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Monitoring of a Suction Pile Jacket for Offshore Wind Turbine During Installation

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Abstract. Full-scale field installation test of an offshore wind power suction pile jacket foundation with pile penetration depth to diameter ratio about 2.0 was carried out, where the structure stress of the suction pile side wall, connection joint stress, pore water pressure and earth pressure distribution were monitored. Measured shaft stress results are affected by the applied pressure difference, and reverse tension and compression stress were identified at the same depth, indicating that the suction pile shaft was under bending. After self-weight penetration the foundation inclination was 5.0°, as a result the measured connection joint stress reached 100~150 MPa after being leveled at the suction penetration stage. Measured pore pressure results reveal the reason of large foundation inclination at the self-weight penetration stage, and the attenuation law of pressure difference in different soil at the suction penetration stage. Total and effective earth pressure are obtained on both sides of the suction pile, which are also affected by the applied suction. The field test provides valuable monitoring data of suction pile jacket foundation installation, which can be used in further mechanism study.

Keywords. Offshore wind power, suction pile, full-scale field test, installation monitoring

1. Introduction

Suction jacket foundations are installed by dead weight and negative pressure generated by pumping watering out of the suction pile. Since the available pressure increase linearly with the water depth, such foundations are particularly suitable for ocean engineering, which have considerable advantages compared to conventional foundations. Owing to the unique installation method, the process of pile driving and the corresponding noise is avoided and the installation of the whole suction jacket foundation

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is carried out in one work step, which increases efficiency. In addition, the foundation as a whole can be retrieved by just pumping water into the suction pile to generate positive pressure difference [1], which could further reduce carbon emissions.

Suction foundations can be further divided into suction bucket and suction pile, according to the in service bearing mechanism. Suction buckets are designed as shallow foundations [2], while suction piles are designed as deep foundations [3]. The difference between suction pile and suction bucket is not definite, here we define suction foundation with penetration depth to diameter ratio above 1.0 as suction pile and suction foundation with penetration depth to diameter ratio less than 0.5 as suction bucket [2,4].

Typical applications of suction bucket or suction pile jacket foundation are listed in Table 1. Suction bucket jacket foundation was first applied in the field of offshore oil and gas engineering [5-7]. More recently, offshore oil and gas platforms are designed as suction pile jacket foundation [1,8]. The underlying reason might be that deep foundations could transmit load to deeper soil layer, which is more suitable to bear cyclic load. In the field of offshore wind power, although monopile is the absolute dominant offshore wind foundation type in sea area with water depths below 30m; suction jacket foundation is gaining edge over monopile, as the water depth reaches 30 to 60 m. Since offshore wind foundations are designed to resist huge lateral force and overturning moment generated by the wind turbine, only suction pile jacket foundations are applied [9-11]. Instead of suction bucket jacket, mono-bucket with diameter larger than 20m is used as the offshore wind foundation [12,13].

Table 1. Typical applications of suction bucket or suction pile jacket foundation.

Project	Water depth (m)	Jacket leg and type	Dimension (m)	
			Diameter	Penetration depth
Europipe 16/11E (Draupner E) platform [5]	71	4 legs suction buckets	12.0	6.0
Sleipner Vest SLT platform [7]	83	4 legs suction buckets	14.0	5.0
Dutch L6 sector platform [8]	34	3 legs suction piles	10.0	9.5
Ophir Wellhead Platform [1]	73	3 legs suction piles	6.0	13.7
DONG Borkum Riffgrund Wind Farm [9]	25	3 legs suction piles	8.0	7.5
Aberdeen Offshore Wind Farm [10]	19~32	3 legs suction piles	9.5	7.0~12.5
Offshore Wind Farm of Fujian province, China	40~45	3 legs suction piles	10.0 ~12.0	19.0~22.0

The in-place bearing behavior of suction bucket jacket foundation as the offshore oil and gas platform is analyzed by Bye et al. [6] and Karunakaran et al. [14], and the bearing behavior of suction pile jacket as the offshore wind foundation are analyzed by Wang et al. [15] and Liu et al. [16]. As for the installation of suction foundations, analysis methods are proposed based on theoretical deduction [17] and model tests [18-20]. In practice, the pressure difference and foundation inclination are generally monitored to guide installation [8, 21, 22]. However, full-scale field tests monitoring the pore water pressure and earth pressure distribution during installation are very limited. And the few cases are focused on mono-bucket foundation [13] with large diameter and small depth to diameter ratio. Accordingly, this study sets out to bridge the research gap by carrying out full-scale field test of a suction pile jacket foundation during installation. The record of the field test can be used for further analyze the mechanism underlying suction pile penetration.

2. Project Overview

2.1. Foundation Type

Three-leg suction pile jacket foundations are applied in a certain wind farm project of Fujian province, China. The project site is about 31~50 km away from the coastline, with the average water depth of 37~45 m. The suction pile jacket foundation is shown in Fig. 1, where the height of the jacket is 85~90 m with a weight of 1800~2500 t and the equi-distant footprint of the jacket is 30 m.

Figure 1. Suction pile jacket foundation.

The diameter, length, embedded depth and wall thickness of the suction pile are 10~12m, 22~25m, 19~21.5m and 30~50mm, respectively. Compared with the mono-bucket foundation, the suction pile not only has a larger length-diameter ratio, but also has the advantage that the reinforcing ribs are placed on the top cover of the suction pile rather than the side wall, which does not increase the penetration resistance. Field test was carried out to investigate the penetration mechanism of suction pile penetration. The relevant weight and geometric parameters of the suction pile jacket foundation for the filed test are summarized in Table 2. The design of different wall thickness at both ends for the suction pile is adopted, where the upper section is 50 mm and the lower section is 30 mm.

Table 2. Suction pile jacket foundation parameters.

External diameter (m)	Length (m)	Embedded depth (m)	Wall thickness (mm)	Foundation total height (m)	Foundation total weight (t)
12	22.5	22	35/50	86	2454

2.2. Geological And Hydrological Condition

The water depth of field test position is around 41m. The overlying layer of the seabed surface mainly consists of soft soil such as slit and silty clay. The stratum distribution and cone penetration resistance of static penetration test are shown in Fig. 2.

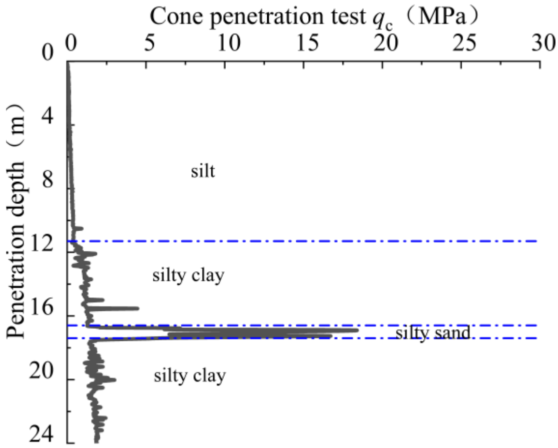


Figure 2. Seabed formation and cone penetration test result.

3. Sensor Deployment

In order to guide installation, pressure sensors were integrated into the pump skid equipment to measure the internal and external pressure difference of the suction pile, and foundation inclination sensors were installed on the flange of the platform. In addition, scientific research sensors were installed on one suction pile of the tested foundation, as shown in Fig. 3.

Significant stress concentration might be produced in the connection section between the jacket and the suction pile under differential penetration of the individual suction pile. Accordingly, stress gauges were placed on the connection point between jacket and suction pile to ensure the structural safety, a ring of 4 stress gauges were adopted for each connection point. The ground formation characteristics was considered in the deployment of sensors along pile depth. The stress gauges placed on the suction pile shaft were arranged in the way of 4 pieces per ring to eliminate the influence of potential overall bending. The distribution of the stress gauges along pile length was based on the principle that most of the stress gauges were deployed at pile tip and few stress gauges were installed on pile top, which ensures that the dense area of sensors near the pile tip pass through the soil layer as much as possible, as shown in Fig. 3(a). Considering that there was no bulkhead on the interior side of the suction pile, the stress gauges were only placed on the exterior wall of the pile, and the interior and exterior resistance component cannot be identified. Pore pressure transducers and earth pressure transducers were deployed on both sides of the suction pile to investigate the difference between the inner and outer soil mass under suction, as shown in Fig. 3(b) and (c). The sensors at the interior and exterior sides of the pile were arranged synchronously to obtain soil effective stress. The number of sensors and other relevant information are summarized in Table 3.

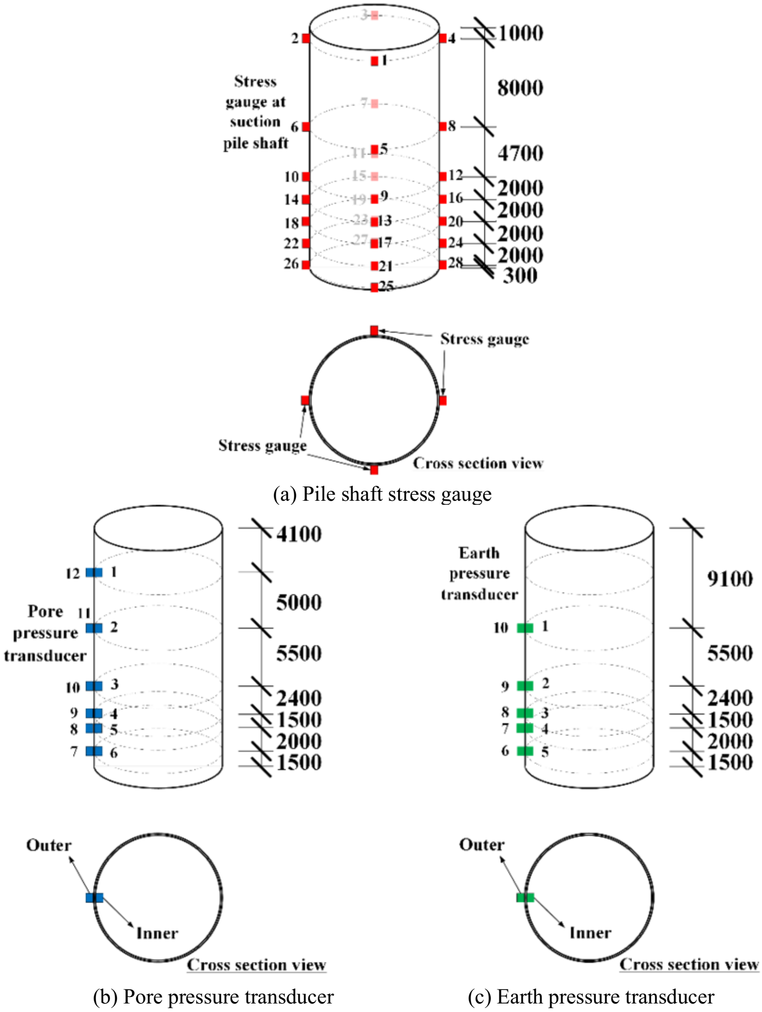


Figure 3. Layout of monitoring sensors.

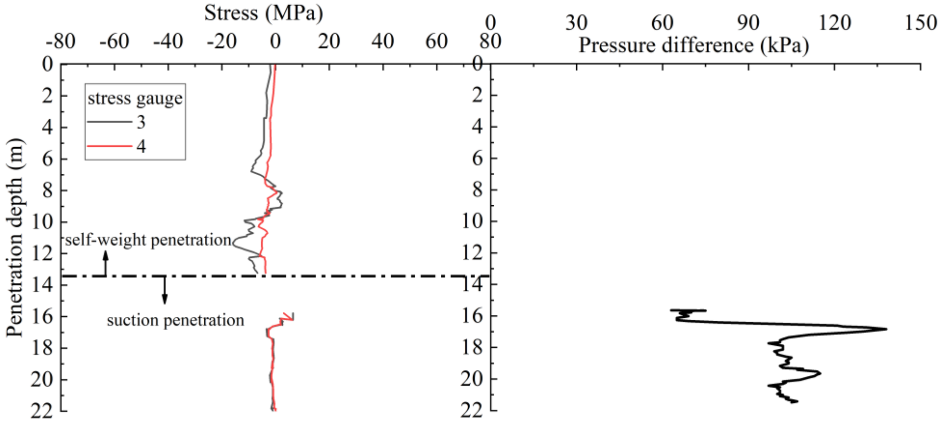
Table 3. Transducer information.

Monitoring item	**Transducer**	**Lateral line (item)**	**Measuring points**	**Total number of measuring points**
Stress at the connection of the jacket and foundation	Stress gauge	3	4	12
Vertical stress at suction pile shaft	Stress gauge	4 (outside)	7	28
Pore water pressure	Pore pressure transducer	2 (Inner and outer sides)	6	12
Earth pressure on pile shaft	Earth pressure transducer	2 (Inner and outer sides)	5	10

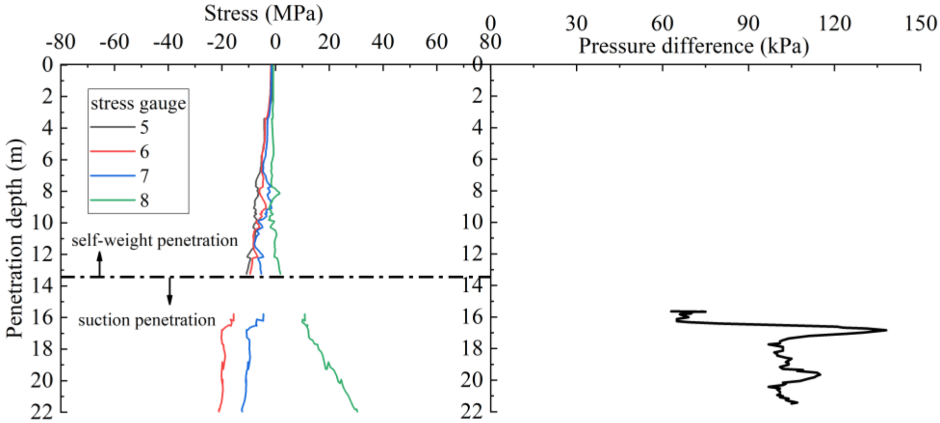
4. Monitoring Results and Analysis

Due to the effect of typhoon, the field test was carried out in two stages: self-weight penetration and suction penetration. The pump skid equipment was retrieved after the completion of the foundation self-weight penetration. At the end of self-weight penetration, the foundation penetration depth and the foundation inclination were about 14 m and 5°, respectively. The suction penetration test was carried out after 18 days. Due to the long interval between the two test stages, the foundation was jacked up by pumping water into the suction pile, at the initial stage of suction penetration test to make it completely leveled. The data of the sensors were acquired, after the foundation had already been leveled and further sunk 2m. Therefore, the data for 14-16 m were not recorded.

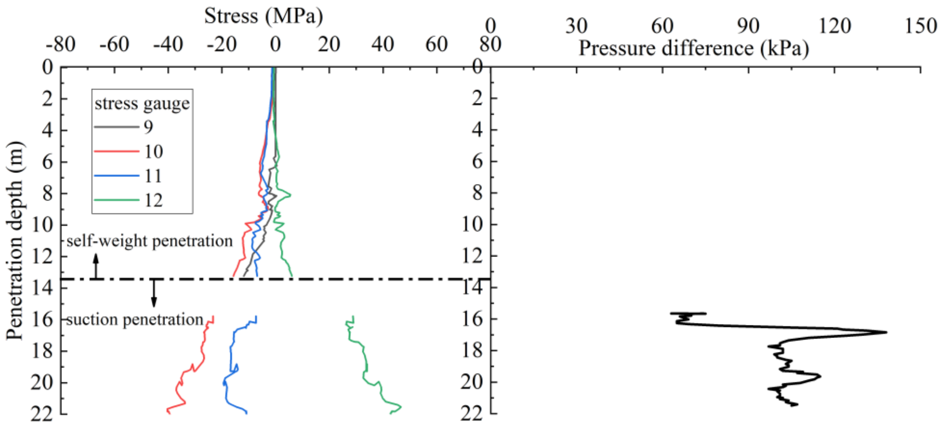
The monitoring results of the stress gauges on pile shaft at various depths are shown in Fig. 4. Stress gauges 1, 2, and 21 failed during the test. In addition, stress gauges 5, 9, 17, 21 and 25 arranged in the same direction in the suction penetration stage all failed, which may be attributed to the large inclination of the foundation during the leveling process. In the self-weight penetration stage, four stress gauges at the same depth show reverse tension and compression forces, which indicates that the side wall of the suction pile was bent under the overall inclination of the foundation. At the suction penetration stage, the results of the stress gauges are apparently related to the interior and exterior pressure difference of the foundation, especially for the stress gauges at the lower part of the suction pile. Reverse of tension and compression stress was recorded at the same depth, indicating that the side wall was under bending.



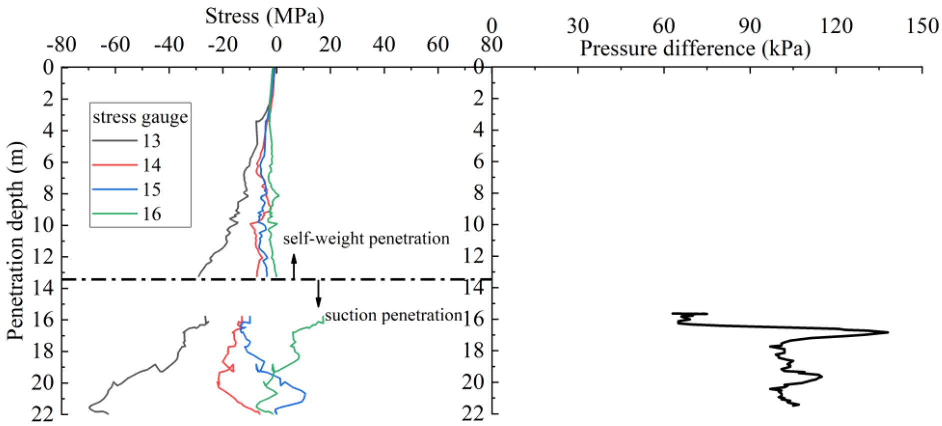
(a) First layer of stress gauges



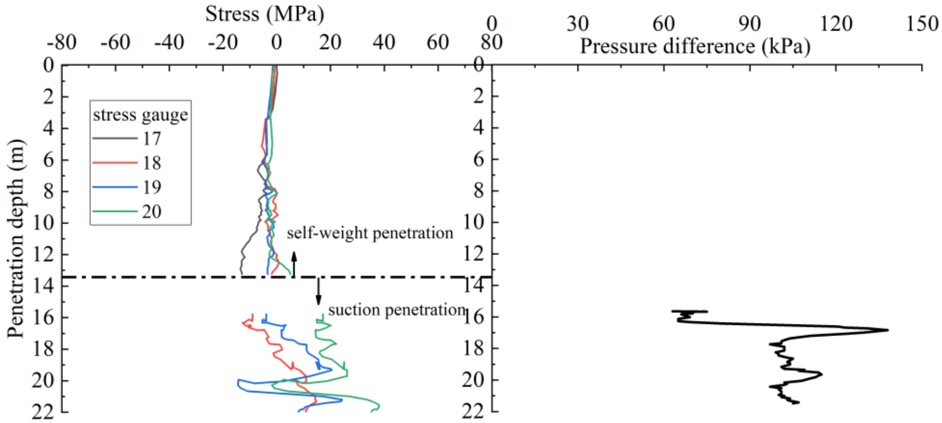
(b) Second layer of stress gauges



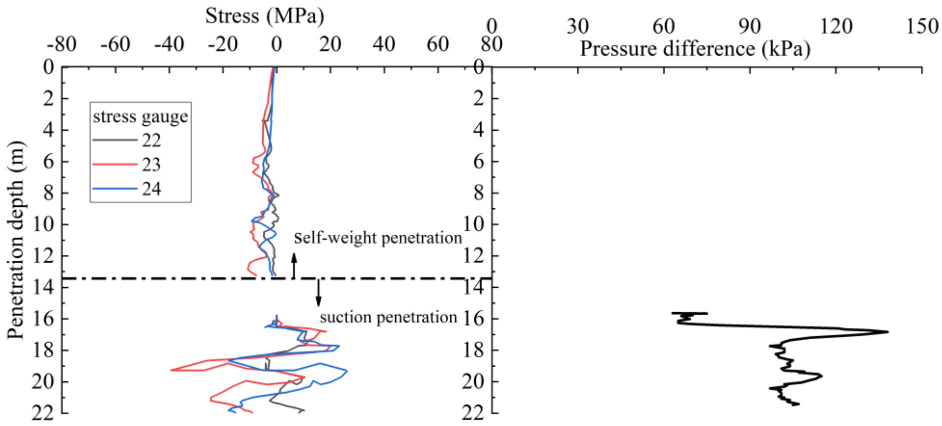
(c) Third layer of stress gauges



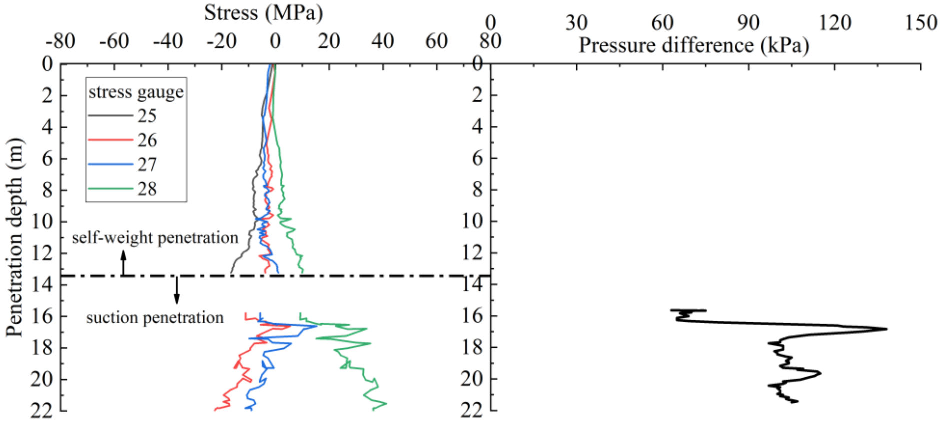
(d) Fourth layer of stress gauges



(e) Fifth layer of stress gauges



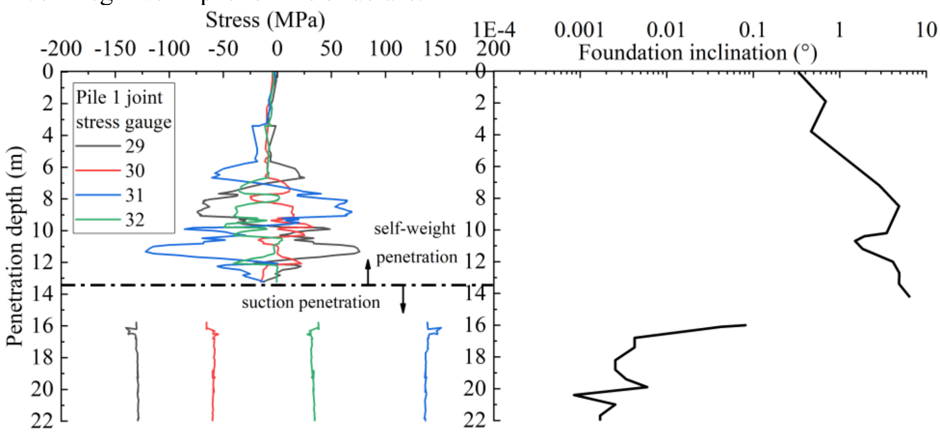
(f) Sixth layer of stress gauges



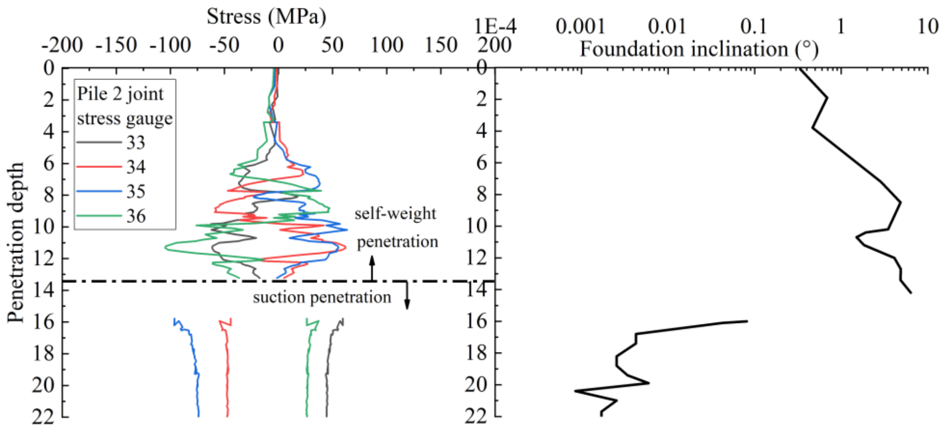
(g) Seventh layer of stress gauges

Figure 4. Measured stress at suction pile shaft.

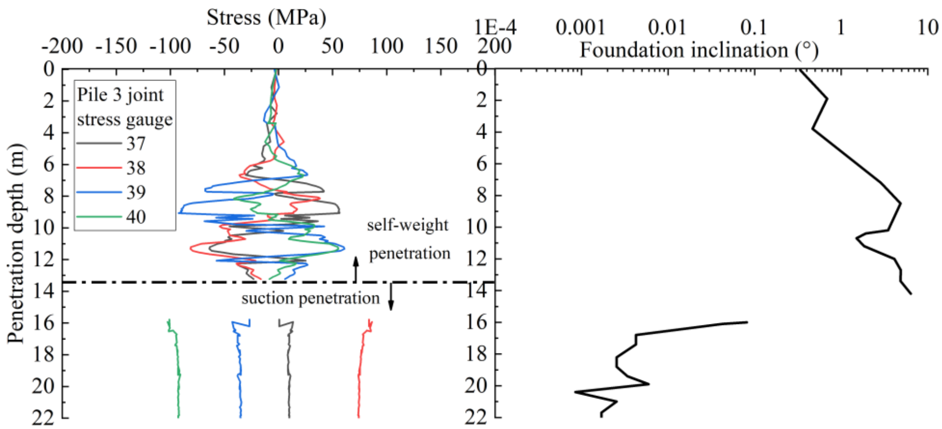
Fig. 5 shows the monitoring results of stress at the connection point between the jacket and the suction pile. It is found that the joint stress is mainly affected by the foundation inclination rather than the pressure difference. The nodal stress can be ignored when the embedded depth of the foundation is less than 2m, while the corresponding foundation inclination gradually increases. Within the range of 2~14 m by self-weight penetration, the nodal stress increases when leveling is carried out by directional water injection jacking. Otherwise, the nodal stress decreases under freely developed foundation inclination. The underlying reason might be that the soil surrounding the suction pile could not deform in complete accordance with the jacket foundation as a whole, and the foundation levelness was parted attributed to deformation at the connection joint. The nodal stress keeps at 100~150 MPa during the suction penetration stage, when the stress monitoring started and the foundation had been completely leveled. This indicates that it is necessary to control the foundation inclination in the self-weight penetration stage, otherwise even if the foundation can be leveled in the future, it will have a negative impact on the structure.



(a) Pile 1



(b) Pile 2



(c) Pile 3

Figure 5. Measured stress at foundation joint

The results from the pore pressure transducers are shown in Fig. 6. The top pore water pressure transducer (outer 12, inner 1) is above the soil surface or only 2m into the soil most of the time. Theoretically, its result should be close to the monitoring results of the differential pressure sensor integrated in the pump skid. In practice, the error between the two sensors is within 5%, indicating that the pore pressure sensor data is basically reliable. It can be seen that the internal pore water pressure is always greater than the external pore water pressure at the stage of self-weight penetration, as shown in Fig. 6, which indicates that the water in pile 1 was not discharged in time. This can be attributed to the incomplete opening of the drain valve and also explains why the overall inclination of the suction pile jacket foundation is greater than the expected.

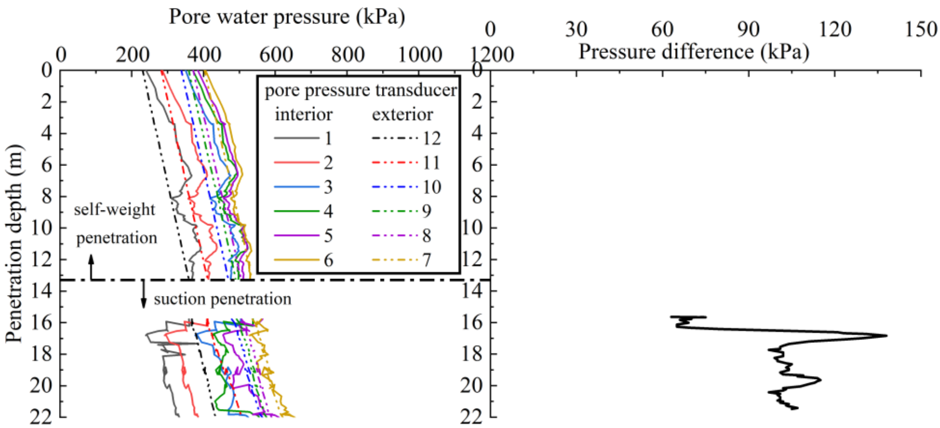
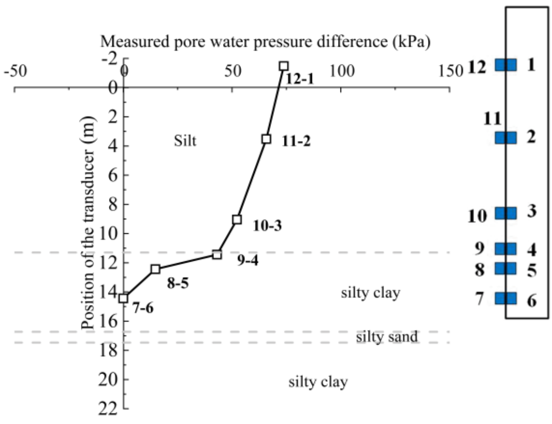
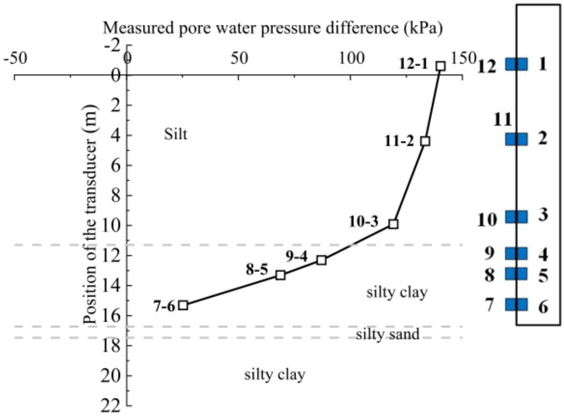


Figure 6. Measured pore water pressure.

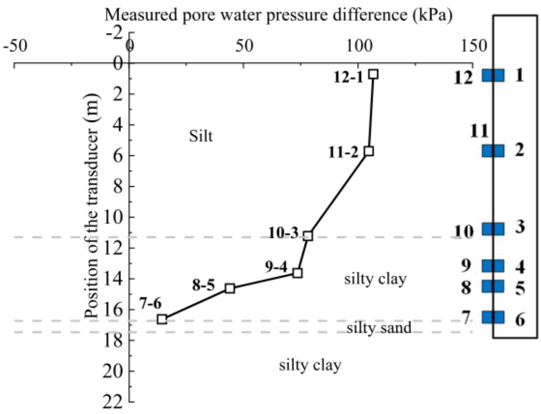
In order to investigate attenuation law of the pressure difference in various soils, the pressure difference at the same penetration depth is obtained by subtracting the internal and external pressure difference, shown in Fig. 7. In the figure, pressure difference with external pressure larger than internal pressure is defined as positive, and negative depth denotes that the pore pressure transducer has not penetrated into soil. The pressure difference gradually attenuates from the pile top to the pile tip and the pressure difference should decay to 0 at the pile tip in theory. The results of pore water pressure transducers (outer 7, inner 6) at the pile tip are close to 0 in most cases. However, the pressure difference at the pile tip shows small values when the pile foundation is about to sink to the design depth. Through further analysis, this phenomenon is mainly caused by the sudden increase of absolute water pressure at the inner pile tip, and its cause needs further investigation.



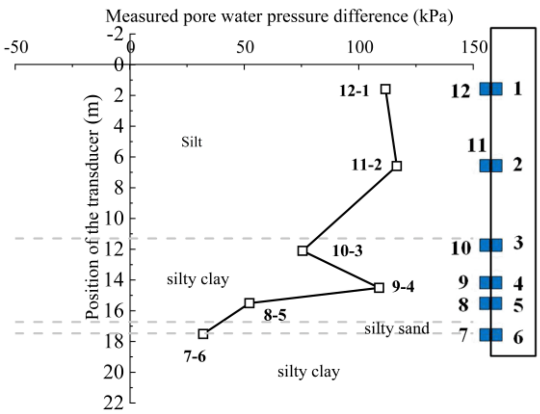
(a) Suction pile penetration of 15.9m



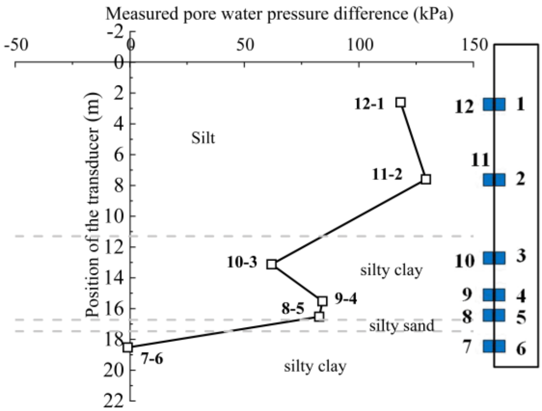
(b) Suction pile penetration of 16.8m



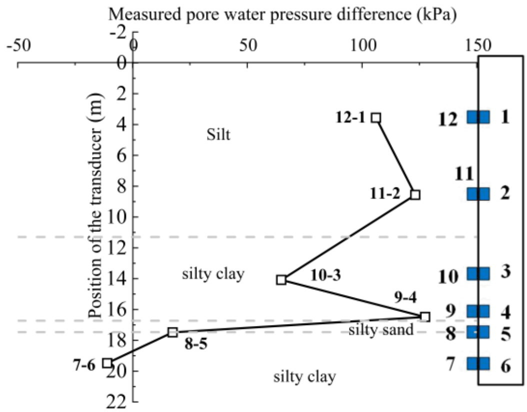
(c) Suction pile penetration of 18.1m



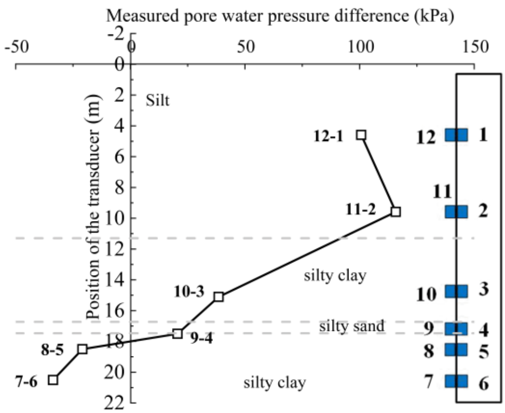
(d) Suction pile penetration of 19.0m



(e) Suction pile penetration of 20.0m



(f) Suction pile penetration of 21.0m

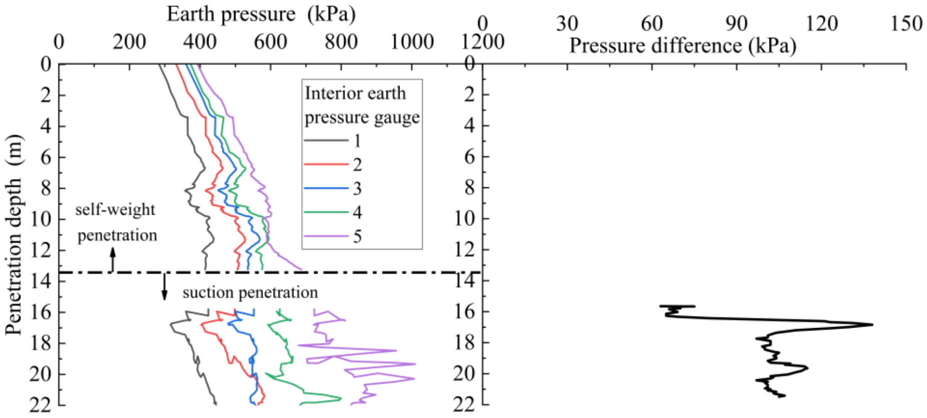


(g) Suction pile penetration of 22.0m

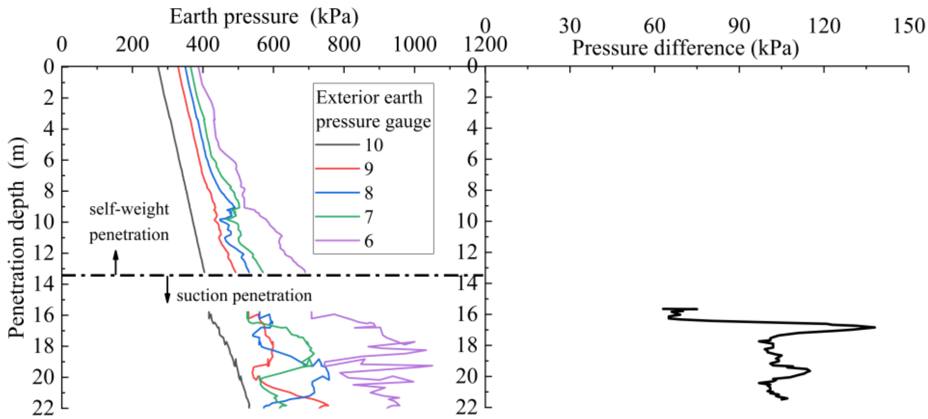
Figure 7. Distribution of measured internal and external pore water pressure difference.

The attenuation value of the internal and external pressure difference along the unit depth of the pile body in the soil layer is defined as the attenuation gradient of the pressure difference, which is the hydraulic gradient defined in soil mechanics. The distribution of pressure difference along the suction pile shows that the attenuation gradient of pressure difference in the silty sand layer is the largest, as shown in Fig. 7 (e) and (f). The attenuation gradient of pressure difference in silty clay is significantly higher than that in silt, as shown in Fig. 7(a), (b), (c) and (d). The variation of attenuation gradient of pressure difference in various soil layers reflects the difference of soil permeability. The larger the attenuation gradient of pressure difference, the greater the seepage force, which is consistent with the resistance reduction mechanism under suction in silty clay found in other studies. The soil mass classification is based on soil permeability in the study of calculation parameters of penetration resistance and should conform to the law that the stronger the permeability of the soil layer, the smaller the calculation coefficient of penetration resistance, that is, the more obvious the effect of resistance reduction under suction. Note that the pressure difference distribution is relatively simple before the pile tip penetrates into the sand layer. When the pile tip reaches the silty sand layer, the pressure difference in the silt layer increases at first and then decreases with depth. A sudden change in the pressure difference in other soil layers can also be found, indicating that the seepage state of the sandy soil and cohesive soil interbedding is relatively complex.

The total and effective earth pressures are shown in Fig. 8 and Fig. 9, respectively. In general, both the total and effective earth pressure increase at greater depth. Since the inner pore water pressure is affected by suction, the interior effective earth pressure results are associated with the pressure difference as expected. The variation of total and exterior effective earth pressure is also associated with the pressure difference. Besides, the earth pressure gauge buried deeper in the soil is more affected, which is in accordance with the pile shaft stress results. The reason of such phenomenon might be attributed to that the suction pile shaft is deformed under the suction.

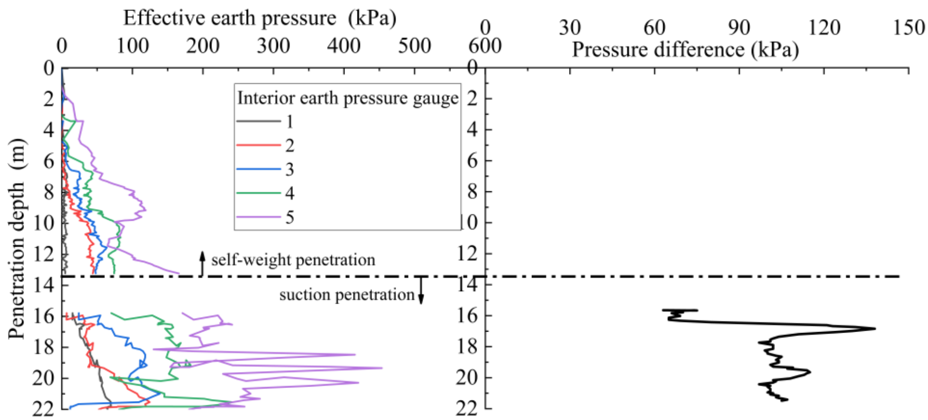


(a) Interior

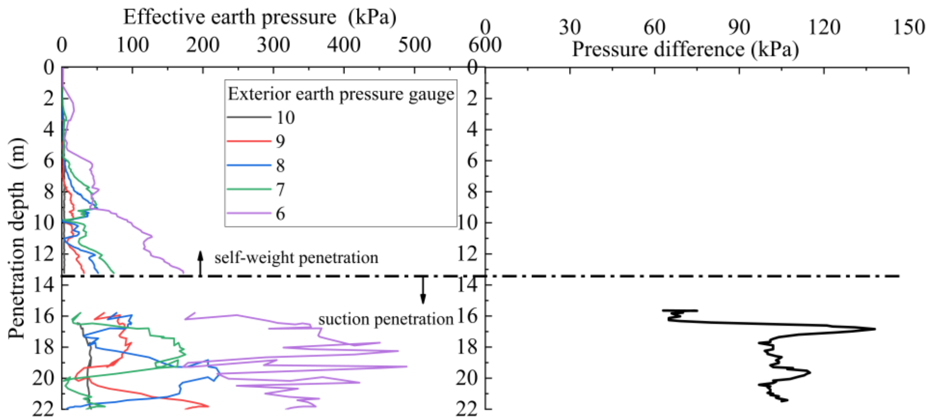


(b) Exterior

Figure 8. Total earth pressure.



(a) Interior



(b) Exterior

Figure 9. Effective earth pressure.

5. Conclusions

Full-scale field installation test of a suction pile jacket foundation was carried out, where the structure stress of the suction pile side wall, connection joint stress, pore water pressure and earth pressure distribution were monitored. This is the first monitoring test of such suction pile with penetration depth to diameter ratio about 2.0. Originally, the stress results of pile shaft were designed to calculate the resistance during suction penetration, as the lower part of the suction pile embedded in soil was thought less affected by the applied pressure difference. However, the measured stress results are contrary to the original assumption. Reverse tension and compression stress were identified at the same depth, indicating that the suction pile shaft was under bending. Further attempts to measure the penetration resistance of suction pile directly should take such interference factors into account. One possible solution is to add a special designed bulkhead within the suction pile, where the effect of suction is avoided. After self-weight penetration the foundation inclination was 5.0°, as a result the measured connection joint stress reached 100~150 MPa after being leveled at the suction penetration stage. Although suction pile jacket foundation could be leveled under inclination up to 5.0 °, it is still necessary to control the foundation inclination in the self-weight penetration stage. Measured pore pressure results reveal the reason of large foundation inclination at the self-weight penetration stage, and the pressure difference of the top transducers is close to the that of the differential pressure sensor integrated in the pump skid. The attenuation law of suction pile pressure difference in different soil is revealed. The pressure difference diminishes the fastest in the silty sand layer, flowed by that in silty clay and that in silt. Such pressure difference distribution could be further used to study the mechanism of penetration resistance reduction under suction. Total and effective earth pressure are obtained on both sides of the suction pile, which are also affected by the applied suction. Although further improvement is needed, the field test provides valuable measured data during the installation of suction pile jacket foundation.

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