EXPERIMENTAL RESEARCH ON SUCTION BENEATH PILE FOUNDATION BEING PULLED OUT FROM COHESIVE SOIL BED

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Abstract. When pile foundations, exampling engineering structures, are pulled out from the underwater cohesive soil bed, negative pressure will be produced beneath them. The suction arisen from negative pressure can affect the structural stability and pullout resistance of pile foundation to some extent. However, its variation characteristics and rules remain unclear at present. For this reason, it is of essential practical significance to research the suction beneath pile foundation being pulled out from the cohesive soil bed. In this research, physical experiments were carried out to measure the shape changes of the cavity, variations of the pressure and pullout force beneath the model pile during its vertical pullout from the cohesive soil bed. Efforts were also made to analyze the effects of parameters, including pullout velocity, embedment ratio of pile foundation and soil properties etc. on pressure beneath the pile. Consequently, the experimental results indicate that in cohesive soil bed the suction arisen from negative pressure beneath the pile foundation exerts a certain effect on the pullout resistance. Besides, during the pullout process, a pore water cavity will be generated beneath the pile foundation. Under the same embedment condition, the negative pressure beneath the pile foundation increases from 4.4 kPa to 7.8 kPa with the acceleration of pullout velocities from 1 $mm \cdot s^{-1}$ to 9 $mm \cdot s^{-1}$, but when the pullout velocity accelerates above 7 $mm \cdot s^{-1}$, its effect on the negative pressure is no longer obvious. At the pullout velocity of 1 $mm \cdot s^{-1}$, the negative pressure of pile foundation increases from 6.2 kPa to 8.3 kPa with the increase of the embedded depth.

Keywords: seabed, foundation, cohesive soil, suction force, pullout force.

Introduction

With the continuous advancement of industrialization, underwater engineering structures have been widely applied gradually. These water-related facilities require the use of different submarine anchoring equipment, such as anchors and piles, to be anchored in water [1; 2]. Different types of anchoring facilities are involved in many application fields. For example, anchors (plate anchors, suction anchors, etc.) or pile foundations are applied in marine drilling platforms, offshore wind turbines, aquaculture fish cages etc. for keeping their positions fixed on the water [3-5]. When the action of pulling out emerges in these water-related engineering structures under the impact of wind, current and other objects, a certain degree of suction will be generated between the underside of the anchoring facilities beneath these structures and the soil. Formed by the complex interaction among the shape of anchoring facilities, the soil properties of bed and the pore water in soil, this suction is manifested as a kind of pullout force, which is similar to "vacuum suction" [6].

Scholars have carried out some research on the bottom suction of submarine facilities and have achieved certain results. In the 1960s, the U.S. Naval Civil Engineering Laboratory measured the suction force of submarine structures with a maximum floating weight of 90 kN in the California port [7]. The study found that suction is the result of a complex interaction between seabed sediment and water. Feng et al. [8] conducted experimental observations on the suction force of sea mud on the bottom of marine engineering structures. They found that the suction force is mainly contributed by vacuum suction under the bottom which involves the rheological, consolidation and thixotropic properties of the sediment. Das et al. [9] also measured the bottom suction of slab anchors with different bottom shapes in soft and hard clay under different loading conditions. Datta and Kumar [10] measured the suction force of cylindrical anchors at different embedment depths under undrained soil and found that the suction force increased with the increase of the embedment depth until the limit was reached when the burial depth/diameter = 8.

The suction force beneath the pile foundation hampers the pullout process and increases the pullout resistance to a certain degree. Therefore, it is of vital practical significance to research the suction on the bottom of anchoring facilities.

Materials and methods

1. Testing soil

The soil samples used in this experiment originated from Jinshan Port of Shanghai. Before the experiment, the soil samples were filtered to screen out the internal impurities, and then the filtered samples were fully stirred. Data related to moisture content(ω), median practical diameter (d_{50}), undrained shear strength (S_u), sensitivity (S_t), density (ρ), permeability coefficient (k), liquid limit (ω_L) and plastic limit (ω_P) of the soil were measured and recorded. The specific parameters of the tested soil are shown in Table 1.

Table 1

Parameters of testing soil

Location	d_{50}, μm	ρ, g·cm^{-3}	S_t	$\overline{S_{u,12}}$, Pa	$\overline{S_{u,18}}$, Pa	$\overline{S_{u,24}}$, Pa	ω, %	K, cm·s^{-1}	ω_L, %	ω_P, %
Jinshan Port	30	1.717	1.409	899.5	943	986.5	31.59	5E-6	34	18

As listed in the table, the moisture content of soil (ω) was measured by the drying method, the median particle diameter (d_{50}) was measured by particle analyser, the density (ρ) was measured by the drainage method, and the undrained shear strength (S_u) and sensitivity (S_t) are measured by the in-situ shear test with the use of SZB-1.0 vane shear tester (the size of the vane head is 25.4 × 50.8 mm, the shear rate is 1°per 10s, and the measured depth of different parameters is set as 0cm, 10cm, 20cm and 30cm, respectively.) In light of the measurement, the permeability coefficient of soil is extremely low (5E-6 cm·s^{-1}), which can be deemed as an undrained condition. The curve of undrained shear strength varying with the depth is presented in Fig. 1. Since the embedded depth of the pile foundation in the experiment involves three different values (12cm, 18cm and 24cm), the average values of undrained shear strength in the depth range of 0~12cm ($\overline{S_{u,12}}$), 0~18cm ($\overline{S_{u,18}}$)and 0~24 cm ($\overline{S_{u,24}}$) are used for calculation.

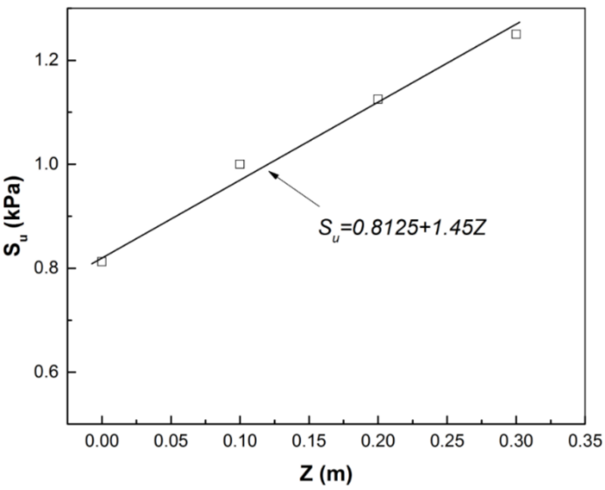

Fig. 1. **Undrained shear strength profile measured by SZB-1.0**

2. Experiment setup

A cylindrical stainless steel bucket with the inner diameter of 35 cm and height of 60 cm was selected for the experiment. The bucket contained testing soil with a depth of 55 cm. The length (L), diameter (D) and mass (m) of the model pile foundation are 26 cm, 6 cm and 1.26 kg respectively. At the bottom of the model pile foundation, three openings are designed to install the ultrasonic Doppler velocimeter (UDV) probe, pore water pressure sensor and vent hole. The model pile foundation and its bottom installation are displayed in Fig. 2. Therein, UDV is used to measure the water depth of the cavity beneath the pile during the pullout process; the pore water pressure sensor is applied to measure the pressure value in the cavity for calculation of suction; and a detachable bolt for sealing is installed on the vent to conduct the comparative experiment. In addition, the sensor is linked with the computer through the signal line, and its data acquisition frequency is 4 Hz.

As displayed in Fig. 3, in a sealed case (the sealing bolt is installed), suction will be generated beneath the model pile foundation being pulled out from the soil. In a vented case (the sealing bolt is detached), the bottom of the model pile foundation will be connected with the outside atmosphere; hence, no suction will be generated beneath the model. Based on the comparative experiment, the specific value of suction beneath the pile foundation can be obtained.

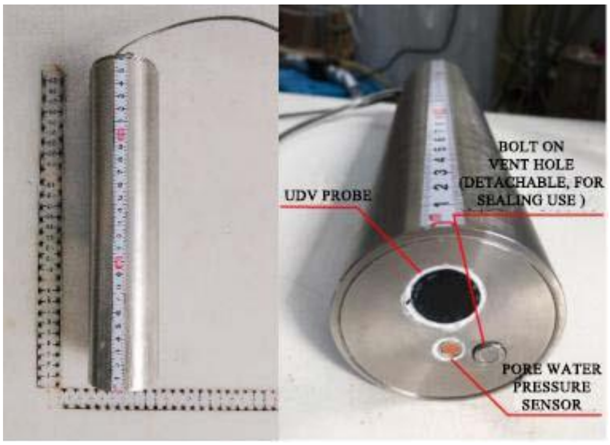

Fig. 2. **Photos of the model pile foundation**

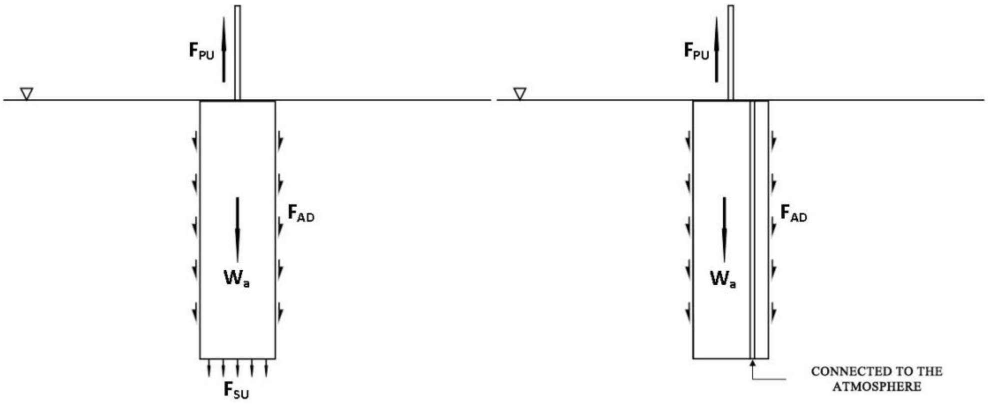

Fig. 3. **Forces on the model pile foundation when bottom sealed and vented**

The experiment setup is specified in Fig. 4. The model pile foundation linking with a 1.2 mm-diametered steel wire is connected to the pullout force sensor through a fixed pulley, and finally connected to the stepper motor. For operational conveniences, the pullout force sensor is linked with the computer, and the pullout force data is acquired by the pullout force acquisition software at a frequency of 4Hz for drawing of the pullout force curve. The rotating speed of the stepper motor is adjusted by speed regulator to control the pullout velocity.

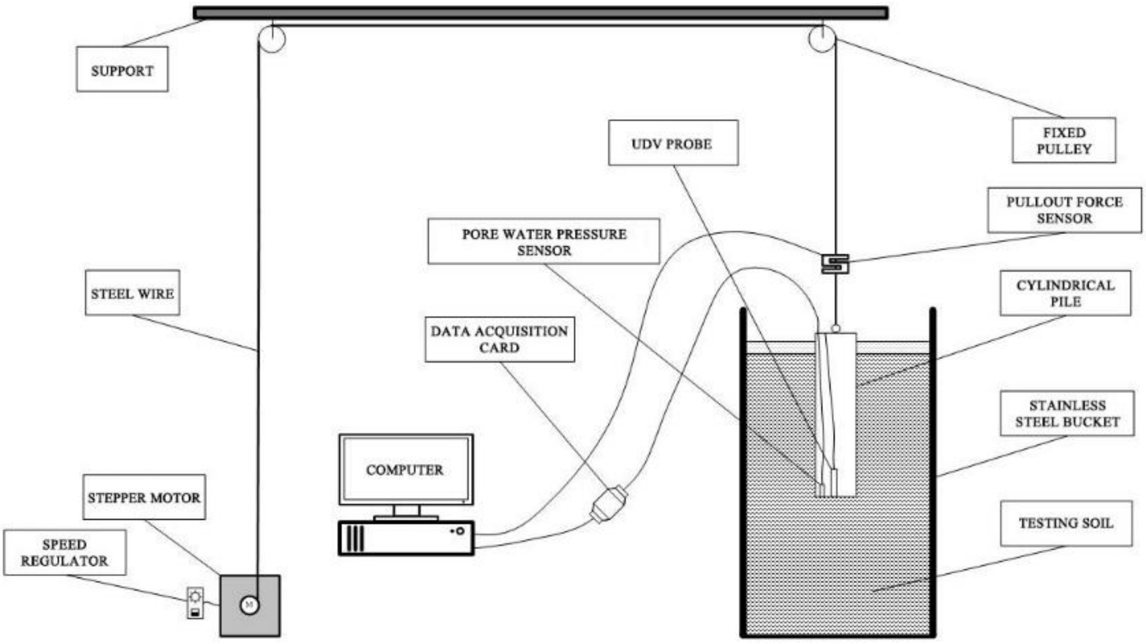

Fig. 4. **Scheme of the experiment setup**

3. Experiment procedures

The main operation procedures of the experiment are as follows.

The prepared testing soil is put in a stainless steel bucket (the thickness of water above the soil is about 1cm). Then, the soil is stirred evenly with an agitator.

The model pile foundation is inserted into the soil vertically, slowly and at an even velocity (1 cm·s^{-1}) to the specified depth. During the insertion process, the velocity and direction are well-controlled to avoid the model's disturbance to its surrounding soil as far as possible. Then, the soil is kept undisturbed for 10 minutes.

The undrained shear strength (S_u) and sensitivity (S_t) of soil in the test bucket are measured.

The computer is turned on and the power supply of the stepper motor and speed regulator is activated. After adjusting the velocity of the stepper motor, the pile foundation starts to be pulled out; meanwhile, the data acquisition software of UDV, pore water pressure sensor and pullout force sensor is functioned to record the data until the pile foundation is completely pulled out from the soil. UDV and pore water pressure sensor are used to record the changes in the water depth of the cavity and pressure beneath the pile respectively; while the pullout force sensor is applied to record the pullout force changes during the pullout process.

The method of stirring the soil mentioned in procedure 1 is exploited to restore the testing soil for repeating the above test.

A total of 30 pullout tests were carried out in this research. At the same embedded depth and in the soil of the same properties these tests were conducted in bottom sealed and vented cases. Additionally, the pullout velocity is set as 1 mm·s^{-1}, 3 mm·s^{-1}, 5 mm·s^{-1}, 7 mm·s^{-1} and 9 mm·s^{-1} respectively, while the embedded depth (H) is specified as 12 cm, 18 cm and 24 cm respectively. The test variables are presented in Table 2. Besides, Fig. 5 shows the two different states, namely, embedment and pullout, of the model pile.

Table 2

Test variables

Pullout velocity, *v*	**1 mm·s^{-1}**	**3 mm·s^{-1}**	**5 mm·s^{-1}**	**7 mm·s^{-1}**	**9 mm·s^{-1}**
Embedded depth, *H*	12 cm		18 cm		24 cm
Embedment ratio, *H*/*D*	2		3		4

Fig. 5. **Embedment and pullout states of model pile foundation**

4. Theoretical analysis

This research is exampled by the cylindrical pile experiment. As shown in Fig. 6, forces on the pile foundation during its vertical pullout from the cohesive soil bed mainly include the side friction exerted by soil on the side of the pile foundation, the effective unit weight of the pile foundation and the suction beneath the pile foundation, which can be described as:

$$F_{PU} = W_a + F_{AD} + F_{SU} \tag{1}$$

In this formula, the pullout force indicates the effective unit weight of the pile foundation, represents the side friction, and denotes suction.

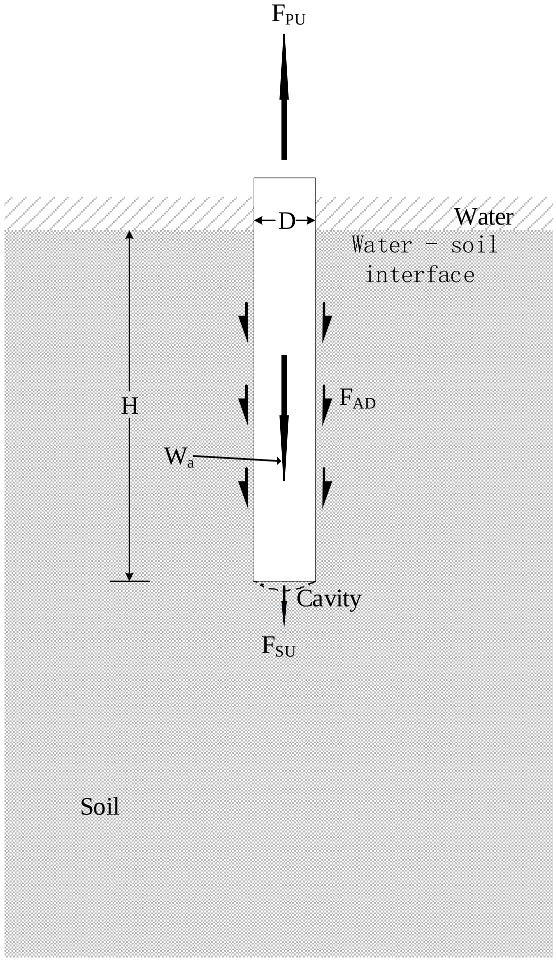

Fig. 6. **Forces on the pile foundation during pullout**

According to the conventional soil mechanics formula proposed by Terzaghi and Peck [7], the side friction can be described as:

$$F_{AD} = \frac{\delta}{S_t} A_s S_{u,ave} \tag{2}$$

In this formula, δ means the adhesion coefficient, S_t indicates the soil sensitivity, A_s represents the lateral area of the pile embedded in soil, and $S_{u,ave}$ denotes the average undrained shear strength of the soil. The adhesion coefficient (δ) of a non-smooth object moving at a lower velocity in cohesive soil can be approximated to 1 [8; 9]. This theoretical formula has been widely adopted by many other scholars, such as Raie et al. [11], O'Loughlin et al. [12], Blake and O'Loughlin [13], etc. They have used the formula to study the forces on the object being pulled out from the cohesive soil bed, and fully proved its scientificity and rationality [14].

Das et al. [9] proposed an empirical formula for calculating the suction beneath the plate anchor through experiments:

$$F_{SU} = A_F S_u \left(5.25 - 0.734 \frac{H}{D}\right) \tag{3}$$

In this formula, A_F means the bottom area of the anchor, Su indicates the undrained shear strength of soil, H represents the embedded depth, D denotes the diameter of the pile foundation underside.

Thus, it can be seen that the suction beneath the plate anchor is associated with the bottom area of the anchor (A_F), the undrained shear strength of soil (S_u) and the embedment ratio (H/D) (the ratio of the anchor's embedded depth to the anchor's diameter). Furthermore, when the anchor is pulled out at different velocities from the same soil, the suction will vary greatly due to the different soil deformation rates or pore water flow rates. Besides, there is a connection between the soil deformation rate or pore water flow rate and the pullout velocity of the anchor. Therefore, the suction beneath the anchor (or the pile foundation) can be expressed in a more general function form.

$$F_{SU} = A_F S_u f\left(\frac{v^2}{2g}, \frac{H}{D}\right) \quad (4)$$

Results and discussion

1. Experimental results

Under two different testing conditions of sealed and vented bottom, 15 sets of experimental data were obtained by a total of 30 pullout tests, the suction force (F_{SU}) was calculated by the difference between each two different testing conditions. The experimental results are listed in Table 3.

Table 3

Experimental results

Embedment ratio H/D	**Pullout velocity v, mm·s^{-1}**	**Soil shear strength S_u, kPa**	**Bottom sealed pullout force F_{PU}, N**	**Suction force F_{SU}, N**
2	1	899.5	33.26	9.10
2	3	899.5	34.68	11.31
2	5	899.5	36.87	13.71
2	7	899.5	37.36	15.68
2	9	899.5	38.43	16.78
3	1	943	34.15	11.20
3	3	943	35.57	13.71
3	5	943	37.76	16.11
3	7	943	38.57	19.48
3	9	943	39.23	21.18
4	1	986.5	36.82	16.04
4	3	986.5	38.24	18.25
4	5	986.5	40.42	20.65
4	7	986.5	40.92	22.62
4	9	986.5	41.98	24.72

2. Variation characteristics of forces on the pile foundation during the vertical pullout process

During the pullout process, the variations of parameters, including the cavity depth, pressure, pullout force and ratio of suction to the pullout force, beneath the pile foundation against the pullout time is shown in Fig. 7 (the pile embedded depth is 12 cm, and the pullout velocity is 5 mm·s^{-1}). During the period of the pullout force (F_{PU}) increasing from 0 to its maximum (from 1st s to 9th s), the pressure reduces from the originally positive value to a negative value, but it does not reach its maximum negative pressure value (shown at the moment of the 13th s). When the pullout force (F_{PU}) reaches its maximum, the negative pressure is generated beneath the pile, and the suction arisen from the negative pressure at this time accounts for about 45% of the pullout force. In this process, the pullout force is mainly composed of the pressure beneath the pile (P), the effective unit weight of the pile (W_a) and the side friction on the pile (F_{AD}). Subsequently (from the 9th s to 13th s), the absolute value of the negative pressure beneath the pile continues to rise to the maximum, accounting for 65% of the total pullout force, which remains stable in a certain range (about 3.6 kg). As the pile continues to be pulled out, the side friction reduces gradually. Therefore, it can be inferred that the pullout force is mainly composed of the bottom suction arisen from negative pressure and effective unit weight (W_a). Moreover, as shown in Fig. 7, the moments when the values of the negative pressure beneath the pile appear (at the 13th s and 24th s) were consistent with the time when the two peaks of the cavity depth appear. This indicates that the negative pressure beneath the pile is positively related to the water depth of the cavity. At the instant of the pile bottom separating from the soil, the pullout force (F_{PU}) is reduced to the gravity of the pile, the negative pressure in the cavity beneath the pile disappears, and the pressure value returns to the value of standard atmospheric pressure.

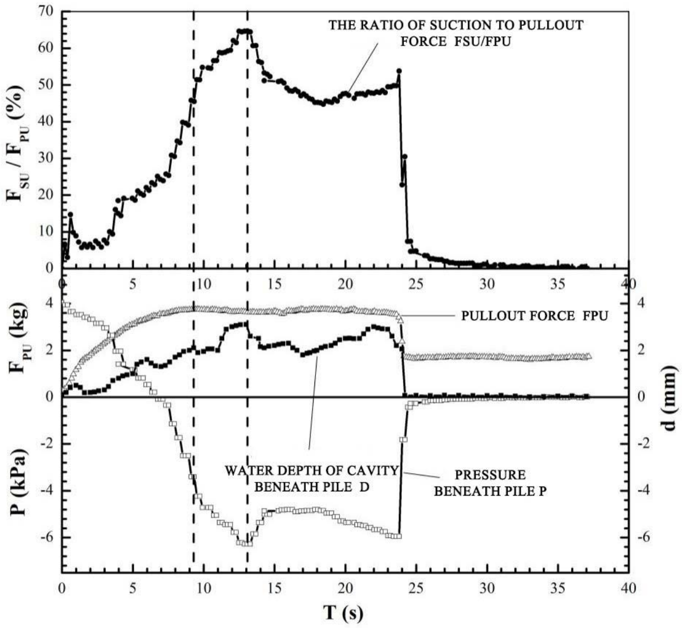

Fig. 7. **Variations of the pressure, pullout force and cavity depth beneath the pile against the pullout time**

3. Influence of pullout velocity on pressure

Under the operational condition with the same embedded depth and soil property, five different pullout velocities (1 mm·s^{-1}, 3 mm·s^{-1}, 5 mm·s^{-1}, 7 mm·s^{-1} and 9 mm·s^{-1}) were adopted to carry out the tests. Fig. 8 shows the variations of the pressure beneath the pile against the pullout time at five different pullout velocities in the case that the pile embedded depth is 12 cm. Through the analysis we can realize that at the same embedded depth, the maximum negative pressure beneath the pile increases from 4.4 kPa to 7.8 kPa with the increase of the pullout velocity. Specifically, the faster the pullout velocity is, the stronger the negative pressure will be, which indicated that the suction force is positively related to the pullout velocity in formula (4). Besides, with the increase of the pullout velocity, the absolute value added to the pressure gradually reduces. This demonstrates that when the pullout velocity increases to a certain value, its influence on the pressure beneath the pile becomes weaker.

Furthermore, from the pressure variation tendency displayed in Fig. 8, it can be discovered that the pressure beneath the pile reduces rapidly from the initial positive pressure value to the maximum negative pressure along with the pile pullout, and then it fluctuates and remains in a relatively stable negative pressure range. When the pile is going to be pulled out from the soil bed, the pressure beneath the pile soars to the value of standard atmospheric pressure. Based on the measurement results of the UDV sensor and the variation tendency characteristics of negative pressure curves at different pullout velocities in Fig. 8, it can be seen that after pullout of the pile, a pore water cavity is formed beneath the pile, and the pressure value in the cavity reduces rapidly and reaches its maximum negative pressure value. In this case, the cavity is in the critical state; in other words, the suction arisen from the negative pressure on the side wall of the cavity reaches its yield stress point. At this point, the soil on the side wall of the cavity will be destroyed, deformed and collapsed, and begin to fill the cavity. Meanwhile, the negative pressure value reduces to a certain extent. Subsequently, the soil is continuously backfilling along with the pile foundation pullout, and the negative pressure value and shape of the cavity keep a dynamic balance with the backfill speed. Since part of the topsoil heaves when the pile foundation is about to be pulled out from the soil, a “sealed space” is formed, so the negative pressure value increases again to the second extreme value. Whereafter, the pile and soil are completely separated, and the pressure value immediately returns to the atmospheric pressure value.

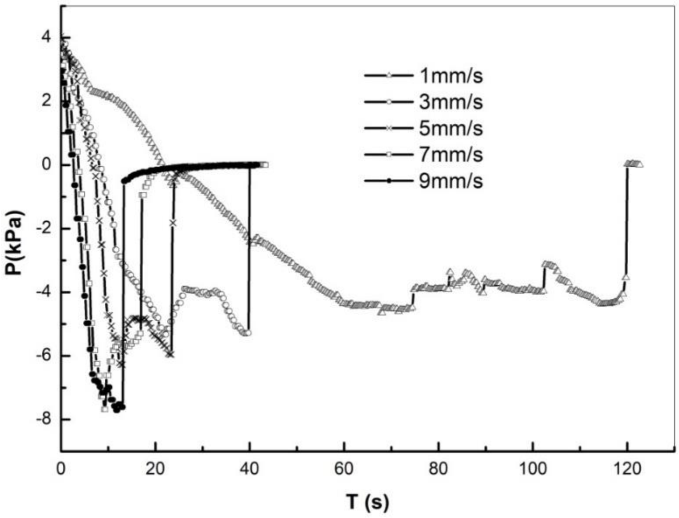

Fig. 8. **Suction force variations against the pullout time at different pullout velocities**

4. Influence of embedment ratio on pressure

The variations of the pressure beneath the pile against the pullout time with the embedment ratios being 2, 3, 4 and the pullout velocity being 1mm·s^{-1} are presented in Fig. 9. The three straight lines in the figure are drawn in accordance with the hydrostatic pressure on the bottom of the pile in the soil corresponding to the pressure beneath the pile revealed in the curves at the same moments. Due to the homogeneous characteristic of the soil, the hydrostatic pressure is in direct proportion to the embedded depth. The difference between the hydrostatic pressure on the bottom of the pile and the pressure beneath the pile reveals the pressure burdened by the pile at the same moment. According to the data analysis, the maximum negative pressures of the pile at the aforementioned embedment ratios are 6.2 kPa, 8.3 kPa and 8.6 kPa respectively. Thus, the negative pressure of the pile becomes stronger with the increase of the embedded depth, it shows that in formula (4), the suction force and embedment ratio are positively correlated. This rule remains true as proved by the results of other tests in this research.

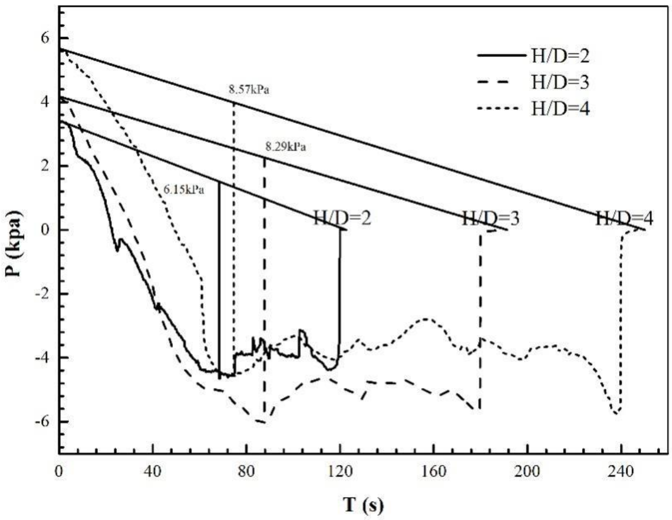

Fig. 9. **Pressure variations beneath the cylindrical pile against the pullout time**

Conclusions

In this research, vertical pullout tests of a smooth and closed short pile in underwater cohesive soil were carried out to measure variations of the cavity shape, pressure and pullout force beneath the pile. In addition, the influence of the pullout velocity and embedment ratio on the pressure beneath the pile was analyzed. The following conclusions can be drawn from these pullout tests.

1. Under the same embedment condition, the maximum negative pressure beneath pile foundation increases from 4.4 kPa to 7.8 kPa with the acceleration of the pullout velocities from 1 $mm \cdot s^{-1}$ to 9 $mm \cdot s^{-1}$, but when the pullout velocity accelerates above 7 $mm \cdot s^{-1}$, its effect on the negative pressure is no longer obvious.
2. During the pile foundation's pullout from the cohesive soil bed, the pore water cavity will be produced beneath the pile foundation. Due to the action of the negative pressure, the cavity will be back-filled by surrounding soil continuously during the pullout process. For this reason, the size of the cavity remains relatively stable.
3. With the pullout velocity, the negative pressure of pile foundation increases from 6.2 kPa to 8.3 kPa with the increase of the embedded depth.

Author contributions

Methodology, experiment setup and formal analysis, Hui Y.; writing – original draft preparation, review and editing, Wenkai W.; administration and funding acquisition, Yuchuan W. All authors have read and agreed to the published version of the manuscript.

References

[1] Xu R., He Y. P., Tan J. H. The concept on several new deepwater mooring systems. China Offshore Platform. 2005, pp. 30-33.
[2] Liu Y. X., Zhang X. W., Wang J. H., Study of design scheme of anchor pile for mooring system. Deepwater Energy Conf. 2015.
[3] Kurt E., Albaugh, H. Tian L. An overview of the global offshore oil and gas floatation equipment – FPSO, Semisubmersible, SPAR, TLP. World Petroleum Industry, 2007, pp. 52-57.
[4] Zheng X. X., Ye C. J., Fu Y. Research and development of operation and maintenance for offshore wind farms. Power System and Clean Energy, 2012, 28(11), pp. 90-94.
[5] Cui Y. Numerical simulation of gravity fish cage and mooring system anti-current characteristics. PhD thesis of Ocean University of China, 2006.
[6] Wang Z. B. The suction force study in silty sediments for spudcan. PhD thesis of Dalian University of Technology, 2012.
[7] Terzaghi K., Peck R. B. Soil mechanics in engineering practice. second edition. 1967.
[8] Feng G. D., Liu Z. D., Yu J. M. et al. Experimental study on the suction force beneath the marine cushion. Engineering Journal of Wuhan University, 1981(1), pp. 1-10.
[9] Das B. M., Shin E. C., Dass R. N. et al. Suction force below plate anchors in soft clay. Marine Georesources & Geotechnology, 1994, 12(1), pp. 71-81.
[10] Datta M., Kumar P. Suction beneath cylindrical anchors in soft clay. Offshore and Polar Engineering Conference, 1996.
[11] Raie M. S., Tassoulas J L. Installation of torpedo anchors: numerical modeling. Journal of geotechnical and geoenvironmental engineering, 2009, 135(12), pp. 1805-1813.
[12] O'Loughlin C. D., Richardson M. D., Randolph M. F. et al. Penetration of dynamically installed anchors in clay. Géotechnique, 2013, 63(11), pp. 909.
[13] Blake A. P., O'Loughlin C. D. Installation of dynamically embedded plate anchors as assessed through. Canadian Geotechnical Journal, 2015, 52(1), pp. 1-9.
[14] Wang W. K., Wang X. F., Yu G. L. Vertical holding capacity of torpedo anchors in underwater cohesive soils[J]. Ocean Engineering, 2018, 161, pp. 291-307.