

Technical Note

# Design and Application of an In Situ Test Device for Rheological Characteristic Measurements of Liquefied Submarine Sediments

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**Abstract:** Liquefied submarine sediments can easily lead to submarine landslides and turbidity currents, and cause serious damage to offshore engineering facilities. Understanding the rheological characteristics of liquefied sediments is critical for improving our knowledge of the prevention of submarine geo-hazards and the evolution of submarine topography. In this study, an in situ test device was developed to measure the rheological properties of liquefied sediments. The test principle is the shear column theory. The device was tested in the subaqueous Yellow River delta, and the test results indicated that liquefied sediments can be regarded as “non-Newtonian fluids with shear thinning characteristics”. Furthermore, a laboratory rheological test was conducted as a contrast experiment to qualitatively verify the accuracy of the in situ test data. Through the comparison of experiments, it was proved that the use of the in situ device in this paper is suitable and reliable for the measurement of the rheological characteristics of liquefied submarine sediments. Considering the fact that liquefaction may occur in deeper water (>5 m), a work pattern for the device in the offshore area is given. This novel device provides a new way to test the undrained shear strength of liquefied sediments in submarine engineering.



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**Keywords:** in situ test; liquefied submarine sediments; rheological characteristics

## 1. Introduction

Submarine sediments can be liquefied under dynamic loads (e.g., wave loads, earthquakes, engineering activities) [1]. Liquefaction refers to the process of increasing excess pore pressure and diminishing vertical effective stress, by which the seabed sediments are transformed from a soil (with particle structure) into a suspension that acts like a liquid. The liquefied sediments are characterized by low shear strength and high fluidity, with properties lying between a solid and fluid [2]. They likely lead to the occurrence of various marine geo-hazards, such as collapses, submarine landslides, and turbidity currents [3–6]. Consequently, offshore platforms, risers, in-field flowlines, pipelines, and other subsea facilities can be destroyed. Moreover, the submarine landform is reshaped due to the sediments' movement [7,8]. Therefore, clarifying the rheological characteristics of liquefied sediments at the solid–fluid transition is of great significance not only for early warning of submarine geo-hazards but also for the in-depth understanding of the evolution of the submarine topography.

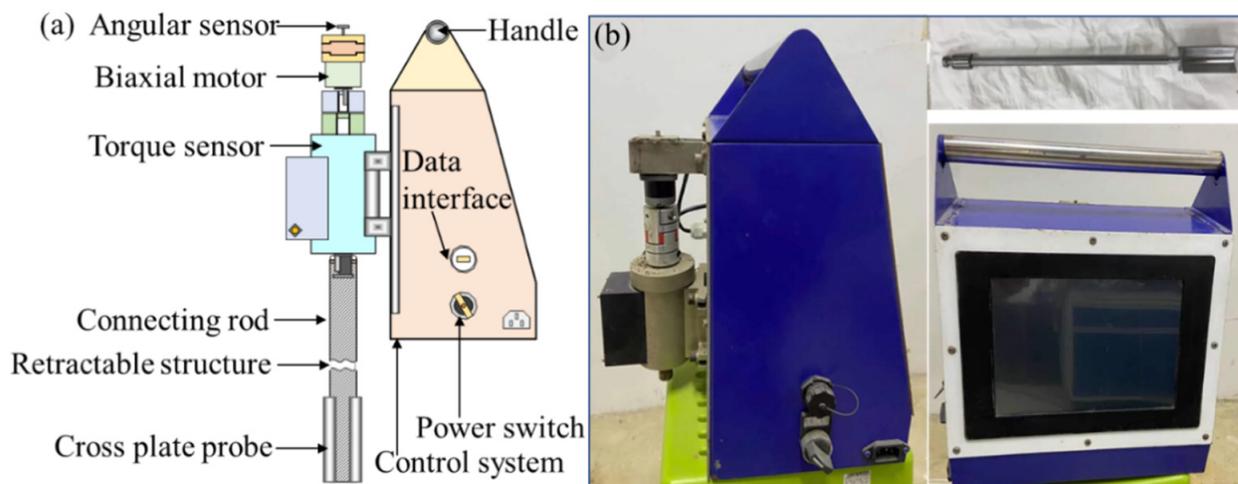
In current practice, sediment sampling and in situ tests are normally used together for the measurement of the shear strength of soft submarine sediments [9–11]. However, there are some major challenges in adopting these approaches for accurate rheological

characterization of liquefied sediments. For sediment sampling, it is difficult to obtain high quality samples of the very soft and fluid liquefied sediments using the gravity piston corer or box corer. In addition, it is difficult to return the sediment to their initial liquefaction state, further affecting the test results. For in situ strength testing of submarine sediments, current test methods, such as the cone penetration test (CPT), full-flow penetration test (T-bar or ball penetrometers), and vane shear test (VST), can only be applied at a very low shear rate (generally  $<0.2 \text{ s}^{-1}$ ), as it is difficult to test the rheological strength at a slightly higher shear rate [12,13]. However, the diameter of the submarine pipeline is often between 0.1 and 1 m, the impact velocity of the liquefied sediments can reach 10 m/s [14,15], the shear rate can reach  $100 \text{ s}^{-1}$ . Moreover, these in situ devices are only suitable for specific homogeneous sediments, but the real sediment condition is very complex. That is, continuous testing of the liquefied sediments at a certain station and at a certain depth cannot be carried out under different shear rates. Therefore, it is necessary to develop an in situ test device to test the rheological strength of liquefied sediments under different shear rates.

To overcome the limitation of current test methods, this paper introduces an in situ test device based on the shear column theory. The device was tested in the subaqueous Yellow River delta. In addition, a laboratory rheological test was conducted as a contrast experiment to qualitatively verify the trends shown in the in situ test data. Moreover, a work pattern for the device in the offshore area is given.

### 2. Design of the In Situ Test Device

The in situ test device is mainly composed of a test system and control system (Figure 1). The test system mainly includes a connecting rod with a retractable structure, a cross plate probe, a torque sensor, an angular displacement sensor, and a data acquisition unit. The torque sensor is connected between the connecting rod and the rotating shaft of the motor, and is used to record the connecting rod torque. The angular displacement sensor is connected with the other end of the motor shaft to detect the rotation angle of the cross plate. The control system is mainly composed of a biaxial motor and control software, which is used to receive the detection signals output by the sensors and transmit them through the data interface. In addition, the device is also provided with a handle, convenient for the staff to hold. The whole instrument weighs approx. 5 kg, and the length of the telescopic rod can be up to 5 m. As a result, the measurement of rheological characteristics of liquefied sediments located at water depth shallower than 5 m can be obtained by adjusting the length of the connecting rod.



**Figure 1.** (a) Design schematic of the in situ device. (b) Photo of the in situ device. Clockwise from top left: whole body of the device; the cross plate probe; the display screen.

During the in situ test, the cross plate head is first inserted into the liquefied sediment sample until it is completely immersed in the sediment. To eliminate the influence of probe insertion on the sediment, the probe should be left in the sediment for stabilization before the test [16]. After stabilization, the motor is controlled to drive the cross plate to rotate and disturb the sediments until the sediments fail in shear. The test principle is shear column theory which is based on the assumption of a uniform stress distribution on the top and bottom ends of the soil cylinder mobilized by the vane. The shear stress can be deduced directly from the measured torque value [16]. The shear stress  $\tau_f$ , shear rate  $S$  and apparent viscosity  $\eta_a$  can be calculated as follows [16,17]:

$$\tau_f = \frac{2M_{max}}{\pi D^2(H + D/3)} \quad (1)$$

$$S = \frac{\partial A}{\partial T} \quad (2)$$

$$\eta_a = \frac{\tau_f}{S} \quad (3)$$

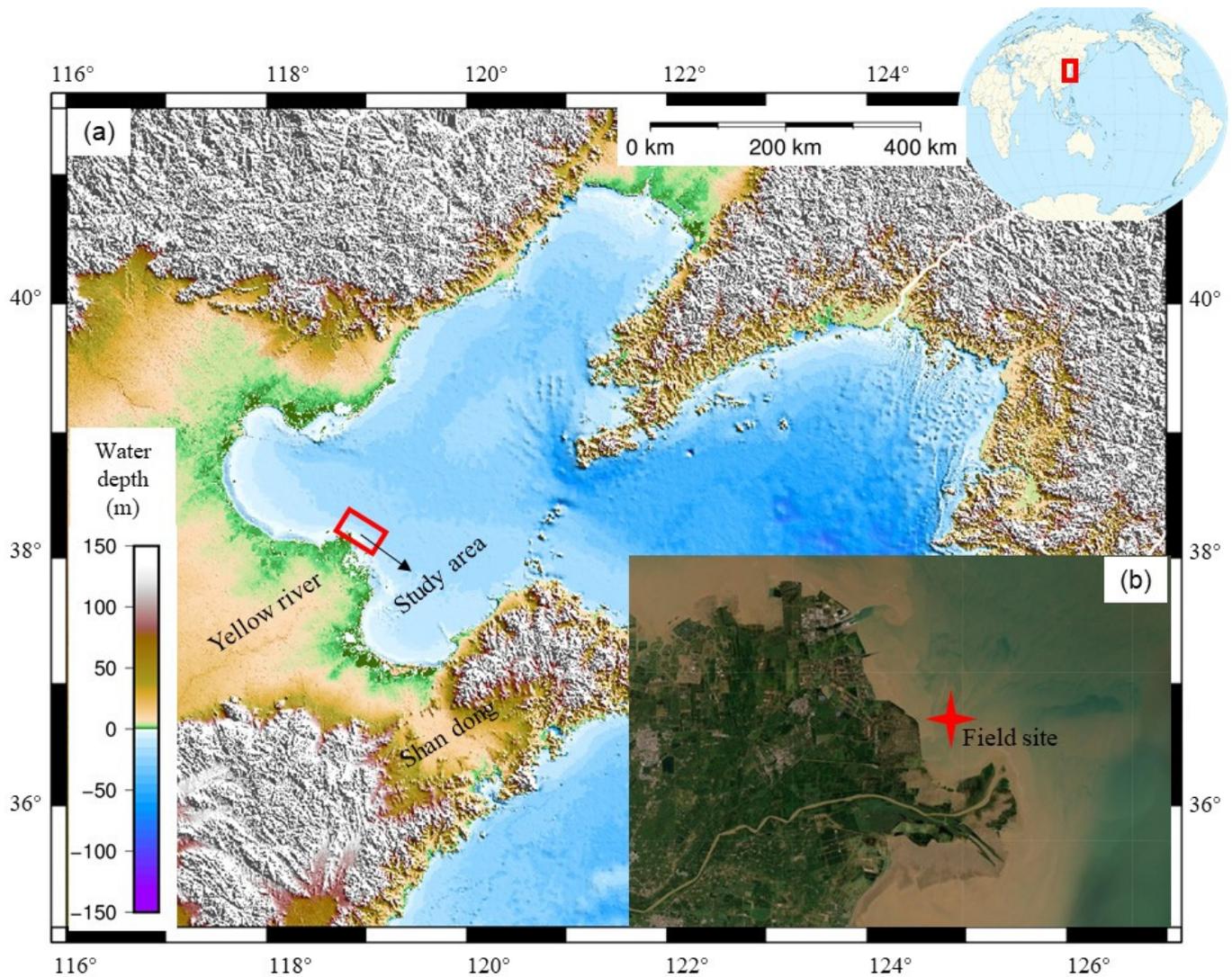
where  $D$  is the diameter of the cross probe;  $H$  is the height of the cross probe;  $M_{max}$ ,  $A$ , and  $T$  are the maximum torque, rotation angle, and corresponding rotation time of the cross plate head when it is rotated at a certain depth of the seabed sediment after insertion, respectively. The rheological parameters at different depths can be obtained by adjusting the telescopic rod.

### 3. Application of the In Situ Test Device

#### 3.1. Field Site

The fieldwork was conducted in the Chengdao Sea area of the subaqueous Yellow River delta, which is located on the western shore of the Bohai Sea, China (Figure 2a). It is the location of the Shengli Oil Field which is the second largest oil field in China. Engineering facilities, such as drilling platforms, submarine cables and pipelines, port and waterway engineering, are common in this area. Sediments in this area are mainly sandy-silt, clayey-silt, and silty-sand, collectively named Yellow River-derived silts (YRDS) [18,19]. The YRDS come from the Quaternary sediments of the loess plateau in northwestern China, and their granulometric composition, mineral composition, and organic matter content show great similarity with the loess in the source area [20]. Extensive studies have already demonstrated that these silty sediments are prone to liquefaction and long-distance flow during high-energy conditions (e.g., occasional typhoons, extreme storms) due to their low internal cohesion [3,5,21–23].

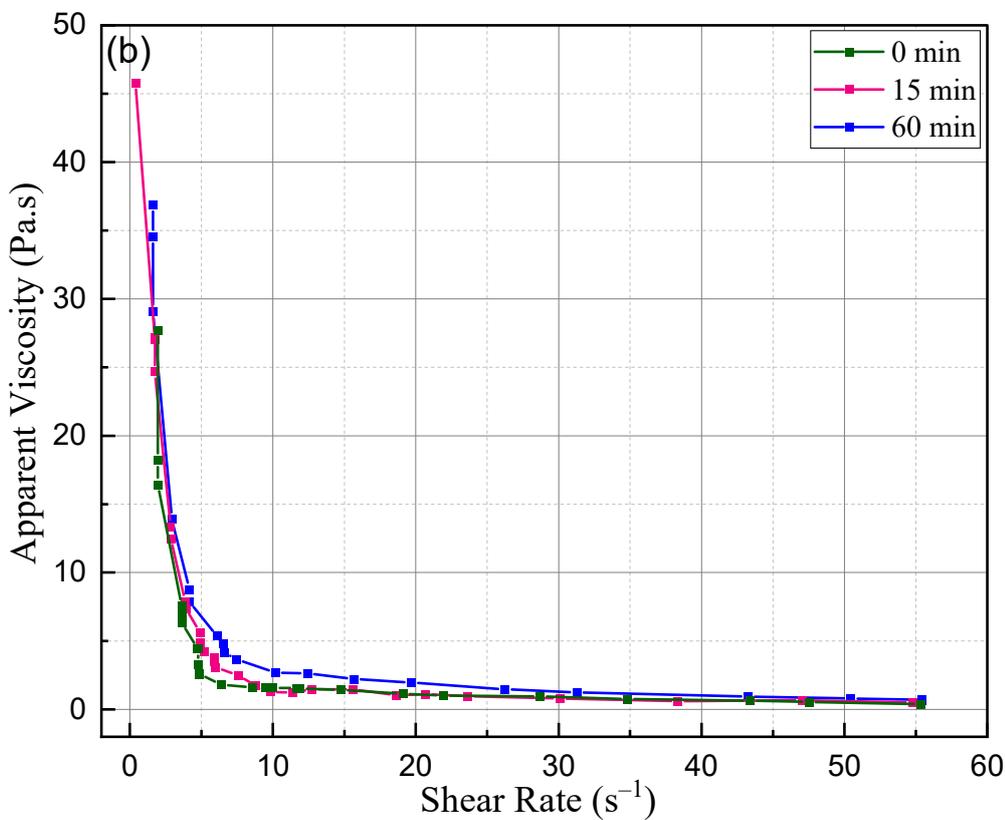
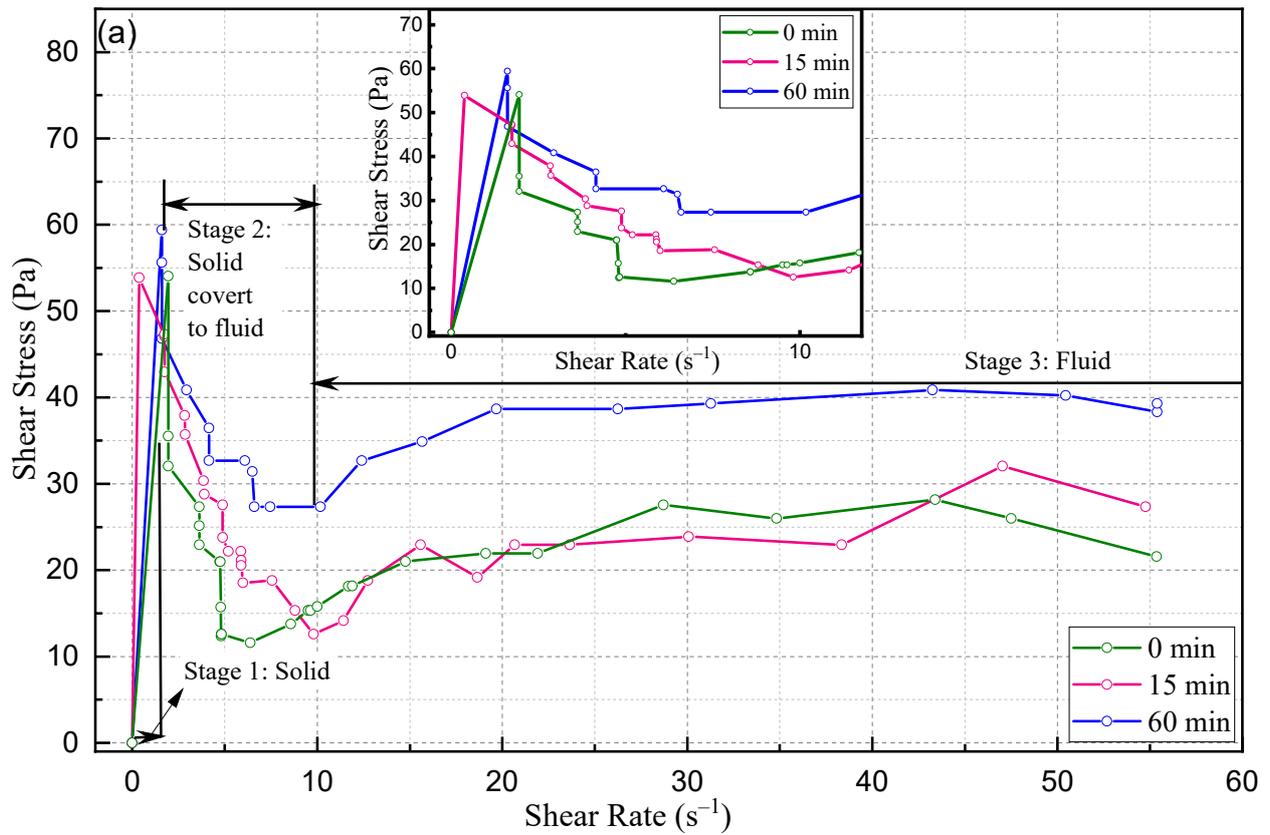
We chose one site (118°52'26" E, 38°12'34" N) to conduct in situ rheological characteristics measurements (Figure 2b). The dominant size fraction of sediments in this site is silt [18,21], and the median grain diameter is similar to YRDS [20]. Therefore, the sediment in this area is representative to study the rheological characteristics of liquefied sediments. Before the test, the simulated wave loading was exerted on the sediments until the sediments liquefied. Our previous studies have verified that the sediment in the study area is characterized by rapid consolidation [20,21]. The excess pore-water pressure developed during the liquefaction process can completely dissipate in ~1500 min and the strength of the sediments significantly recovered during this rapid consolidation process [20]. The dissipation of the excess pore-water pressure can be divided into two stages, with a rapid dissipation in the first 120 min followed by a decrease at a slower rate. At 120 min, the strength of the sediments recovered nearly half of the initial strength. Sediments behind this stage already could not be regard as liquefied sediment. Therefore, we planned to conduct the test at 0, 15, 60 and 120 min according to the dissipation rate of excess pore-water pressure. Unfortunately, the test data at 120 min was not obtained because of a flood tide. The shear rate was applied in an increment of 0.2 s<sup>-1</sup>/s and the whole procedure continued for 300 s.



**Figure 2.** Location map of the study area (a) and in situ test site (b).

### 3.2. In Situ Test Results

Figure 3a shows the rheological curves of the liquefied sediments tested by the in situ device. As shown, the relationship between the shear stress and shear rate is non-linear. Therefore, the liquid sediment is a non-Newtonian fluid. The development of shear stress with the change in shear rate can be divided into three stages: (1) a rapid and initial increase, (2) a sudden decrease, and (3) a period of increase at a slower rate. The shear stress increased significantly at first until reaching the maximum value under a lower shear rate. The sediment at this stage showed an obvious elastic deformation behavior. Then, the shear stress decreased sharply with the increase in shear rate, indicating that the elastic deformation had transformed into plastic deformation. At this stage, the state of sediments gradually changed from solid to fluid due to the destruction of the sediment structure. After a period of decrease, the shear stress began to increase with the shear rate, indicating that the sediments had completely converted to a fluid state. This stage change is also reflected by the change in apparent viscosity (Figure 3b). The apparent viscosity decreased quickly in the beginning when the shear rate increased, and then slightly afterwards to a steady value, indicating obvious shear-thinning behavior. Therefore, the liquefied sediments can be regarded as “non-Newtonian fluid with shear-thinning characteristics”.



**Figure 3.** (a) Rheological curves of liquefied sediments. The insert figure is an enlargement of the left side. (b) Curves of apparent viscosity under different shear rates.

#### 4. Verification of the Accuracy of the In Situ Test Device

Considering the low shear strength and fluid characteristics of liquefied sediments, it is difficult to rely on conventional geotechnical testing instruments and methods to verify the reliability of the in situ test results. Therefore, we conducted a laboratory rheological test as a contrast experiment to verify the accuracy of the in situ test data. The laboratory rheological test was performed using an R/S rheometer, designed by Brookfield company, USA. This rheometer is equipped with a paddle rotor (with a diameter and height of 20 and 40 mm, respectively), which is widely used in testing the rheological properties of non-Newtonian fluid [24,25].

##### 4.1. Laboratory Sediment Samples and Sample Preparation

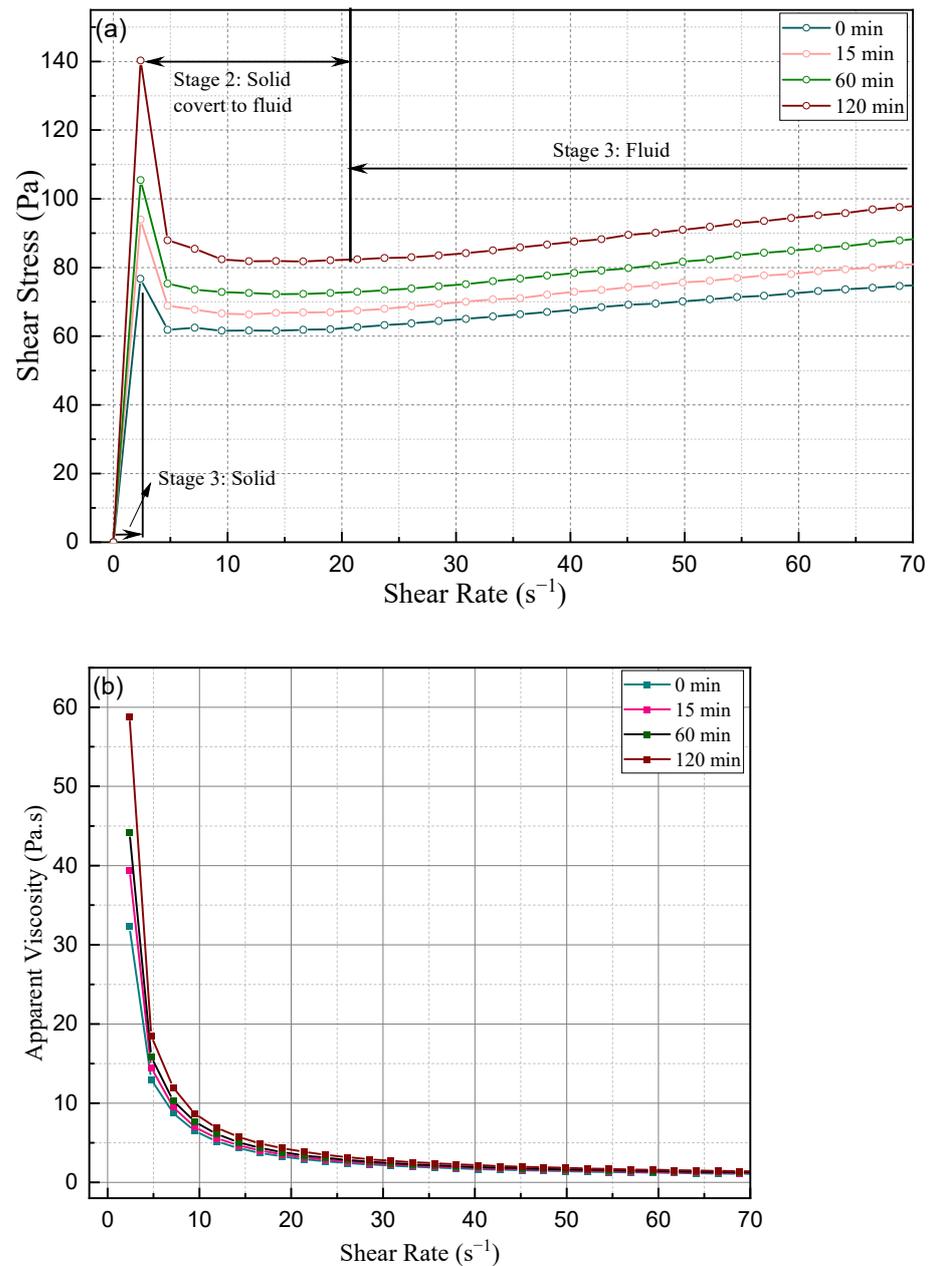
Sediment samples were collected by a box corer from the same in situ test site and were well sealed with plastic bags to prepare them for the laboratory test in this study. Following the Chinese national standard for soil testing method (GB/T50123-1999), the basic physical index properties of the sediment samples were measured. All of the physical index properties were tested in triplicate to obtain average values in order to ensure that the laboratory geotechnical test results were representative. The mean values are summarized in Table 1. The sediments are dominated by silt particles and can be classified as clay silt. The water content is obviously higher than liquid limit, which demonstrates that the sediment is in a fluid state [26]. The sediment samples were then dry sieved through a sieve with openings of 2 mm in diameter, in order to remove large shell fragments from the material to avoid potential damage to the instrument [12]. The sieved material was reconstituted with seawater to a water content of about 43% in a mixer and was mixed under vacuum. The deaired sediments were then scooped and placed into a cylinder box. Afterwards, the sediments were left to stand for 0, 15, 60, and 120 min before conducting the rheological test to ensure the removal of the impacts of consolidation time. The shear rate was applied in an increment of  $0.2 \text{ s}^{-1}/\text{s}$  and the whole procedure continued for 300 s.

**Table 1.** Physical index properties of the sediments. The data represent mean values.

Wet Density ( $\text{g}/\text{cm}^3$ )	Water Content (%)	Atterberg Limits			Particle Size Analysis			Water Content/Liquid Limit
		Liquid Limit (%)	Plastic Limit (%)	Plastic Index	Clay Content (%)	Silt Content (%)	Sand Content (%)	
1.47	43.33	31.04	19.55	11.49	24.83	72.67	2.50	1.40

##### 4.2. Laboratory Test Results

Three clear stages were identified through the rheological curves of the liquefied sediments (Figure 4a). For sediments at different consolidation times, after an initial rapid increase, the shear stress decreased gradually and eventually settled at a range of values, indicating that the sediments experience a transformation from solid to fluid. For any given shear rate, the shear stress increased with the consolidation time. As the shear rate increases, the apparent viscosity decreases rapidly (Figure 4b). When the shear rate was smaller than  $20 \text{ s}^{-1}$ , the consolidation time had an obvious influence on the apparent viscosity. However, with the increase in shear rate, the sediments showed obvious shear-thinning behavior, and the apparent viscosity of sediments under different consolidation time was very close.



**Figure 4.** (a) Rheological curves of liquefied sediments under different consolidation time. (b) Curves of apparent viscosity under different consolidation time.

## 5. Discussion

### 5.1. Comparison of In Situ and Laboratory Tests

Our test results show that both the shear stress and apparent viscosity showed a similar change trend during the in situ and laboratory tests; however, the shear stress developed in the laboratory test is approximately twice as large as that in the laboratory test at any given shear rate (Figures 3a and 4a). The reason for the differences can be attributed to the sample quality. Horng et al. (2010, 2011) investigated the effects of the sample quality on undrained shear strengths using several samplers with different geometries [27,28]. They concluded that the sample quality has a certain degree of influence on sediment strength properties. Moreover, another reason for the difference may be the sediment properties. Studies have verified that the sediment in the study area is characterized by rapid consolidation, i.e., the sediment strength could recover in a short time [18,19]. However, the consolidation process is controlled by many factors, such as the drainage condition,

external loading, and the hydrodynamic condition [21,29]. Therefore, the value tested in the laboratory was higher under the combined effects of size and sediment properties.

### 5.2. Applicability of the In Situ Device in the Offshore Area

Considering the fact that liquefaction may occur in deeper water (>5 m), upon improving the design of our in situ test device, it was possible for it to work in the offshore area. Based on the original design, the device is equipped with a sealed compartment and communication module. Almost all of the working parts are placed in the sealed cabin except for a small part of the cross plate head and connecting rod. Moreover, an underwater altimeter, which is used to determine whether the device arrives at the seabed, is installed in the capsule. After all the detection signals are transmitted to the control module, they are transmitted to the upper computer through the communication module via wired or wireless transmission to allow to realize data interaction. During the in situ test, the device was connected to a mooring rope and was hoisted to the sea by the shipboard crane of the auxiliary ship. Then, by adjusting the telescopic rod, the cross plate head was inserted into the soil sample and the test was conducted. Figure 5 is a schematic of the in situ test device work in the offshore area. Due to the submarine condition being very complex, there are still many unresolved problems, such as additional factors that need to be considered for the probe coefficient.

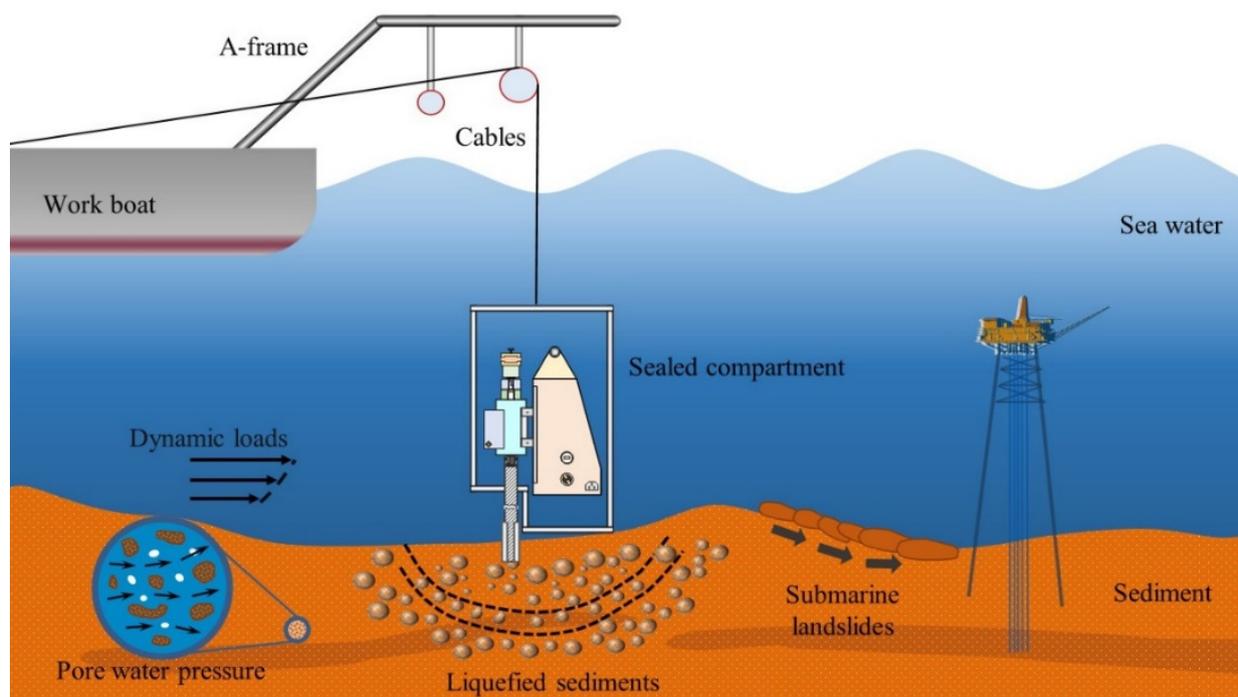


Figure 5. Schematic of the in situ test device work in the offshore area. Note this figure is not to scale.

## 6. Conclusions

In this study, an in situ test device was developed for the measurement of the rheological characteristics of liquefied sediments. It is mainly composed of a test system and control system. The test principle is based on the shear column theory. The device was tested in the subaqueous Yellow River delta, and the test results indicate that the liquefied sediments there can be regarded as “non-Newtonian fluids with shear thinning characteristics”. Moreover, a laboratory rheological test was conducted as a contrast experiment to verify the accuracy of the in situ test data. Through the comparison of experiments, it was shown that using the in situ device in this paper is suitable and reliable for the measurement of the rheological characteristics of liquefied submarine sediments. In addition, a work pattern

for the device in the offshore area is given. This novel device provides a new way to test the undrained shear strength of liquefied sediments in submarine engineering.

**Author Contributions:** Conceptualization, X.L.; Methodology, H.Z. and A.C.; Project administration, X.L.; Supervision, X.L.; Writing—original draft, H.Z.; Writing—review & editing, X.L., H.Z., W.L., Y.L., X.G. All authors have read and agreed to the published version of the manuscript.

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