Transition of soil strength during suction pile retrieval

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Abstract

A field suction pile retrieval test was conducted inside the Okpo Harbor in southern Korea during the summer of 2003. A steel suction pile was used to install a permanent embedded anchor in the clay seafloor soil. After the embedded anchor was installed, the suction pile was retrieved using positive water pressure inside the pile. The field test provided detailed instrumentation on the relationship between the applied positive water pressure inside the pile and the resulting pile pullout. This paper describes the transition of the soil strength during the suction pile retrieval process.

Keywords: suction pile, retrieval, mobilized soil strength.

1 Introduction

Suction piles have been used with great success in offshore locations in recent years due to its significant advantages over conventional piles. Wider use of suction piles in near future is therefore expected. Almost all suction piles constructed to date are designed as permanent structure. However, it may be necessary to retrieve such piles due to many reasons, e.g., misalignment of the pile axis during installation, reuse of the pile at different locations, restoration of the seafloor for environmental concerns, etc. Therefore, an accurate analytical solution method needs to be established, providing incremental values of the correct positive water pressure inside the pile for safe retrieval of suction piles. This will further expand the utilization of suction piles in offshore and maritime applications.
The main objective of this study is to describe the clay strength variation during suction pile retrieval so that an analytical solution method for safe retrieval of suction piles using increased water pressure inside the pile can be established. The proposer has already developed an analytical solution for suction pile installation for the US Navy with calibration and validation completed through small-scale laboratory model tests, centrifuge model tests, and field experiments [1]. This analytical solution utilizes the concept of the “mobilized soil strength ratio,” which describes the transition of the soil strength during installation. Following similar approach, an analytical solution for suction pile retrieval is expected to be developed soon.

2 Mobilized soil strength ratio

Suction piles typically have a large diameter with a relatively small length-to-diameter ratio. They are installed by applying a suction pressure inside the pile, which acts as an external surcharge to push the pile into the seafloor. They may be retrieved later by applying a positive pressure inside the pile. The details of the suction piles with regard to its use, mechanism, installation, and analysis and design methods can be found in references [2, 3, 4, 5, 6, 7].

The suction pile system has advantages over conventional underwater foundation systems due to its large bearing capacity, simplicity, and efficiency. However, during installation and retrieval of suction piles in clay seafloor, the soil inside or outside the pile may be weakened due to the disturbance caused by the pile movement. This will obviously result in a reduction of the soil strength. To quantify this reduction in clay strength, the concept of the “mobilized soil cohesion ratio” has been introduced [8, 9]. The mobilized soil cohesion ratio is the ratio between the mobilized soil cohesion and the fully available soil cohesion. The mobilized soil cohesion is the required soil cohesion so that the pile-soil system is in a balancing state having the factor of safety of 1.0. The fully available soil cohesion is the maximum cohesion of the soil.

The mobilized soil cohesion may vary along the pile length. However, an analytical solution method that incorporates the variable mobilized soil cohesion ratio, which is a function of many parameters, will be extremely complicated. Therefore, an approach has been taken to utilize the average mobilized soil cohesion ratio, i.e., a single representative value at a given state.

Previously, a series of experimental laboratory model tests were conducted to calibrate the mobilized soil cohesion during suction pile installation [10, 11]. This paper describes the calibration of the mobilized soil cohesion ratio during suction pile retrieval in clay. Details of the field tests including the suction pile installation and retrieval procedures and the test results are also included.

3 Analytical solution for suction pile retrieval

An analytical solution that can estimate the correct suction pressure for safe penetration of suction piles into the seafloor soil has been made and published previously [1]. Similarly, the analytical solution for suction pile retrieval should
be capable of estimating the correct positive pressure that can safely retrieve the pile from the seafloor without creating any instability at a given pile penetration depth.

In order to retrieve the suction pile successfully from the seafloor, the soil resistance must be overcome. The resistance of the pile is the pile pullout resistance corresponding to the state of the pile embedment. The minimum required positive pressure inside the pile at given embedment depth can therefore be determined from the equilibrium. The equilibrium requires that the pullout resistance of the pile equal to the external forces including the weight of the pile, the applied surcharge, and the pressure inside the pile. When the positive pressure with the resulting total external force exceeding the pile pullout resistance is applied, the pile starts to move upward. However, as soon as the pile starts to move, the positive pressure inside the pile should be reduced to prevent a sudden pop-out of the pile. This procedure repeats until the pile retrieval is completed.

During the retrieval process, the clay in contact with the pile may be weakened due to the pile movement caused by the positive pressure inside the pile. This will result in a reduction of the soil cohesion and the adhesion between the soil and the pile. To quantify this reduction in clay strength, the concept of the “mobilized soil cohesion ratio,” $\beta$, has been introduced. It is defined as

$$\beta = \frac{C_m}{C}$$

where $C_m$ = mobilized soil cohesion necessary for the equilibrium between the external force and the pile pullout resistance and $C$ = fully available soil cohesion.

The variation of $\beta$ can be determined from the results of experimental tests by matching the calculated pile embedment length with the observed pile embedment length at given conditions.

The total pile pullout resistance is the sum of the frictional capacity developed both inside and outside the pile plus the buoyant weight of the pile and the surcharge on top of the pile. The total pile pullout resistance, $Q$, therefore can be expressed as

$$Q = Q_{outside} + Q_{inside} + W_{pile} + W_{surcharge}$$

where $Q_{outside}$ = frictional capacity between the outside surface of the pile and the soil, $Q_{inside}$ = frictional capacity between the inside surface of the pile and the soil, $W_{pile}$ = buoyant weight of the pile, and $W_{surcharge}$ = effective weight of the surcharge on top of the pile.

Details of the estimation of the soil side frictional capacity are beyond the scope of this paper. They can be found in reference [12].
4 Field tests

The Daewoo Engineering and Construction Co., Ltd. conducted a field test on suction pile installation and retrieval inside the Okpo Harbor located in southeastern Korea during the summer of 2003. The main objective of the field test was to measure the ultimate pullout resistance of an embedded anchor installed by a suction pile. The steel suction pile was 9.25 meters long with the outside diameter of 2.5 meters and the thickness of 3 cm. For installation, the embedded anchor was attached at the tip of the suction pile and then driven as a unit with the suction pile by the applied suction pressure inside the pile. After the anchor reaches the desired depth, the suction pile was retrieved by applying a positive pressure inside, leaving the anchor permanently within the seafloor soil. During the retrieval of the suction pile, the relationship between the applied positive pressure inside the pile and the resulting pile upward movement was carefully measured. This allowed us to calibrate the mobilized soil cohesion ratio relationship during the retrieval process.

To obtain the soil properties, a total of three borehole investigations at the test site were made. In each borehole, undisturbed soil samples were collected at every 1-meter interval. A series of laboratory tests were conducted with the soil samples. The soil was classified to be highly plastic clay (CH) according to the Unified Classification System. The average saturated unit weight of the soil was 14.23 kN/m$^3$. The average undrained soil shear strength determined from the Unconsolidated Undrained tests increased with depth (Figure 1), ranging from 4.4 kN/m$^2$ at the depth of 1 meter to 6.8 kN/m$^2$ at the depth of 5 meters.

The average water depth of the test site was approximately 15 meters and the maximum height of the tidal variation was approximately 4 meters. The effect of the tidal variation was observed by measuring the water pressures inside and outside the pile at the same elevation near the top during the tests. It was concluded that the tidal variation could be neglected, since the pullout test was completed in a relatively short period of time.

The water pressures were measured by piezometers (pluck-type vibrating wire sensor with built-in RTD temperature sensor) installed near the inside and outside top of the suction pile. Therefore, the water pressure difference between the outside and inside the pile could be instrumented directly from the water pressure measurements regardless of the height of the tide. A tiltmeter (Electro Level tiltmeter with biaxial electrolytic tilt sensors) was installed at the top of the pile, which monitored the inclination angles in two perpendicular directions. The pile penetration was measured by two wire crack-extensometers. The entire instruments were connected to a laptop computer through a data control box. Each set of data was recorded at every three seconds.

The entire field tests were conducted on a Self-Elevating Platform (SEP) type barge. It has a displacement tonnage of approximately 2,300 tons and dimensions of 39.5 m by 39.5 m with a 22.5 m by 22.5 m opening in the middle. The entire barge was completely fixed by hydraulically penetrating four steel piles (D=2.3 m and L=69 m) located at the corners into the seafloor. A 200-ton capacity self-crawling crane sitting on top of the barge was used for the storage,
transportation, and handling of suction piles. Figure 2 shows a picture of the SEP barge.

Figure 1: Soil undrained shear strength variation.

Figure 2: Photo of SEP barge.
After the suction pile and anchor assembly was completely penetrated into the seafloor, the pile retrieval test was conducted by directly pumping the water into the pile. This created positive water pressure inside the pile whose magnitude was greater than the outside ambient water pressure and therefore worked as the pullout force. The amount of water pumped into the pile was controlled rather than the pressure inside the pile. This worked extremely well as the water pressure automatically decreased as the pile was pulled out gradually.

Table 1: Calculated mobilized soil cohesion ratios.

<table>
<thead>
<tr>
<th>Remaining Pile Embedment Length (m)</th>
<th>Water Pressure (kPa)</th>
<th>Mobilized Soil Cohesion Ratio $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.6</td>
<td>78.1857</td>
<td>0.830</td>
</tr>
<tr>
<td>8.5</td>
<td>78.3819</td>
<td>0.838</td>
</tr>
<tr>
<td>8.4</td>
<td>78.2838</td>
<td>0.845</td>
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<tr>
<td>8.3</td>
<td>77.0085</td>
<td>0.847</td>
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<td>8.2</td>
<td>76.7142</td>
<td>0.855</td>
</tr>
<tr>
<td>8.1</td>
<td>77.9895</td>
<td>0.867</td>
</tr>
<tr>
<td>8.0</td>
<td>76.1256</td>
<td>0.867</td>
</tr>
<tr>
<td>7.9</td>
<td>75.6351</td>
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<td>7.8</td>
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<td>7.6</td>
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<td>71.7111</td>
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<td>0.980</td>
</tr>
<tr>
<td>6.6</td>
<td>70.5339</td>
<td>0.975</td>
</tr>
</tbody>
</table>

5 Test results

Table 1 shows the results of the applied positive water pressure, the pile embedment depth, and the calculated mobilized soil cohesion ratio. As can be seen from the table, the positive water pressure decreases as the pile pullout distance increases.
Results of suction pile retrieval test are shown in Figure 3, which shows the relationship between the positive water pressure inside the pile and the mobilized soil cohesion ratio. For comparison, the mobilized soil cohesion ratios during installation are also included. Figure 4 shows a similar relationship between the pile embedment depth and the mobilized soil cohesion ratio.

![Figure 3: Water pressure vs. mobilized soil cohesion ratio.](image)

![Figure 4: Pile embedment depth vs. mobilized soil cohesion ratio.](image)

It is noted that the value of the mobilized soil cohesion ratio ($\beta$) generally increases as the pile is pulled out, i.e., as the pile embedment length gets smaller. Similarly, as the water pressure decreases, the mobilized soil cohesion ratio increases, indicating that the mobilized soil cohesion ratio is the smallest at the beginning of the pile retrieval process.
6 Conclusions

Field test on suction pile retrieval was conducted in clay seafloor. Measurements indicate that the retrieval of suction piles can be achieved successfully through a careful control of the water flow rate instead of the pressure. Detailed analysis indicates that the soil strength reduction has occurred as expected during the suction pile retrieval.

Field test results indicate that the positive water pressure inside the pile should decrease as the pile is pulled out during retrieval. It is also observed that the magnitude of the water pressure difference needed to initiate the pile pullout is much higher than that for full pile penetration. The results of the field instrumentation have been used to estimate the mobilized soil cohesion ratios by equating the applied external loads with the pile pullout resistance at various embedment depths. Higher mobilized soil cohesion ratios are observed during retrieval than installation of suction piles.

With additional laboratory and field tests, the variation of the mobilized soil cohesion ratio for various clay seafloor soils can be established and used for the design of safe retrieval of suction piles.

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References


