep sea. New technology and equipment were used to improve the observation platform. Research results based on these observations have greatly deepened the understanding of the near-bottom boundary layer and ocean dynamic processes.

2. General Settings
Cyclic loads such as waves and earthquakes can cause seafloor instability and seabed liquefaction, resulting in soil sliding failure, which is harmful to offshore oil platforms, submarine pipelines, and cables. For example, in 1969, under the influence of Hurricane Camille, platform B of the Mississippi Delta in the United States overturned and slid down the slope by 30 m, which caused more than 100 million dollars of damage [17,18].

The landslide occurred on the slope of the east side of the Fulimen waterway to the west of Zhujiajian Island (Fig. 1). The area is relatively close to the Yangtze River Estuary, and the material source is obviously affected by the material entering the sea from the Yangtze River. In terms of strict geomorphic types, the subarea largely belongs to the pre Delta area of the modern underwater delta of the Yangtze River [19]. The slope is 7°–12°. Clear landslide mass, sliding surface, sliding bed, sliding wall, and sliding step can be found from the shallow profile records. The sliding body has an irregular “feather-like” bedding. The whole sliding zone is parallel to the island shoreline, extending about 2 km, and is about 250-m wide. The water depth extends from about 5 m nearshore to about 70 m. The buried depth of sliding surface is generally 5–6 m, and the maximum is about 10 m, which has the structural characteristics of traction landslide. The estimated total volume of the landslide body is about 290 × 10^4 m^3, which is a giant landslide [20].

On the basis of the data from ZK1a to ZK4a of Zhujiajian landslide (Fig. 3), the stratum structure of the landslide sediment can be divided into three layers. The top layer is a high compressible fluid plastic silt layer with a thickness range of 5.6–11.9 m, the lower layer is a flow plastic muddy silt with a thickness of more than 30 m, with a thin layer of silt mixed locally, and the bottom layer is a soft plastic muddy silt layer. According to the field investigation, a 1–4-m-thick floating mud layer is developed on the surface.
The strong contrast of scouring and silting between the middle channel and the bank slope caused by the geological geomorphology and hydrodynamic characteristics of the channel-type deep-water bay in the island area is the main environmental condition for the accumulation of unstable factors of bank slope soil sliding. For the case of small waves and large water depth, the results of infinite slope calculation under the action of gravity are very close to those calculated by Henkel’s method considering wave bottom pressure and circular slip surface, which indicates that the landslide in this area is mainly caused by gravity [20]. The stability of the submarine slope in Zhujiajian Island of Zhoushan was evaluated by analyzing the stability of the slope under the action of waves. Calculation results show that the wave load affects the stability of the submarine slope and that the submarine slope near Zhujiajian Island has the risk of landslide [21].

3. In situ Observation

3.1 Observation sites

In situ observations were carried out at Zhujiajian landslide (29°54′16.5855″N,122°20′41.2655″E) in the Zhoushan area, as shown in Fig. 1a. The landslide area is located on the northeast side slope of the tidal current scouring trough on the southwest side of Zhujiajian Island, with a depth of more than 100 m. According to the water depth data of Zhujiajian landslide, combined with the sub-bottom profiling, the terrain of the area is high in the northeast and low in the southwest, and the terrain is concave. The upper part of the landslide is located on the slope break between the beach and the slope, with a slope of about 10°. The sub-bottom profile (Fig. 2) shows an obvious sediment interface 13 m below the seabed.

3.2 Instruments and emplacement

The Submarine Landslide Monitoring (SLM) system [22] used in the observation consists of three parts: a Shape Accel Array (SAA) for recording seabed deformation at different depths, a pore pressure probe rod for recording pore pressure, and a monitoring seabed base for recording hydrodynamic data (e.g., waves, tides, and currents). The main part of the SLM system is an SAA that was manufactured in Canada by Measurand Inc. and consists of a rope-like array of triaxial microelectromechanical system-chip accelerometers (Fig. 4a). The SAA can be placed vertically into the sediments for measuring the horizontal deformation at different depths, being 6-m long and having a resolution of 2 arcsec and an accuracy of 0.18 mm. The SAA was installed into the seabed using offshore drilling techniques. The pore water pressure probe rod is 7 m and has four sensors located at 1, 3, 5, and 7 m. The sensor used for the pore water pressure probe rod (Fig. 4b) is us10000 silicon piezoresistive pressure sensor produced by MEAS Company of the United States, which has high precision and can adapt to the harsh environment, and can meet the requirements of field observation. The pore water pressure probe rod penetrates the seabed sediment with counterweight. The monitoring
seabed base, shown in Fig. 4c, carries a variety of sensors, including a wave-tide gauge and two current meters. The SAA was embedded between 7.5 and 13.5 m below the mudline, while the hydrodynamic monitoring seabed base and pore pressure probe were deployed less than 10 m from the SAA. The observation began on August 25 and ended on October 15. A typhoon event occurred on October 2.

![Fig.4](image)

**Fig.4** Instruments used in the observation. (a) a Shape Accel Array (SAA) for recording seabed deformation. (b) a pore water pressure probe rod for recording pore pressure. (c) a monitoring seabed base for recording hydrodynamic data.

4. Results

4.1 Significant wave height
A large typhoon event occurred during the monitoring period. Affected by it, the hydrodynamic conditions in the observation area changed dramatically, and the effective wave height increased significantly from about 0.1 m under calm sea conditions to the highest 0.5 m.

![Fig.5](image)

**Fig.5** Variation of significant wave height during observation

4.2 Current
Statistics of the observation results of the seabed-based current meter showed that the minimum flow rate was 0.001 m/s, which appeared at the bottom; the maximum flow rate was 2.02 m/s, which appeared at 3.2 m from the top of the current meter.
Fig. 6 Velocity distribution near bottom during observation

The velocity in spring tide was higher than that in neap tide: the average velocity in the bottom layer of spring tide was 0.40 m/s higher than that in neap tide; the average velocity in the middle layer of spring tide (5.7 m) was 0.48 m/s higher than that in neap tide; the average velocity on the surface layer of spring tide was 0.48 m/s higher than that in neap tide. In the vertical direction, from the surface layer to the bottom layer, the velocity decreased gradually. The maximum velocity in spring tide decreased from 1.72 to 1.24 m/s, whereas that in neap tide decreased from 1.25 m/s to 0.88 m/s, from 0.49 to 0.40 m/s, from 0.42 to 0.34 m/s, from 0.05 to 0.01 m/s, and from 0.02 to 0.01 m/s.

| Depth (m) | Spring tide (m/s) | Neap tide (m/s) |
|-----------|-------------------|-----------------|
|           | Maximum           | Average         | Minimum | Maximum | Average         | Minimum |
| 10.2      | 1.72              | 0.49            | 0.05    | 1.25    | 0.42            | 0.02    |
| 5.7       | 1.49              | 0.48            | 0.02    | 1.17    | 0.40            | 0.02    |
| 0.7       | 1.24              | 0.40            | 0.01    | 0.88    | 0.34            | 0.01    |

The velocity of each layer has an order of magnitude change in the tide period (Tab. 1). The time of occurrence of the maximum and minimum velocities of each layer was different. The maximum velocity appeared in spring tide, and the minimum velocity appeared in neap tide. As shown in Tab. 2, the velocity of rising tide was greater than that of falling tide, the average velocity of rising tide in spring tide was 0.49 m/s faster than that of falling tide, and the average velocity of rising tide in neap tide is 0.45 m/s faster than that of falling tide.

In the vertical direction, from the surface layer to the bottom layer, the average velocity in spring tide gradually decreased from 0.48 to 0.40 m/s; the ratio of rising tide to falling tide velocity gradually decreased from 1.21 to 0.97; the ratio of rising tide to falling tide velocity gradually decreased from 0.42 to 0.34 m/s in neap tide and the ratio of rising tide to falling tide velocity gradually decreased from 1.40 to 1.26. The mean vertical velocity of spring tide (0.45 m/s) was slightly higher than that of neap tide (0.38 m/s).

| Depth (m) | Rising tide | Falling tide | Ratio | Average | Rising tide | Falling tide | Ratio | Average |
|-----------|-------------|--------------|-------|---------|-------------|--------------|-------|---------|
| 10.2      | 0.53        | 0.44         | 1.21  | 0.48    | 0.49        | 0.35         | 1.40  | 0.42    |
| 5.7       | 0.51        | 0.43         | 1.19  | 0.47    | 0.46        | 0.35         | 1.33  | 0.40    |
| 0.7       | 0.42        | 0.43         | 0.97  | 0.40    | 0.38        | 0.30         | 1.26  | 0.34    |
| Average   | 0.49        | 0.42         | 1.17  | 0.45    | 0.45        | 0.33         | 1.33  | 0.38    |

4.3 Pore pressure

In this observation, the piezoelectricity-type pore water pressure observation probe rod independently developed was adopted. Data were collected for 5 min every hour at a frequency of 5 Hz. The in situ pore water pressure change data of 1, 3, 5, and 7 m under the seabed were obtained and recorded as follows:
Fig. 7 Variation of pore water pressure during observation
The pore water pressure values at different depths showed similar rising and falling trends with the tide fluctuation. This rise and fall can be ascribed to the change in hydrostatic pressure with water depth. The change amplitude of pore water pressure varied at different depths. The greater the depth under the seabed, the smaller the change amplitude. This is due to the tide. The load resulted in excess pore water pressure in the seabed, which significantly affected the pore water pressure at different depths.

4.4 Displacement

Fig. 8 Variation in seabed displacement during observation
The above figure shows the overall change in horizontal combined displacement observed by the array displacement meter at different depths, and the different curves represent the observation results at different dates. Obvious lateral cumulative displacements occurred between $-12 \text{ m}$ and $-13.5 \text{ m}$ under the seabed. Although the displacement was small, the change trend of the two nodes was synchronous and obvious. No obvious displacement occurred between $-9.5 \text{ m}$ and $-12 \text{ m}$ under the seabed, and obvious lateral cumulative displacement occurred at $-7.5 \text{ m}$ to $-9.5 \text{ m}$ under the seabed. In addition, the displacement magnitude varied at different depths.

5. Discussion

5.1 Response of pore water pressure to wave-induced subsidence
The change in pore water pressure in the seabed is closely related to hydrodynamic conditions. The action of wave produces excess pore water pressure in the seabed. The principle of effective stress indicates that the effective stress and seabed stability decrease with increasing excess pore water pressure in the seabed. Changes in the hydrodynamic force and pore water pressure in the seabed during the observation period were recorded in detail, providing reference data for the analysis of seabed stability under different sea conditions.

Wave action can significantly affect the excess pore water pressure in the seabed. The variation in pore water pressure in the seabed caused by wave action is usually divided into two categories. One is the oscillating pore water pressure caused by instantaneous load, and the other is the residual pore water pressure caused by the accumulation of excess pore water pressure. This observation records the wave changes and pore water pressure of the seabed during the observation period. The monitoring data can be used to investigate the response of pore water pressure at different depths of the seabed under different sea conditions and to
evaluate the stability of the seabed. Under the influence of typhoon, the effective wave height increased significantly. Accordingly, the excess pore water pressure of the seabed also changed significantly with the change in wave strength. The data of excess pore pressure during typhoon were selected for analysis, and the data of excess pore pressure recorded continuously every hour for 5 min were compared to study the change in the seabed excess pore pressure under the influence of waves. With the enhancement of wave, the excess pore pressure in the sediment under the seabed showed obvious oscillation under the action of wave, and its amplitude was 2–4 kPa. By contrast, the amplitude of excess pore pressure oscillation was about 0.5 kPa under calm sea conditions, and the wave enhancement significantly increased the excess pore pressure in shallow sediments of the seabed. The values of excess pore pressure recorded continuously for 5 min showed no obvious accumulation caused by wave action.

![Fig.9 Variation in excess pore pressure at 1 m under the seabed during typhoon (a) and calm sea conditions (b)](image)

**Fig.9** Variation in excess pore pressure at 1 m under the seabed during typhoon (a) and calm sea conditions (b)

![Fig.10 Comparison of changes of excess pore pressure at 1 m under seabed in 5 min](image)

**Fig.10** Comparison of changes of excess pore pressure at 1 m under seabed in 5 min

Similar laws were observed in other depths under the seabed. Different from the shallow sediments of 1 m under the seabed, the overpressure of the deeper sediments under the tide load was higher. Even under the influence of the wave, the overpressure still presented a regular vibration in a large time range, whereas the overpressure of the shallow sediments due to the influence of the tide itself was the same as that of the wave. The effect was equivalent; thus, its oscillation regularity was not obvious.
Variation in excess pore pressure at 1 m (b) and 3 m (c) below the seabed during typhoon Due to the shallow water depth, the shallow sea sediment was obviously affected by wave action. Wave action includes vertical wave pressure and lateral wave-induced shear stress. The change of wave pressure affects the accumulation of pore pressure of the sediment and leads to liquefaction damage. At the same time, wave-induced shear stress can cause erosion damage of the sediment and contribute to lateral displacement.

5.2 Analysis of influencing factors of seabed lateral displacement
In this observation, the array displacement sensor was placed in a deep position, ranging from −7.5 m to −13.5 m. Previous observation and analysis results revealed that the influence range of liquefaction and erosion of the seabed caused by waves is difficult to reach such a depth, but this observation still revealed a relationship between wave action and deep displacement of the seabed slope. As shown in the figure, in the three periods of peak value of effective wave height, the rapid accumulation or large fluctuation of lateral displacement occurred at different depths.

The current meter mounted on the hydrodynamic observation platform was used to observe the velocity of the seafloor profile. The influence of velocity change on sediment displacement was explored by comparing the change of near-bottom velocity and the displacement of different nodes.
The above figure shows the change curves of sediment displacement rate and horizontal velocity at −13.0 m and −12.5 m, and the positive and negative flow velocity indicate the direction. Comparison results showed that the displacement rate at the bottom depths of −13.0 m and −12.5 m positively correlated with the change of velocity and that the change in near-bottom horizontal velocity was related to the change of sediment boundary layer displacement in the deep seabed slope.

Combined with the monitoring data of pore pressure, the correlation analysis and discussion of pore pressure and displacement change were carried out. Given the large embedded depth of the array displacement sensor, the relationship between the changes in pore pressure at -7 m and displacement at different depths was mainly analyzed. The pore monitoring data at -7 m reflect the pore pressure state and change of the upper sediment. The figure shows the curve relationship between the changes in pore pressure and displacement at different depths:
1. The response law of pressure displacement varies with the depth of pore;
2. The changes in the amplitude and mean value of pore pressure oscillation lead to sudden change in displacement and velocity;
3. The relationship between the deep displacement of the slope and the variation of pore water pressure is closer.

On the basis of the above analysis, the effective wave height, velocity, pore pressure, and displacement changes are summarized and analyzed, and the following curve is drawn, which can be seen clearly from the figure:
1. The simultaneous appearance of the peak value of the effective wave height and the peak velocity affects the sudden change of the displacement and the short-term change of the displacement rate;
2. The amplitude and mean value of pore water pressure oscillation lag behind, but their changes affect the long-term change of displacement rate;
3. The influence of pore pressure and velocity on deep displacement is obvious.

Fig.15 Significant wave height, current velocity, and pore pressure–displacement variation curve
Comparative analysis revealed that hydrodynamic factors, such as wave height and velocity, exerted a short-term effect on the deep displacement of the slope, whereas the change in pore water pressure amplitude and mean value changed the displacement rate of the deep sediment of the slope for a long time. Although the sediment boundary layer was located in a deep position, it was still affected by the changes in pore pressure and velocity, and the correlation was obvious, which are the key areas for landslide monitoring and early warning.

6. Conclusions
In situ observations of seafloor instabilities were carried out with displacement sensor arrays, pore water pressure probe rod, and hydrodynamic monitoring of the seabed base in Zhujiajian landslide. The following conclusions are obtained from the analysis of monitoring data:
(1). The slope is basically in a stable state, creep occurs during the monitoring period, and the deformation is 0.5 mm.
(2). During the typhoon, the effective wave height increased significantly from about 0.1 m under calm sea conditions to the highest 0.5 m.
(3). Due to the enhancement of waves, the value of excess pore pressure in the sediments 1 m below the seabed fluctuated obviously under the action of waves, and its amplitude was 2–4 kPa. By contrast, the oscillation amplitude of excess pore pressure was about 0.5 kPa under calm sea conditions, and the enhancement of waves significantly increased the value of oscillatory excess pore pressure in shallow seabed sediments.
(4). Comparative analysis revealed that wave height and velocity exerted short-term effects on the slope deep displacement, and the change of pore water pressure changed the displacement rate of deep slope sediments for a long time. Although the sediment boundary layer was deep, it is still affected by the changes in pore pressure and velocity, and the correlation was obvious.

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