KSCE Journal of Civil Engineering (2022) 26(4):1632-1642
DOI 10.1007/s12205-021-0779-1

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Geotechnical Engineering

# Cyclic Behavior of Bucket Anchor Foundation in Silty Sand under Sustained Pull-Out Loads via Centrifuge Model Tests

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## ARTICLE HISTORY

Received 5 May 2021
Accepted 31 October 2021
Published Online 17 December 2021

## KEYWORDS

Cyclic loads
Suction foundation
Suction anchors
Centrifuge
Offshore wind

## ABSTRACT

In recent, suction anchor foundations have been encouraged as an alternative for supporting offshore wind turbines in the deep sea. The foundation for offshore wind turbine foundation should be designed considering the cyclic forces, which cause an accumulated displacement of the structure and degradation of the stiffness of the ground-foundation system. However, previous researches for suction anchor behaviors have mostly focused on static loads, although the forces applying on the offshore structure are cyclic in the sea. Moreover, since the suction anchors are always subjected to sustained pullout loads combined with cyclic loading due to the buoyancy forces of the structure, evaluating the in-service performance of suction anchor foundations considering cyclic loadings with sustained pullout loads is also required. In this study, the responses of a suction anchor foundation under cyclic loading along with sustained pull-out loads were investigated via centrifuge model tests. Consequently, it was observed that the behavior of the suction anchor are dependent on the sustained pullout loads, as well as the cyclic loading. This study highlights that the ratio of sustained pull-out loads as well as the cyclic load effect must be considered when analyzing design loads to accurately evaluate the bearing resistance of the suction anchor foundation.

## 1. Introduction

Since the Kyoto Protocol in 1997, many countries have tried to resolve environmental pollution caused as a result of burning fossil fuels by adopting alternative reusable energy sources. In particular, wind energy, one of the promising renewable energy sources, had been emerged to resolve the pollution problems (Santamarina and Cho, 2011; Jeong et al., 2019). According to the EWEA (2013), two trends are being highlighted in offshore wind energy. First, the installation location of turbines is gradually far away from the seashore, and the capacity of the turbines is increasing up to 10 MW. Second, the installation depth of the turbines is continuously increasing. These trends have led that suction anchors have been adopted as substitutes for conventional foundations because of the unique features applicable for the deep-water installation of offshore wind turbines.

For industrial applications, the limit state design based on the ultimate load carrying capacity is considered to be an important design issue. The ultimate capacity of a suction bucket foundation has been extensively evaluated and has been successfully applied (Ibsen et al., 2005; Houlsby et al., 2005b; Leblanc et al., 2010; Zhu et al., 2013; Kim et al., 2013a; Choo et al., 2014a). However, the necessity to address the following issues has been emphasized for the offshore wind turbine (OWT) design: 1) maintaining the performance of the OWT within serviceability limit state and 2) evaluating variation in the permanent displacement and the stiffness of the OWT system caused due to cyclic loading. Byrne and Houlsby (2004) proposed that the requirements in the serviceability state, rather than the ultimate state, should be given preference while developing the design. In other words, it is significant to evaluate the cyclic performance of the OWT system at low amplitudes (i.e., service limit state (SLS) and fatigue limit state (FLS)) (Jeong et al., 2020a).

Forces subjected to OWT are typically cyclic in nature, and

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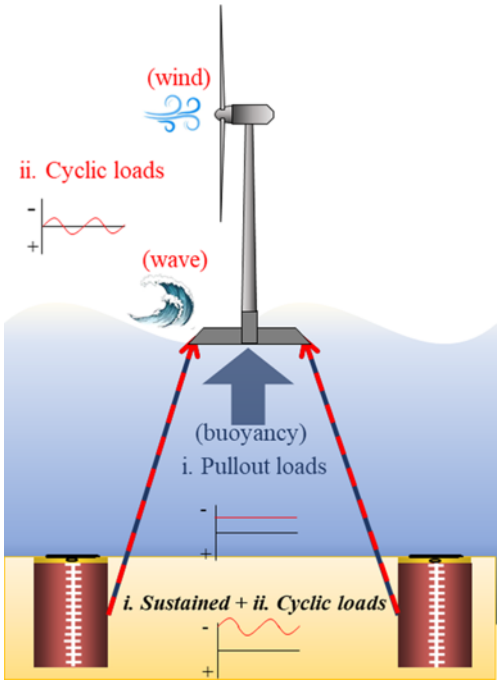


**Fig. 1.** Loading Components Acting on the Suction Anchor

thus, an offshore foundation system is required to be designed considering these cyclic loads. When the soil is subjected to cyclic loading, the pore pressure of the undrained or partially drained soil increases significantly, resulting in the gradual accumulation of soil strain and a decrease in the soil strength and the bearing capacity of the foundation. In other words, the soil foundation system behaves plastically under cyclic loading, as differed from dynamic loading (Peralta and Achnus, 2010; Wang et al., 2018a; Wang et al., 2018b). However, so far, studies on foundation behavior have predominantly focused on static or dynamic loading, even with offshore sea structures being subjected to natural cyclic loading. In addition, suction anchors are always subjected to sustained pull-out loads owing to the buoyant forces acting on the structure. Fig. 1 shows the sustained pull-out loads and cyclic loads acting on the suction anchors simultaneously. This fact requires the studies for the behavior of suction anchors under the action of sustained pull-out loads and cyclic loading. This study aims to assess the performance efficiency of suction anchor foundations subjected to cyclic loadings along with sustained pull-out loads for its service lifetime.

Centrifuge model tests were conducted with varying quantities of sustained pull-out loads and cyclic loadings to the suction anchor. The permanent displacement and cyclic stiffness of the ground-foundation system were assessed with different loading conditions. The silty Saemangeum sand was collected and treated to be used as the soil specimen. A load-controlled actuator was equipped to apply the sustained cyclic loadings.

In this study, there are no target prototype structures at a real site. Those are experimental limitations to this study for expecting real prototype behavior. However, to increase the practical applicability of the results to the field, the testing results were converted into a prototype scale considering the scaling law. Moreover, the dimensions of the model structure were determined in consideration of the typical size of the bucket commonly used for the suction anchors (Senders, 2009; Tjelta, 2015). Besides, the relative density was determined to be dense considering the ground conditions of North Sea region, where the offshore wind turbines are most widely installed (Byrne, 2000; Houlsby et al., 2005a). The soil type was selected as silty sand, which is commonly distributed in the possible installation depth of the suction anchor.

## 2. Cyclic Loading Test System and Soil Preparation

### 2.1 Testing Apparatus (Geo-centrifuge)

It is essential to accurately model in-situ conditions for the simulation of an appropriate prototype model. The beam-type centrifuge installed at Korea Advanced Institute of Science and Technology (KAIST) was used in this study. It has a radius of 5 m and an asymmetric beam centrifuge of 240 tons. The general specifications are summarized in Table 1 (Kim et al., 2013b).

### 2.2 Modeling of Suction Anchor Foundation

The suction anchor model was fabricated using steel to prevent its deformation under the subjected load. The dimensions of the caisson were 137.5 mm (wall height, L), 137.5 mm (diameter, D), and 3 mm (wall thickness, t), representing 9.63 m × 9.63 m × 0.21 m in a prototype satisfying the scaling law of 1:70 (70 g centrifugal acceleration). Generally, the ratio of a thickness of the bucket to a diameter ranges from 0.3% to 0.6% of the OWT foundation (Senders, 2009). Moreover, Villalobos et al. (2010)

**Table 1.** Geo-centrifuge Specificationss

| Item | Specifications |
|---|---|
| Radius of the centrifuge arm | 5.0 m |
| Load carrying capacity | 240 g-tons |
| Maximum centrifugal acceleration | 130 g with 1,300 kg payload |
| Maximum payload | 2,400 kg subjected to 100 g |

**Table 2.** Evaluation of Pile Behavior for Rigid to Flexible

| Pile diameter, $d$ (mm) | Pile thickness, $t$ (mm) | Pile penetration, $l$ (mm) | Pile stiffness, $E_p$ (MPa) | Soil stiffness, $E_s$ (MPa) | $\frac{E_p I_p}{E_s l_L^4}$ |
|---|---|---|---|---|---|
| 137.5 | 3 | 137 | 210,000 | 47.1 | 37.5 |

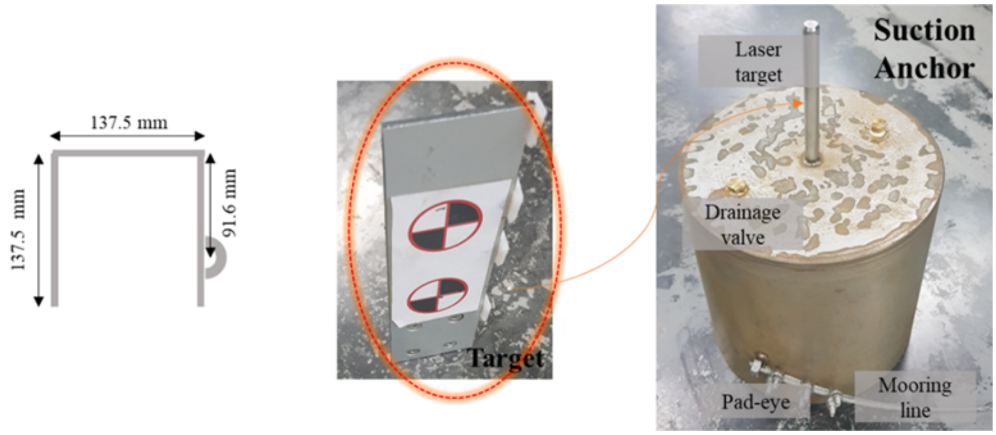


**Fig. 2.** Schematics and Photographs of Suction Anchor Model

**Table 3.** Basic Soil Properties of the Tested Saemanguem Sand

| Item | Properties |
|---|---|
| Specific gravity, $G_S$ | 2.67 |
| Max. dry density (kN/m$^3$) | 16.2 |
| Min. dry density (kN/m$^3$) | 11.8 |
| Median grain size diameter ($D_{50}$, mm) | 0.08 |
| Uniformity coefficient, $C_U$ | 2.11 |
| Relative density | 70% |
| Dry unit weight (kN/m$^3$) | 14.5 |
| Fine contents (passing #200) | 37% |
| Plastic index | NP |
| Soil classification, USCS | SM |

Note: Values were obtained from Kim et al. (2018) and Jeong et al. (2021)

and Hung et al. (2017) suggested a 0.67%, and Wang et al. (2019) recommended a 0.7% in previous studies. However, the bucket thickness was 2.2% in this study due to the constraints in the fabrication process. The behavior of the suction bucket subjected to the loads was assumed to be rigid without the structural deformation. The range of the rigid pile behavior was calculated using the criteria (Eq. (1)) given by Poulos and Hull (1989):

$$\frac{E_p I_p}{E_s l_L^4} = \begin{cases} >0.208 \; Rigid\ pile\ behavior \\ <0.0025 \; flexible\ pile\ behavior \end{cases}, \tag{1}$$

where $E_p$ is the elastic modulus of the foundation, $I_p$ is the area moment of inertia, $E_s$ is the elastic modulus of the soil, and $l_L$ denotes the embedded depth of the pile. Table 2 shows that the

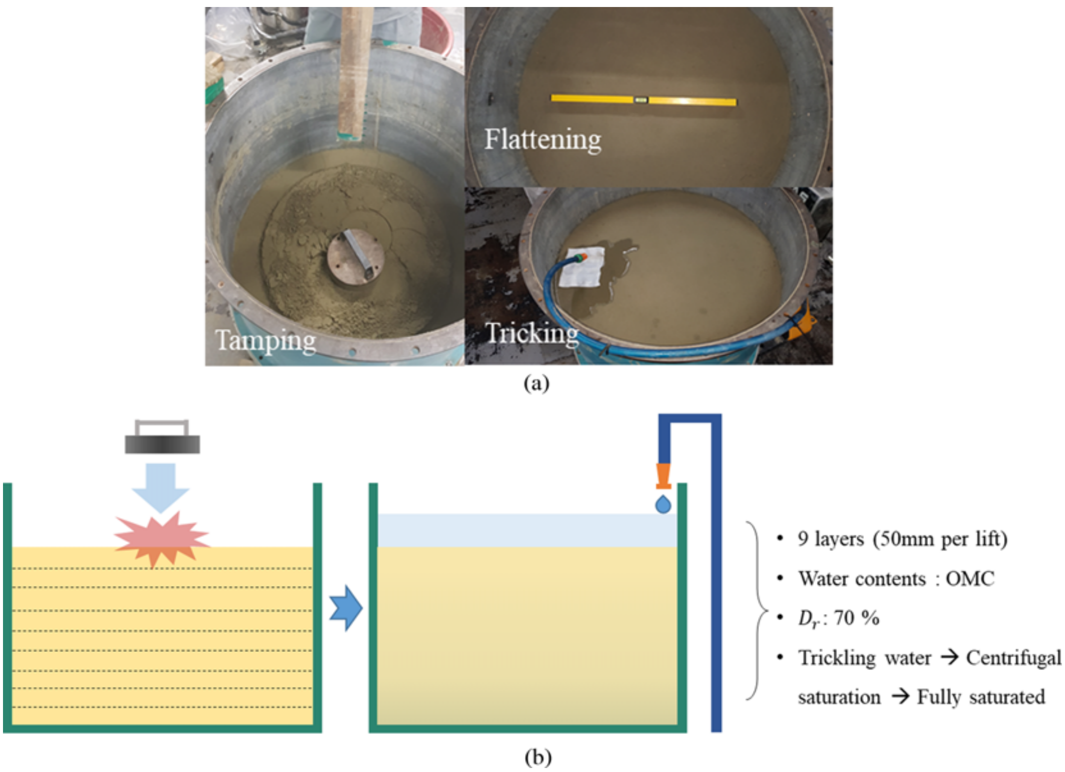


**Fig. 3.** Photographs and Schematics of Soil Preparations: (a) Photographs of the Soil Preparations, (b) Schematics of Soil Preparations

model pile has a non-dimensional stiffness ratio, which is larger than the rigid behavior criteria. Thus, it can be concluded that this model pile behaves rigidly.

The pad-eye (which implies loading point) is at 2/3 of the length from the top lid, which is the optimal loading point resulting in a minimum displacement of the bucket foundation (Bang et al., 2006; Kim et al., 2015). Fig. 2 shows the schematic and photographs of the suction anchor model.

### 2.3 Soil Preparation

Soil specimen for the centrifuge model was collected from the West Sea of Korea. Salty water sand, which is reclaimed sand with high proportions of fine content, is classified as silty sand (SM) abided by a USCS (unified soil classification system). The properties of soil are summarized in Table 3. To conduct the soil specimen at an optimal moisture content (OMC, w: 18.1%), a predetermined amount of dry soil sample per sub-layer were mixed with water in a cylindrical container (Choo and Kim, 2010). The dimensions of the soil container were 700 mm in depth and 900 mm in diameter. The moisture tamping method at the OMC was used to prepare the sand specimens and was divided into nine lifts. The dimensions of the soil specimen were 450 mm in depth and 900 mm in diameter as shown in Fig. 3.

## 3. Testing Procedure and Program

### 3.1 Testing Procedure

Generally, to saturate the soil specimen, the vacuum is frequently applied for removing the air from the soil particles. However, owing to the limitations of equipment, a saturation method using centrifugal acceleration was used instead of vacuum application. First, water was slowly trickled on the soil specimen at a constant rate (1 drop/sec). The soil container was then settled on the centrifuge platform carefully. The centrifuge was spinning up to 70 g and maintained for the stabilization of the soil specimen. To evaluate the saturation level, the air that comes from the ground was detected during the inflight state, and the spinning continued until the air no longer occurred. After the soil was stabilized, the centrifuge was spinning down to 1 g (Bienen et al., 2018a; Choo et al., 2014b). Furthermore, the specimen container was kept outside the testing chamber for two days (Jeong et al., 2020b). The relative density of the soil could increase after the spinning and stabilization process. Unfortunately, the volume change of the ground was not measured during and after spinning, and therefore the relative density after the spinning could not be calculated. Nevertheless, the density of the ground may not change significantly after the stabilization of the dense soil. It was judged that it would not significantly affect the results of this study because all experiments were conducted under the same conditions.

The bucket was penetrated using the actuator at the 1-g level into the soil at 2.5 mm/s in the model scale, which was possibly comparable to the recommended installation rate of 2 mm/s for the sand by Bolton et al. (1999). Two holes were kept open during the installation to exclude the installation effects of the suction bucket. Furthermore, the model container was installed on the centrifuge, spinning up to 70 g, and maintained for 1 hr to stabilize the soil in advance. After the soil was stabilized, the centrifuge tests were conducted by applying the loading according to the testing condition. A 1D actuator was used to apply cyclic loading along with sustained pull-out loads. Since the aim of this research is to evaluate the behavior according to the ratio of sustained load and cyclic load, it is essential to control the actuator in load control, not displacement control. Therefore, in the cyclic loading test, the actuator was controlled in the load control, and the loading rate was set to 0.022 kN/sec according to 0.1 mm/sec in the displacement control, which corresponds to

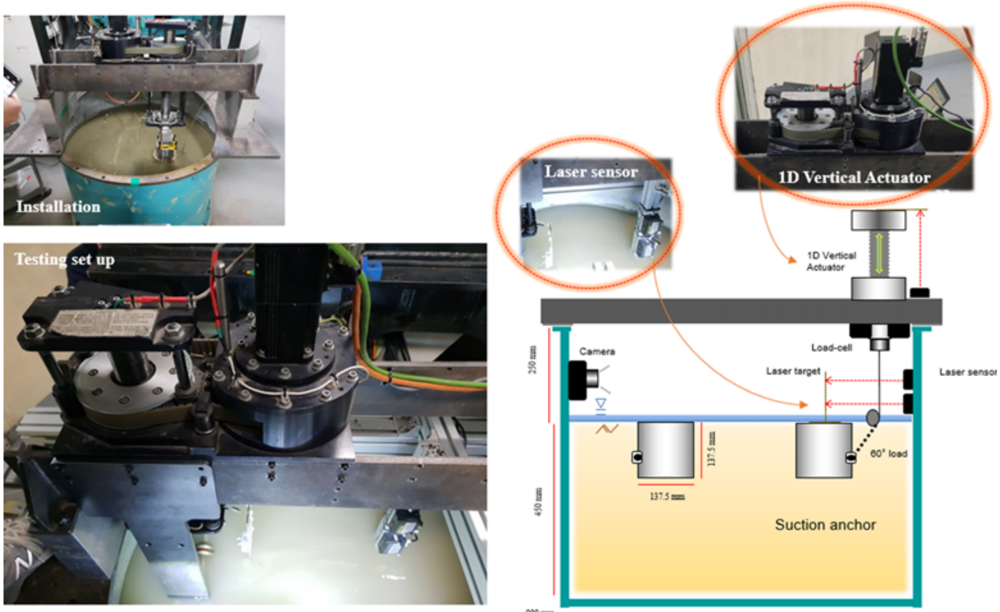


Fig. 4. Photographs and Schematics of Testing Set-Up

**Table 4.** Testing Program

| Test ID | Sustained (%) | Cyclic (%) | Rate | Cycles N |
|---|---|---|---|---|
| Mono | Monotonic | - | 0.1 mm/sec (in model scale) | - |
| T0-0.05 | 0% ULS without sustained load | 5% ULS | 0.022 kN/sec (in model scale) | 50 cycles |
| T0-0.10 | | 10% ULS | | |
| T0-0.15 | | 15% ULS | | |
| T0-0.20 | | 20% ULS | | |
| T0-0.25 | | 25% ULS | | |
| T0-0.30 | | 30% ULS | | |
| T0-0.35 | | 35% ULS | | |
| T0-0.45 | | 45% ULS | | |
| T0.1-0.05 | 10% ULS 0.27 kN (in model scale) | 5% ULS | | |
| T0.1-0.10 | | 10% ULS | | |
| T0.1-0.15 | | 15% ULS | | |
| T0.1-0.20 | | 20% ULS | | |
| T0.1-0.25 | | 25% ULS | | |
| T0.3-0.10 | 30% ULS (FLS) 0.81 kN (in model scale) | 10% ULS | | |
| T0.3-0.15 | | 15% ULS | | |

Note: ULS: the ultimate load capacity related for the limit state; FLS: the fatigue limit state defined to be 30% of the ULS (DNV, 2014)

the fully drained condition (Finnie and Randolph, 1994).

After the load was applied continuously for 5 min (model scale) at the target sustained load, the cyclic loading was applied up to 50 cycles. The centrifuge equipment has an arm radius of 5 m, belongs to a relatively large device, so it is difficult to conduct the experiment for a long time because of safety problems. In addition, because the actuator can continuously apply a load up to 50 cycles, so the number of cycles was limited to 50. In addition, after 50 cycles, the next loading step was performed by applying a 5% larger cyclic loading than the one before the step. Three laser sensors were used to observe the movement of the anchor. Load cell was installed to observe the load subjected to the bucket as drawn in Fig. 4. The data was collected at a sampling rate of 10 Hz by the DAQ system.

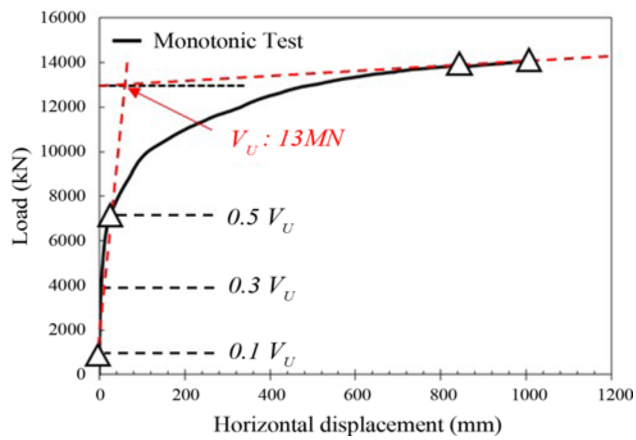


**Fig. 5.** Monotonic Loading Test Result

## 3.2 Testing Program

The testing program consisted of monotonic and cyclic loading tests as summarized in Table 4. A monotonic loading test was performed to assess the bearing capacity of the suction anchors using a 1D actuator. To avoid occurrence of an excess pore pressure, the foundation was slowly installed at a rate of 0.1 mm/sec. The drained condition of the soil-foundation system was confirmed according to the following equation required for the normalized penetration velocity ($V$) as shown in Eq. (2):

$$V = \frac{v \cdot d}{c_v}, \quad (2)$$

where $v$ = rate of loading (0.1 mm/s, model scale); $d$ = caisson diameter (137.5 mm, model scale); $c_v$ = coefficient of consolidation (3,226 mm$^2$/sec, model scale) from Kim et al. (2014). In this experiments, $V$ was calculated to 0.0042, which is smaller than the criteria for the drained condition (i.e., $V < 0.01$) proposed by Finnie and Randolph (1994). As a result, the monotonic loading test was conducted in a complete drain without the effect of excess pore water pressure (Jeong et al., 2020b).

Figure 5 shows the results of the monotonic loading test. In this graph, the values in the positive direction indicate an upward displacement tilted at 60° and the loading amplitude corresponding to the pull-out load. The black dotted lines are drawn along to the initial elastic stiff section and the plastic flexible section. An intersection point is defined as the yield load (ULS: ultimate limit state) following Villalobos (2006), which is denoted as $V_U$. This shows that the pull-out capacity was approximately 13 MN.

In the testing program (Table 4), the first number of 'Test ID' is the ratio of sustained loading amplitude to the ultimate load of the suction anchor, and the second number is the ratio of the cyclic loading amplitude to the ultimate load (T [sustained ratio to ultimate]-[cyclic ratio to ultimate]). As definitions for defining the loading level, DNV (2014) suggested the design cyclic loads as follows. A limit state means beyond which the structure no longer satisfies the requirements. The following categories of limit states are of relevance for structures: 1) the ultimate limit state (ULS) corresponds to the limit of the load-carrying capacity, i.e., to the maximum load-carrying resistance, $V_U$; 2) the serviceability limit state (SLS) corresponds to tolerance criteria applicable to normal use, which happens approximately $10^2$ times in the offshore wind turbine lifetime; and 3) the fatigue limit state (FLS) corresponds to the possibility of failure state due to the cumulative damage effect of cyclic loading, which happens approximately $10^7$ times in the lifetime. In practice, the SLS and FLS are defined to be 50% and 30% of the ULS respectively.

## 4. Testing Results and Discussions

All of the testing data was recorded in the prototype scale representing 70:1. The sign convention of the data was defined such that the upward displacement was tilted at 60° and pull-out load acquired positive values. The conventional factors required for normalization are listed in Table 5. The definitions of the various types of displacement (i.e., permanent and incremental displacement) and stiffness are depicted in Fig. 6.

### 4.1 Cyclic Loading Test Results with 0% and 10% Sustained Load

Figure 7(a) depicts the stiffness of the ground-foundation system

**Table 5.** Factors for Normalization of the Results

| Item | Value (Prototype Scale) |
|---|---|
| Submerged unit weight, $\gamma'$ | 10.92 kN/m$^3$ |
| Diameter of suction bucket, $D$ | 9.63 m |
| Length of suction bucket, $L$ | 9.63 m |

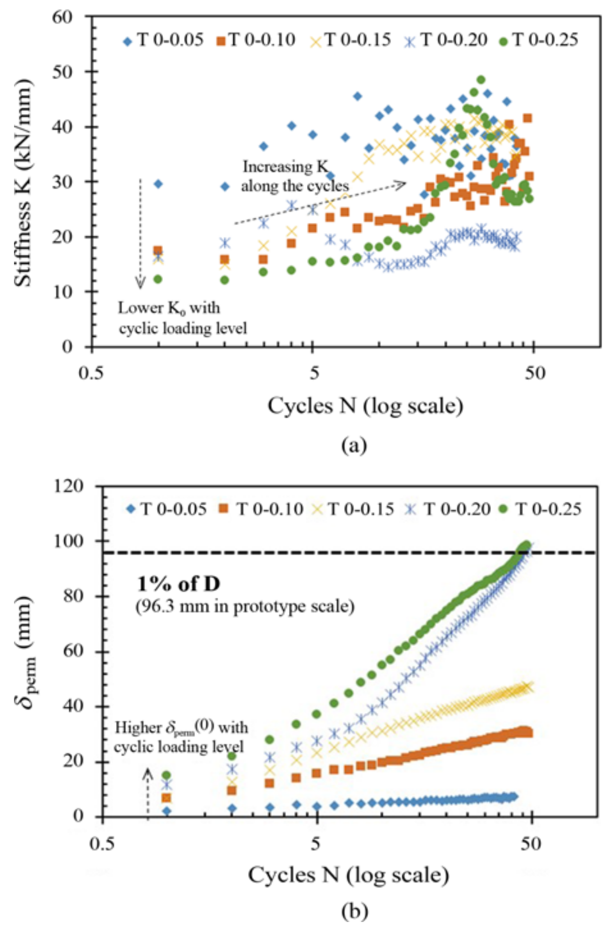


**Fig. 7.** Results for 0% Sustained Loading Test: (a) Stiffness with the Number of Cycles, (b) Permanent Displacement with the Number of Cycles

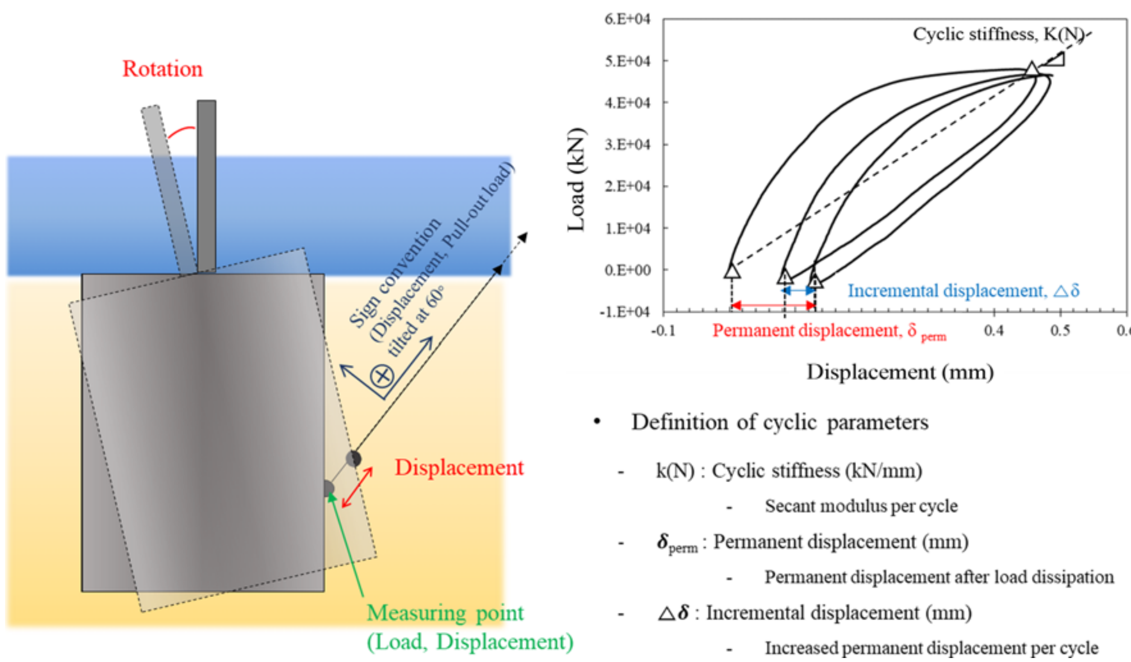


**Fig. 6.** The Definitions of the Various Types of Displacement (i.e., permanent and incremental displacement) and Stiffness

with 0% of sustained pull-out loads for different cyclic load amplitudes. These variations are as follows: T 0 – 0.05 (0% of ULS sustained load + 5% of ULS cyclic load); T 0 – 0.10 (0% sustain + 10% cyclic); T 0 – 0.15 (0% sustain + 15% cyclic); T 0 – 0.20 (0% sustain + 20% cyclic); and T 0 – 0.25 (0% sustain + 25% cyclic). From Fig. 7(a), it is observed that as the loading level increases, the initial stiffness ($K_0$) of the soil-foundation system tends to decreases, owing to the nonlinearity of the soil (Youn et al., 2008). These results are in line with the researches evaluating the changes in stiffness of tripod suction foundation and monopile foundation (Villalobos, 2006; Kim et al., 2014; Jeong et al., 2021). Moreover, the stiffness increased with the cycles in all the tests. Thus, the densification of the surrounding soil substantially occurs around the skirt with cycles, even for loads less than 30% of the ULS, resulting in a significant increase in the ground stiffness. These results are similarly related to the previous studies that focused on the cyclic behavior of suction bucket foundations (i.e., monopile, monopod, and tripod) for wind turbines (Leblanc et al., 2010; Kim et al., 2014; Bienen et al., 2018b; Jeong et al., 2020b; Jeong et al., 2021). In conclusion, the stiffness declines with the loading level owing to the nonlinearity of the soil; and soil hardening occurs gradually when the same load is applied periodically.

Figure 7(b) depicts the displacements of the foundation for the same tests on a semi-logarithmic scale. From Fig. 7(b), it is shown that the initial permanent displacement ($\delta_{perm}$ (0)) increases with the loading level. In addition, the accumulation of permanent displacement increases linearly on a log scale. In other words, a large amount of permanent displacement occurs at the beginning of the cyclic load loading, and the increase in displacement gradually decreases with the cycles.

Figure 8 represents the stiffness variation and the displacements of the system for different cyclic loading amplitudes along with 10% sustained pull-out loads. These variations are as follows: T 0.1 – 0.05 (10% of ULS sustained load + 5% of ULS cyclic load); T 0.1 – 0.10 (10% sustain + 10% cyclic); T 0.1 – 0.15 (10% sustain + 15% cyclic); T 0.1 – 0.20 (10% sustain + 20% cyclic); and T 0.1 – 0.25 (10% sustain + 25% cyclic). As shown in Fig. 8, the stiffness tendency and the displacements have a very similar trend to that of the 0% sustained load experiments. Thus, it is denoted that the sustained pull-out load for 10% of the ULS does not have much effect on the resistance of the ground compared to the cyclic loading tests with the 0% sustained loads. Detailed quantitative comparisons of the 0% and 10% sustained load experiments will be discussed later.

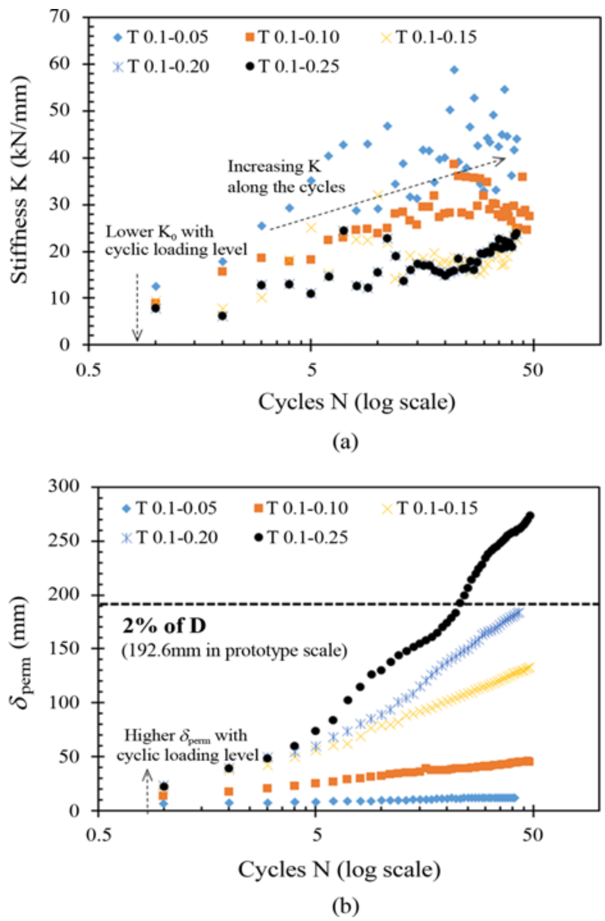


**Fig. 8.** Results for 10% Sustained Loading Test: (a) Stiffness with the Number of Cycles, (b) Permanent Displacement with the Number of Cycles

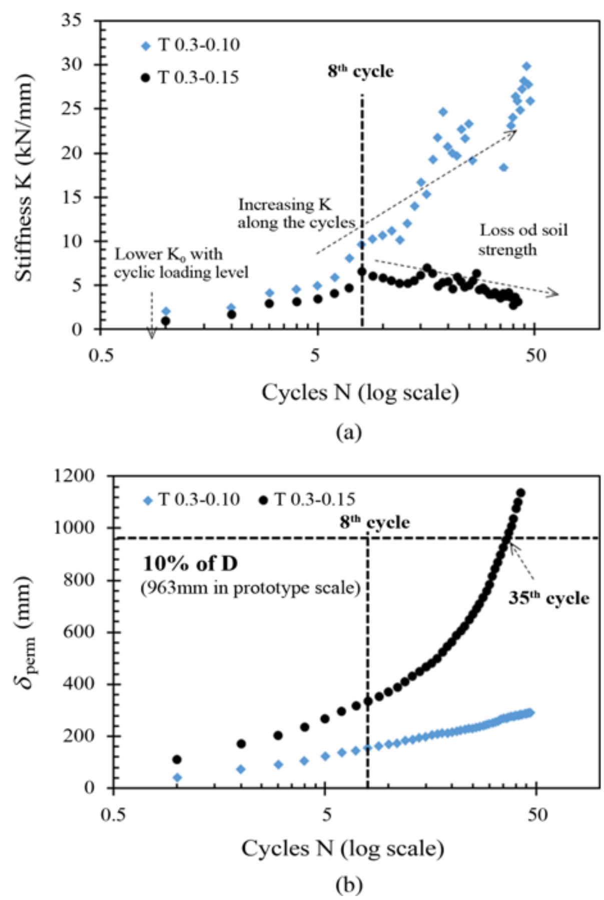


**Fig. 9.** Results for 30% Sustained Loading Test: (a) Stiffness with the Number of Cycles, (b) Permanent Displacement with the Number of Cycles

### 4.2 Cyclic Loading Test Results with 30% Sustained Load

Figure 9(a) represents the the stiffness of the system for the 30% sustained pull-out loading tests. For 10% of the ULS cyclic loading level test (T 0.3 – 0.10: 30% sustain + 10% cyclic), the overall behavior trend is similar to the 0% and 10% sustained loading tests. As the cyclic load was applied continuously, the stiffness increased and the displacement increased more gradually. However, in the case of the 15% cyclic loading test (T 0.3 – 0.15: 30% sustain + 15% cyclic), the variation in the cyclic stiffness exhibited a different trend. At the beginning of the cyclic loading (up to eight cycles), the stiffness increased similar to the results for another test (T 0.3 – 0.10). However, after a certain cycle (approximately 8$^{th}$), a sudden reduction in the stiffness was observed, which led to the loss of the resistance of ground. Furthermore, it resulted in an excessive permanent displacement of the anchor system, surpassed the failure limit (10% of the pile diameter) at the 35th cycle as shown in Fig. 9(b).

Although the difference in the loading level between the two experiments was small, the stiffness responses were exceedingly different. The reduction in stiffness could be associated with several reasons. First, the pore-pressure accumulation could cause a reduction in stiffness. In this tests, it was unlikely to build up the pore water pressure because the soil system was maintained in a fully drained condition. Second, fatigue failure could be one of the reasons for the stiffness alleviation (Jeong et al., 2021). According to Goulois et al. (1985), fatigue failure could develop because of the accumulation of deformations. Another possible reason is the contraction in the soil interface causing gaps between the soil and the foundation structure, thereby leading to the loss of the interface shear strength. According to Houlsby et al. (2006), the soil softens caused by the gaps at the side of the bucket when the cyclic pull-out loading act on the soil. In addition to that, the alleviation of the contact frictional resistance between the steel and soil particle is an additional attribute (Uesugi et al., 1989).

### 4.3 Comparison of Results Based on the Ratio of Sustained Pull-Out Load Amplitude

To analyze the effect of the sustained pull-out load on the cyclic load, the results of the tests subjected to the same peak loads were compared. Fig. 10 depicts a comparison between the test results for the same peak loading amplitude along with different sustained pull-out loads (i.e., summation of sustained and peak point of cyclic load is same). From Fig. 10, it is observed that the displacement for 10% of ULS sustained load case is slightly larger compared to a pure cyclic load with 0% of ULS sustained load. However, the difference of the displacement between the two tests is not quantitatively large and is less than about 0.3% of the bucket diameter. Thus, it implies concluded that the trends in the cyclic behavior are similar to those of the two tests where the magnitude of the sustained loading was less than 10%.

However, when the magnitude of the sustained loading was 30% of the ULS load, entirely different results were observed. Fig. 11 represents the experimental results for the same peak pull-out load along with different sustained loads (i.e., 0% and 30% of the ULS). From Fig. 11(a), it is denoted that the stiffness variations with number of cycles are different in the two experiments. First, the initial stiffness of the system subjected to cyclic loads with 0% of ULS sustained load was considerably larger than that of a sustained load case. Furthermore, it is discerned that the stiffness continues to increase with number of cycles. Despite a relatively large pull-out load (45% of the ULS), the soil resistance increases owing to the soil hardening.

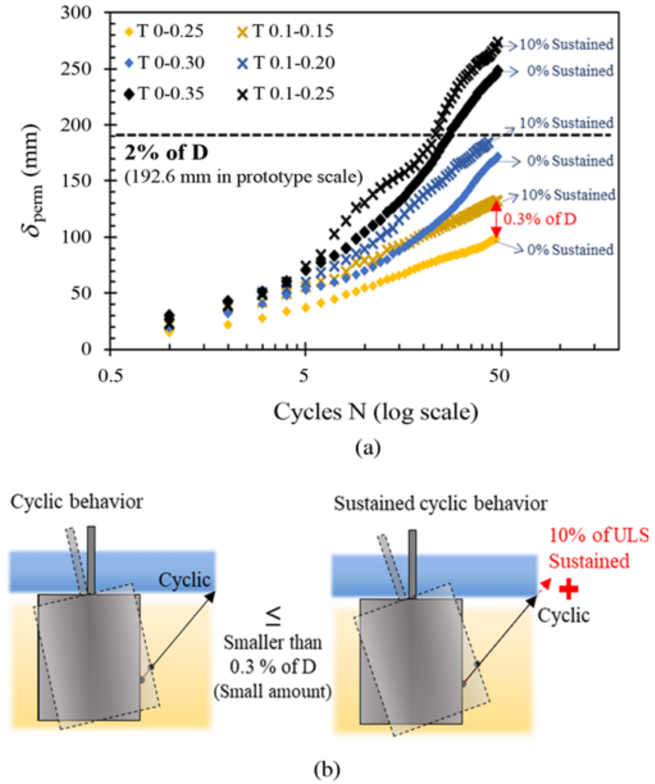


**Fig. 10.** Testing Results for Same Maximum Pullout Loading Tests: (a) Permanent Displacement of Suction Bucket Foundation (T 0-0.25, 0.30, 0.35; T 0.1-0.15, 0.20, 0.25), (b) Schematics of Testing Results

In the case of the cyclic load test with a sustained pull-out load of 30%, the stiffness gradually increases from the beginning of the cyclic loading, and later the ground stiffness begins to decrease rapidly from the 8$^{th}$ load cycle. Furthermore, the soil loses most of its resistance owing to the soil failure. Finally, a very large permanent displacement larger than 10% of D occurred as shown in Fig. 11(b). Thus, if the sustained loading ratio is more than 30% of the ULS, the foundation is very vulnerable to the additional cyclic load, even when the cyclic load is small. Generally, the foundation design for OWT is produced by multiplying a factor of safety with the design load based on the limit state design. The factor of safety is determined according to the design load scenarios and is normally set at the value of two for the foundation design case (DNV, 2014). However, if the proportion of the sustained load is more than 30%, the behavior of the foundation is extremely sensitive to additional cyclic

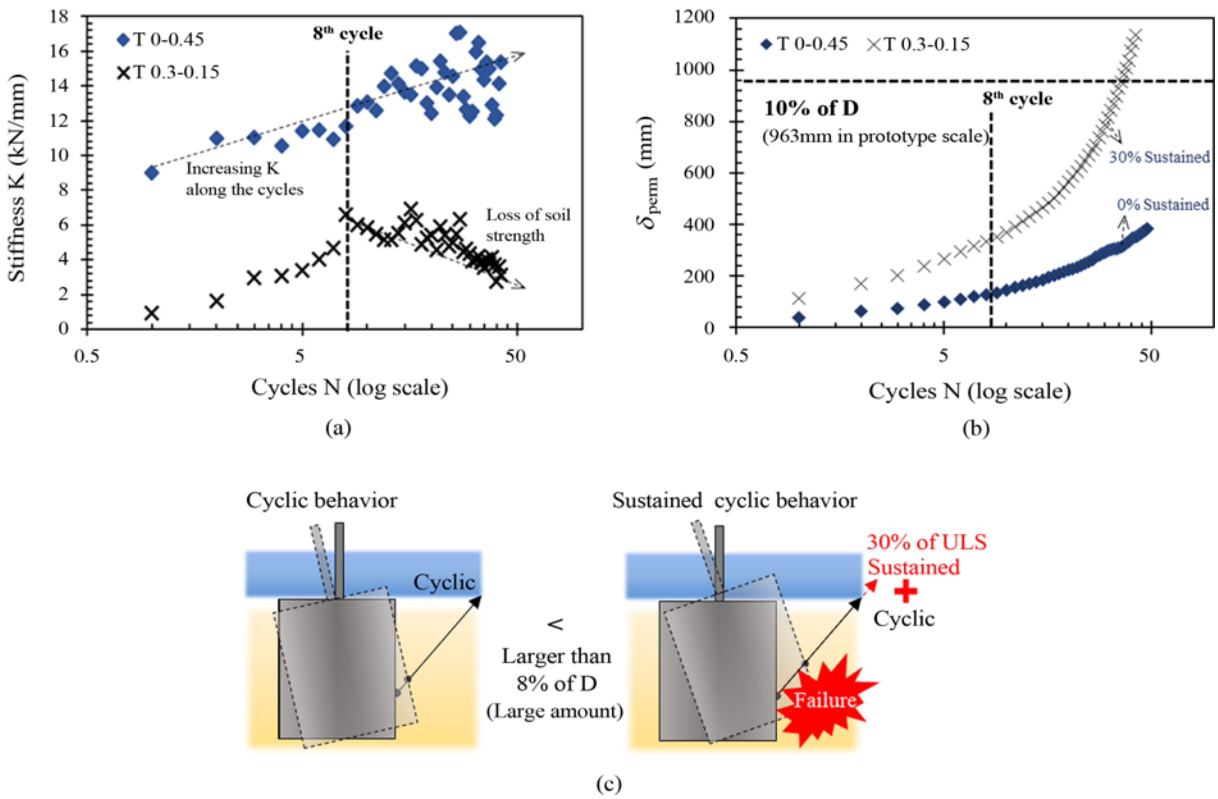


**Fig. 11.** Testing Results for Same Maximum Pullout Loading Tests: (a) Stiffness with the Number of Cycles, (b) Permanent Displacement with the Number of Cycles, (c) Schematics of Testing Results

loads, and therefore, applying a general factor of safety could cause a potential risk. Based on this fact, it is concluded that the ratio of the sustained loads, as well as the cyclic loads, should be considered in the foundation designing process.

## 5. Conclusions

In this study, a stiffness of the ground-foundation system and a permanent displacement, caused as a result of the cyclic load, were observed. Furthermore, the behavior of the suction anchor depending on the ratio of the sustained pull-out loads and cyclic loading was analyzed. To understand the effects of confining pressure at the real site, the geotechnical centrifuge equipment was used to assess the response between the foundation and the surrounding soil subjected to 70 g level centrifuge condition. Based on the results of this study, the following conclusions were remarked:

1. The cyclic response of the foundation system with 0% of ULS sustained pull-out load is similar to that of other types of foundations (i.e., monopile, monopod, and tripod). The initial stiffness with loading level decreased owing to the nonlinearity of the soil. In addition, the stiffness of the system gradually increased with the cycles because of soil hardening, thereby leading to the occurrence of accumulated displacement.
2. The cyclic response of the suction anchor foundation with sustained pull-out loads differed dependent on the ratio of the sustained loads to the cyclic loading.
   - In the case of 10% of the ULS sustained loading, the trends in the stiffness and the permanent displacement are similar to that of the 0% sustained load experiments. Thus, it is concluded that the sustained pull-out load for 10% of the ULS does not comparably affect the change in the resistance of the ground.
   - When the sustained loading level is 30% of the ULS, the behaviors of suction anchor quite depends on the cyclic loading amplitude. In case of the 10% of ULS cyclic loading level, the overall behavior trend is similar to the 0% and 10% sustained load experiments. Whereas in case of the 15% of the ULS cyclic loading, the cyclic stiffness rapidly decreases leading to a large amount of occurrence of permanent displacement whose extent lies significantly above the failure criterion. The loading size between the two experiments was very small (5% of ULS cyclic loading), but the results are markedly different.

Consequently, it is denoted that the response of the suction anchor depends on the sustained pull-out loads, as well as the cyclic loading. In particular, the soil-foundation system with 30% of the ULS sustained pull-out loads is very sensitive to additional cyclic loading. Since the design methodology of the OWT foundation is based on the limit state design method, the ratio of the sustained load to the cyclic load should be considered for calculating the design loads. This study has an originality that evaluated the behavior of the suction anchor foundation considering not only the cyclic loading but also the sustained pull-out loads. In addition, since the state-of-art centrifuge equipment was used to simulate the in-situ confining pressure, this study is significant in terms of providing a basis for expanding the applicability of suction anchors and improving safety measures for OWT. But, the further verification is required for the application of this study results to the design. Moreover, further studies are required on the effect of pore water pressure based on the load speed and scouring problem.

## Acknowledgments

This research was conducted with the support of the "National R&D Project for Smart Construction Technology (No.20SMIP-A158708-01)" funded by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport, and managed by the Korea Expressway Corporation.

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