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Numerical analysis of suction pile behavior with different loading locations and displacement inclinations

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Abstract. Recently, interest of offshore structure construction in South Korea is growing as the land space becomes limited for further development and the renewable energy grows to be more attractive for the replacement of the fossil energy. In order for the optimal construction of optimum offshore floating structures, development of safe and economical offshore foundation technologies is a priority. In this study, the large-deformation behavior of a suction pile, which markets are rapidly growing nowadays, is analyzed for three different loading locations (top, middle, and bottom of the suction pile) with three different displacement inclinations (displacement controlled with displacement inclinations of 0, 10, and 20 degrees from the horizontal). The behavior analysis includes quantifications of maximum resistances, translations, and rotation angles of the suction pile. The suction pile with its diameter of 10 m and height of 25 m is assumed to be embedded in clay, sand, and multi layers of subsea foundation. The soil properties of the clay, sand, and multi layers were determined based on the results of the site investigations performed in the West sea of South Korea. As analyses results, the maximum resistance was observed at the middle of the suction pile with the displacement inclination of 20 degrees, while the translations and rotations resulting from the horizontal and inclined pullouts were not significant until the horizontal components of movements at the loading points reach 1.0 m.

Keywords: suction pile; numerical analysis; resistance; polar decomposition; translation; rotation

1. Introduction

Recently, contracts and interests on offshore construction projects are rapidly increasing. The major categories of the offshore construction project include offshore energy plant construction, undersea mineral resource development, platforms for oil and gas production, and so on. Accordingly, the demand of offshore foundations is also sharply rising. Among the different types of offshore foundation, in this study, we focus on the behavior of a suction pile, which is cost-efficient and fast in terms of installation under the deep sea.

Under the deep sea, which depth is deeper than 50 m, due to the limitations of pile installation equipment and sizes of barges, driven piles or drilled shafts are no longer economical or possible; therefore, the foundations are designed in combinations of anchors and mooring lines. Drag anchors and suction piles are widely used for their economic benefits and good-constructability. However, the suction pile has an advantage that its behavior under certain loads is more predictable (has less

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uncertainty) than those of drag anchors (Sukumaran 1998).

The typical shape of suction pile looks like a up-side-down cylindrical cup, which length-to-diameter ratio is less than 3.0. The installation process of the suction pile is relatively simple. As the suction pile is initially embedded into subsea foundation and forms a bed-skirt by its self-weight, a suction pressure is generated inside of the suction pile; therefore, a force exerted by the difference between its inner and outer pressures induces insertion of the suction pile.

There are many previous studies on the suction pile behavior by means of analytical solutions, experiments, and numerical analyses. Bang and Cho (2001) derived analytical solutions for the ultimate lateral resistance of the suction pile and compared the calculated ultimate lateral resistance with the results of centrifugal tests. From the comparison, it was found that the results of the analytical solution reasonably matched with the experimental results. Typically, the mooring line is attached to the middle point of a suction pile shaft. Bang and Cho (2001) questioned whether the maximum resistance is mobilized at the middle point of the suction pile shafts or not. From their analytical solutions, Bang and Cho (2001) showed that the mooring locations where the maximum lateral resistance is mobilized change with the geometries of suction piles and soil layer characteristics (soil types and soil strengths). Furthermore, Bransby and Randolph (1999) and Bang and Cho (2000) derived analytical solutions for pullout capacities of suction piles under various inclined loadings.

Hogervorst (1980) conducted full-scale tests of suction piles to examine their behaviors during installation and under axial and lateral loads. Larsen (1989) performed laboratory tests on suction model piles with different length-to-diameter ratios for sandy and clayey soils to identify the lateral capacity under static and cyclic loads. Clukey *et al*. (2003) did centrifugal tests on suction piles to assess their pullout capacities under axial and inclined loads. Zhang *et al*. (2007) conducted centrifuge tests to examine the behavior of suction pile for tension leg platform. Chen and Randolph (2007) carried out a series of centrifuge tests using model suction pile in sensitive clays for the uplift capacity evaluation. Lee *et al*. (2011) evaluated suction pile behavior under lateral loads varying the loading points along the suction pile shaft. Maniar (2004) developed a computational procedure to the analysis of suction pile behavior with axial and inclined loads.

In reality, an actual suction pile behavior against inclined pullout will be somewhere between a load controlled behavior and a displacement controlled behavior. However, this paper focuses on the numerical analysis on the behavior of a suction pile under displacement controlled condition with fixed displacement inclination of 0, 10, and 20 degrees from the horizontal varying the soil layer conditions and the loading locations.

2. Analysis method

For a suction pile with its diameter of 10 m and length of 25 m, finite element analysis was conducted using ABAQUS (HKS 1997). Fig. 1 shows the finite element meshes of the foundation and the suction pile. The soil layers used in the simulation are consisted of three dimensional (3D) continuous elements with 20 nodes having degree-of-freedom at the elements' corners for pore water pressure. Suction pile is modeled three dimensionally using platy shell element with 8 nodes. For the calculation of stresses and strains of the foundation and suction pile, “reduced integration method” is used. Three different soil layer conditions are assumed: (1) clay layer, (2) sand layer, and (3) a layer with 15 m-clay layer on top of the sand layer.

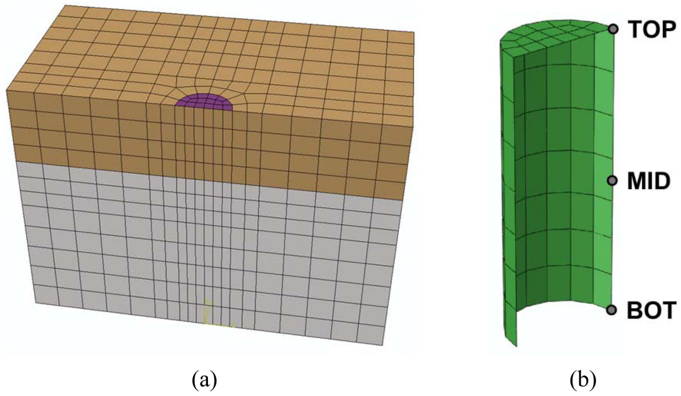

Fig. 1. Finite element meshes of (a) foundation and (b) suction pile; points indicated by TOP, MID, and BOT are the loading locations

Table 1 Soil parameters for the clay and sand models

	Modified cam clay model parameters							
Clay	γ_t (kN/m^3)	e	κ	ν_{el}	λ	M	OCR	k (m/s)
	14	2.0	0.043	0.1	0.434	1.0	1	1×10^{-8}
	Linear-elastic mohr-coulomb model parameters							
Sand	γ_t (kN/m^3)	e	E (MPa)	ν_{el}	c (kPa)	ϕ (deg)	ψ (deg)	k (m/s)
	16	0.8	10	0.1	-	25	5	1×10^{-3}

*γ_t is the total unit weight, e is the void ratio, κ is the gradient of loading-unloading line, ν_{el} is the poisson's ratio at overconsolidated state, λ is the gradient of pressure-void ratio curve at isotropic normally consolidated state, M is the stress ratio at limit state, OCR is the over-consolidation ratio, k is coefficient of permeability, E is the elastic modulus, c is the effective cohesion, ϕ is the effective friction angle, and ψ is the dilatancy angle.

The modified Cam-clay model is selected for the analysis of clay behavior, while the linear-elastic model and Mohr-Coulomb model is used for that of sand behavior. The soil parameters required for each model are summarized in Table 1. The soil properties are determined based on the offshore site investigation results at West sea of South Korea. The properties of steel suction pile are assumed as follows: unit weight = 75 kN/m^3; Elastic modulus = 2×10^5 MPa; and Poisson's ratio at over-consolidated state = 0.3. No contact element is adapted for our analyses. In other words, a slippage between the suction pile and soil may be represented by a shear band formulated vicinity of the interface.

Finite element analyses on a suction pile were performed by controlling displacements on the three different locations (points shown in Fig. 1) with fixed displacement inclinations of 0, 10, and 20 degrees from the horizontal. The analyses were done until the horizontal components of the displacements at their loading locations reach 1.0 m. For convenience, the loading locations correspond to the top, middle, and bottom along the suction pile shaft are denoted as "TOP," "MID," and "BOT," respectively. The suction pile made of steel has a relatively small length-to-diameter ratio and a much higher stiffness compared with the stiffnesses of soils; therefore, it

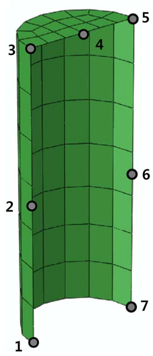

Fig. 2. Seven locations on the suction pile boundary selected for the calculation of six parameters in Eq. (2)

exhibits rigid body behavior. The motion of suction pile can be represented by two quantities; translation and rotation. The two dimensional (2D) rigid body motion of the suction pile is analyzed with respect to the center of the suction pile. If the coordinate of the center of the suction pile before and after its movements are assumed to be represented by (x, y) and (x', y'), respectively, the following relationship exists

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} a & b & m_x \\ c & d & m_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{1}$$

where a, b, c, and d are the coefficients related to rigid body rotation and deformation of the suction pile; and m_x and m_y are the horizontal and vertical components of the translation.

For the calculations of these six parameters (a, b, c, d, m_x, and m_y), the coordinates of the 2D movements of the seven locations on the boundary of the suction pile shown in Fig. 2 are analyzed through linear equations represented by the following matrix

$$\begin{bmatrix} x'_1 & y'_1 \\ x'_2 & y'_2 \\ \vdots & \vdots \\ x'_7 & x'_7 \end{bmatrix} = \begin{bmatrix} 1 & x'_1 & y'_1 \\ 1 & x'_2 & y'_2 \\ \vdots & \vdots & \vdots \\ 1 & x'_7 & x_7 \end{bmatrix} \begin{bmatrix} m_x & m_y \\ a & c \\ b & d \end{bmatrix} \tag{2}$$

where the subscripted numbers indicate the numbers corresponding to the points in Fig. 2.

The matrices in Eq. (2) will be denoted as $[Y]$, $[X]$, and $[M]$, respectively, for convenience. The number of the linear equations in Eq. (2) is larger than the number of the unknown parameters in matrix $[M]$ by 1; therefore, the unknown parameters can be obtained using the least-squares method by finding the case of the minimum $\{[Y]-[X][M]\}^2$. Then, using the coefficients (a, b, c, and d) , another matrix $[H]$ can be defined as follows

$$[H] = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \tag{3}$$

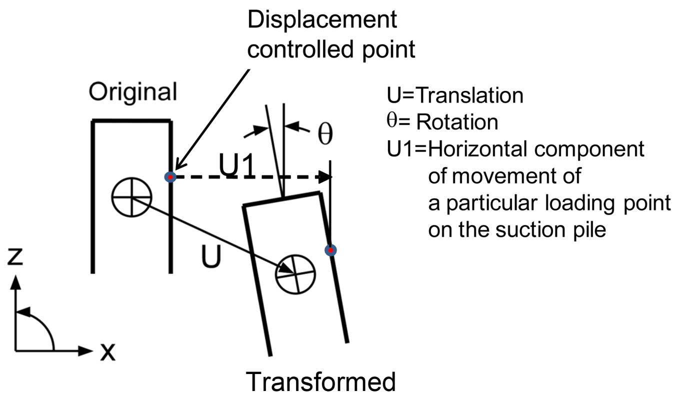

Fig. 3. Definition of translation (U), Horizontal component of movement of loading point (U1), and rotational angle (θ)

The matrix $[H]$ can be decomposed into the following two matrices, the translation matrix $[H_t]$ and rotation matrix $[R]$, using the polar decomposition technique (Shabana 2010) as follows

$$[H] = [R][H_t] \tag{4}$$

The rotation matrix $[R]$ can be represented in terms of rotational angle q defined in Fig. 3 as follows

$$[R] = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \tag{5}$$

The notations of translation (U), horizontal component of movement of a loading point (U1), and rotational angle (θ) of the suction pile can be defined as those in Fig. 3.

3. Analysis results

As mentioned earlier, three soil layers (clay; sand, and clay-sand layers) are considered with three different loading locations (TOP, MID, and BOT) and thee different displacement inclinations (α = 0°, 10°, and 20°) at each displacement controlled location. The displacement inclination angle a is the angle of displacement direction from the horizontal. Typically, suction piles with a mooring system do not have high displacement inclination angles a to the horizontal except for the suction piles used for the tension leg platforms (TLPs) or those for the "taut mooring system" (Maniar 2004). The finite element (FE) analyses are performed to analyze the behavior of the suction pile for different soil layer conditions, loading locations, and displacement inclinations.

3.1 Pullout resistance RF

Suction pile resistances RF against the horizontal and inclined displacement are calculated with respect to the horizontal component (U1) of the suction piles' movements from the displacement

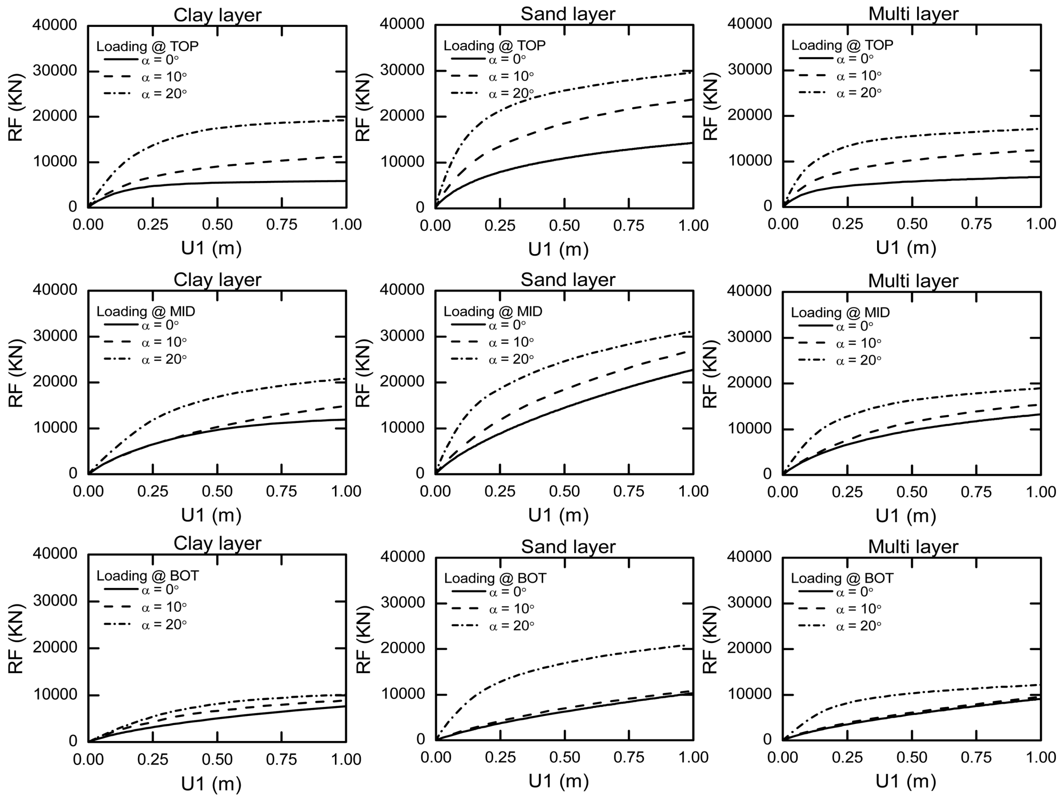

Fig. 4 Resistance RF of the suction pile versus its horizontal component of movement of loading point U1

controlled points. The results, changes of RF within the U1 range of 0-1.0 m, are summarized in Fig. 4. The authors decided to show the results for U1 < 1.0 m because a horizontal movement corresponding to 10% of suction pile diameter is a large deformation. The FE analyses were able to provide reasonable results stably.

The maximum RF with respect to the displacement inclination angle a for three soil layer conditions and three displacement controlled locations are plotted separately in Fig. 5 and summarized in Table 2. To compare maximum RF values of plots easily, the scales of *x*-axes and *y*-axes of all the plots were set to be equal. The RF increased as the horizontal component U1 of displacement controlled point movement increased.

The maximum RF approximately ranged from 5 to 30 MN depending on the loading location and the displacement inclination angle α. Regardless of the soil layer conditions and the displacement controlled locations, the maximum RF increased with an increasing a as shown in Fig. 5. For the loading locations of TOP and MID, the maximum RFs were highest for sand layer while the maximum RF values for clay and multi layers were similar. Therefore, it is inferred that the maximum RF values for the displacement controlled locations of TOP and MID are more dependent on the soil properties of the upper part of soil layer rather than those of the lower part. Overall, for each soil layer condition and displacement inclination angle, the maximum RF values were observed at the loading location of MID. It could be concluded that the connections between the mooring lines and the suction piles for the given soil layer conditions are better to be made at the

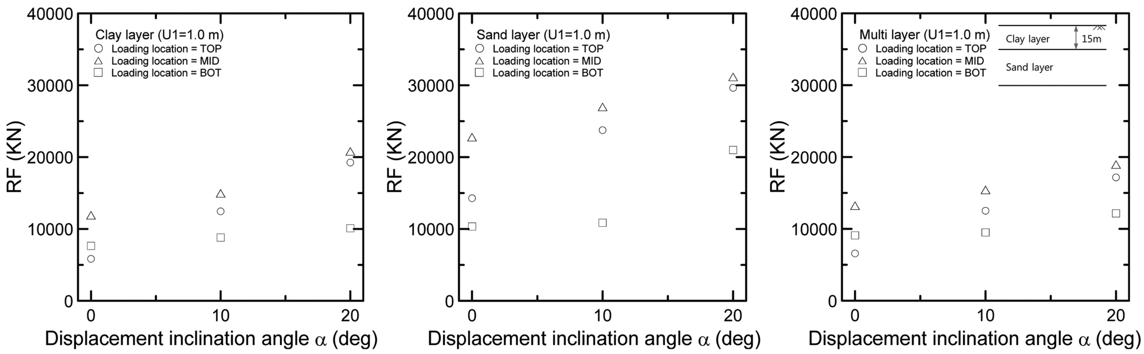

Fig. 5 Maximum RF of the suction pile versus displacement inclination angle a for U1 = 1.0 m

Table 2 Resistance RF corresponding to U1 = 1.0 m for each analysis case (unit: kN)

α	Clay layer			Sand layer			Multi layer		
	TOP	MID	BOT	TOP	MID	BOT	TOP	MID	BOT
0	5,842	11,920	7,648	14,280	22,793	10,347	6,589	13,242	9,103
10	12,452	14,971	8,805	23,746	26,986	10,863	12,524	15,440	9,506
20	19,244	20,807	10,095	29,634	31,170	20,986	17,162	18,967	12,157

"MID" location, rather than the other locations (TOP or BOT).

The results of maximum RF changes with an increasing a in the present paper are different from the results by Cho and Bang (2002) and Bang *et al*. (2011). Direct comparison of suction behavior in this paper to those in other literature may not be possible due to the difference in soil layer and pile condition. Especially, it should be reminded that most of the previous researches focus on the suction pile behavior by 'load control' while the analyses in this paper were done by 'displacement control'. Generally, there is a tendency that analyses by displacement control overestimate the RF. Cho and Bang (2002) and Bang *et al*. (2011) insisted that the RF does not change significantly with an increasing load inclination within a load inclination range of 0^o and 20^o. Especially, if soils (both clay and sand) are weaker in terms of strength, the change of RF with respect to load inclination becomes more negligible for lower load inclinations ($0^o - 20^o$). However, the results from the analyses in the present paper show that there exists a clear increase of RF with an increasing displacement inclination angle α (Fig. 5). In the each plot of Fig. 5, for the loading location of MID, the RF increased almost linearly with an increasing a. For the other loading locations, RF also increased with an increasing a but their relationships are not as linear as those for the loading location of MID.

3.2 Translation U

The changes of translations U of the suction pile with an increasing U1 were examined for different soil layer conditions and the displacement inclination angle α. The method of translation calculation was explained earlier in this paper. The results are summarized in Fig. 6 and in Table 3. As explained earlier, the translation U denotes the shortest distance from the centers of the suction

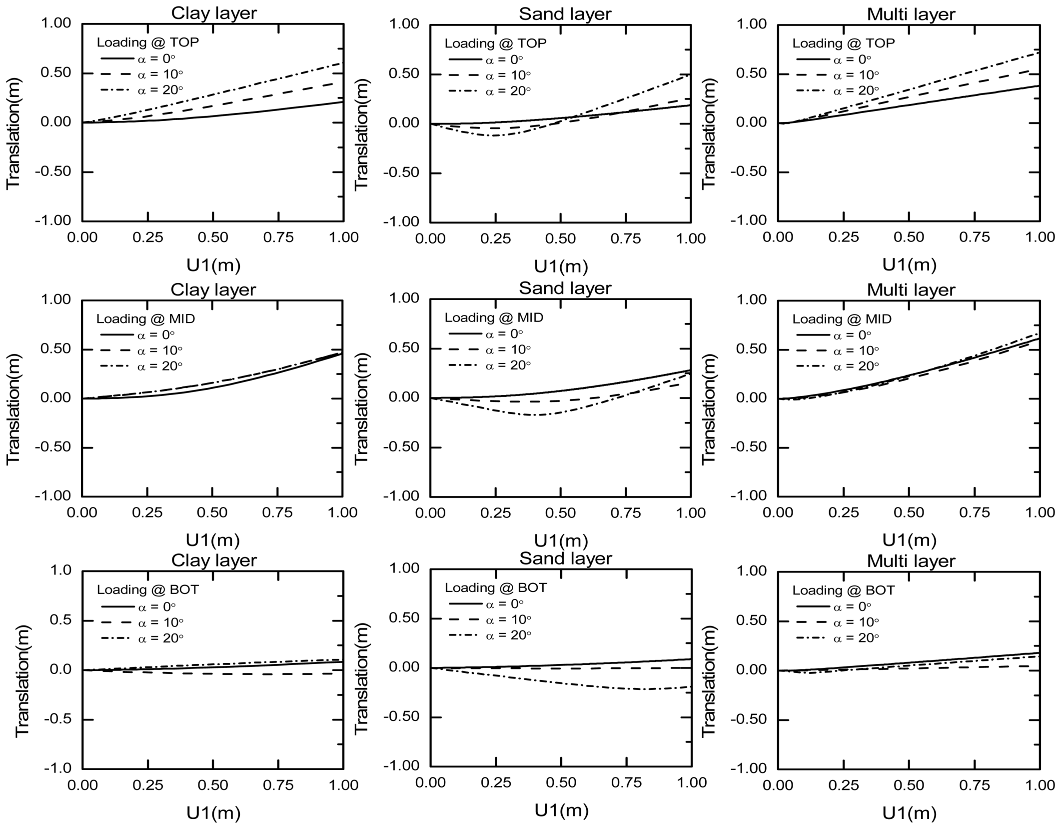

Fig. 6 Translation U of the suction pile versus its horizontal component of movement of loading point U1

Table 3 Translation U corresponding to U1 = 1.0 m for each analysis case (unit: m)

α	Clay layer			Sand layer			Multi layer		
	TOP	MID	BOT	TOP	MID	BOT	TOP	MID	BOT
0	0.21	0.45	0.09	0.19	0.28	0.09	0.38	0.61	0.18
10	0.43	0.43	0.11	0.26	0.13	0.00	0.56	0.60	0.05
20	0.62	0.47	-0.03	0.50	0.25	-0.19	0.72	0.67	0.14

pile before and after its transform. Fig. 6 shows that the overall changes of translation with respect to U1 for clay and multi layers are similar to each other for each loading location. For the loading location of TOP and MID and for the sand layer, it is interesting to observe that the translations at the beginning of the loading stage were negative (movement directions of the center of the suction pile were opposite to loading direction at the initial loading) and then they became positive as U1 increased.

Regardless of the soil layer conditions, the effect of the displacement inclination angle on the translation was most pronounced for the loading location of TOP. For a given combination of the soil layer condition and the loading location, as the displacement inclination angle a increases the absolute translation quantity (i.e., regardless of the direction of the translation) also tend to increase.

In addition, for the clay layer and multi layer conditions, the translations with respect to U1 were almost identical to each other for the load locations of MID and BOT.

3.3 Rotation θ

The rotation amount θ with respect to U1 for different soil layer conditions and loading locations were summarized in Fig. 7 and in Table 4. The maximum rotation angle θ observed from the results of the FE analyses was about 3 degrees. It was interesting to know that, for the given soil and suction pile properties and suction pile geometry, absolute rotation amounts were not significant. In addition, it is notable that the displacement inclination angles a of 10º or 20º changed the rotation θ

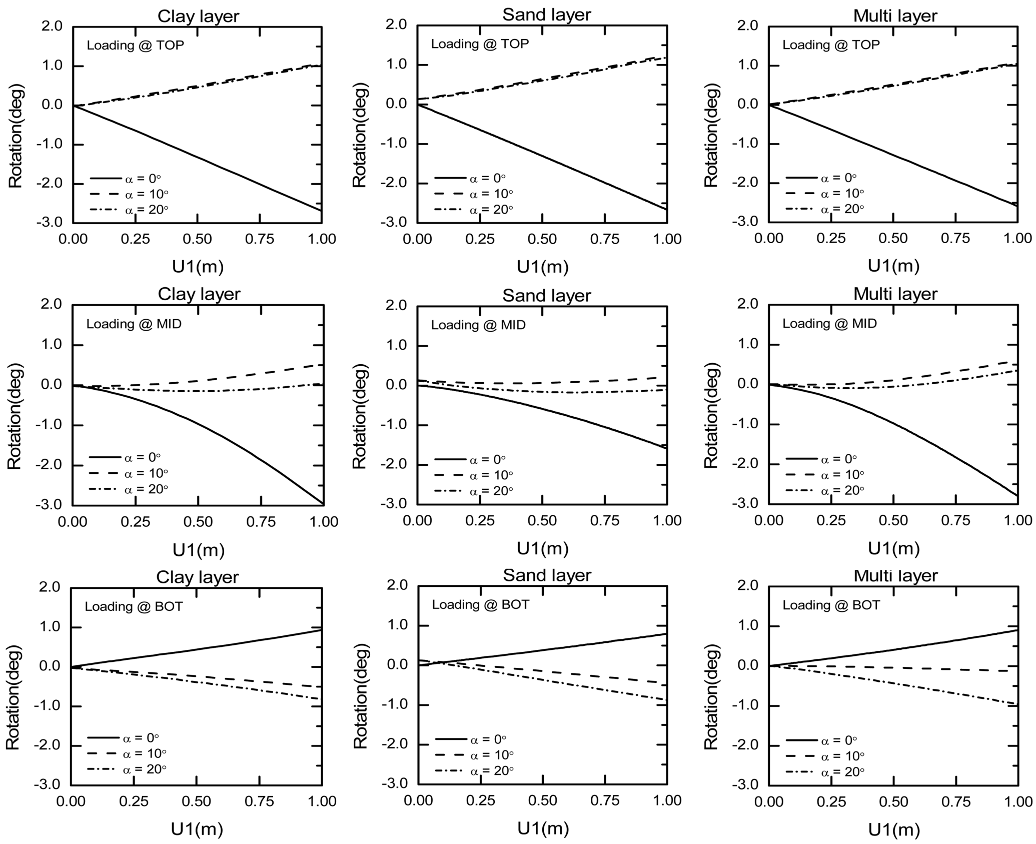

Fig. 7 Rotation of the suction pile versus its horizontal component of movement of loading point U1

Table 4 Rotation corresponding to U1 = 1.0 m for each analysis case (unit: degree)

α	Clay layer			Sand layer			Multi layer		
	TOP	MID	BOT	TOP	MID	BOT	TOP	MID	BOT
0	-2.66	-2.94	0.94	-2.67	-1.59	0.80	-2.59	-2.79	0.91
10	1.08	0.54	-0.82	1.24	0.19	-0.45	1.09	0.62	-0.13
20	1.03	0.05	-0.51	1.19	-0.11	-0.87	1.05	0.36	-0.96

direction compared to those directions for $\alpha = 0^o$. The authors suspect that these rotation directions are determined based on the patterns of the yielding zone developed with increasing U1. To analyze this phenomenon, more complete FE analyses may be required.

4. Conclusions

The primary goal of this paper is to evaluate maximum resistances, translations, and rotations of the suction pile for different soil layer conditions, different loading locations, and different displacement inclination angles from the results of numerical analyses. The analyses are done until the horizontal component of movement of displacement controlled point reaches 1.0 m. The soil properties used in the analyses are determined based on the site investigation on West sea of South Korea. For the given soil layer conditions, the resistance was highly depend on the loading location and the displacement inclination angle. Overall, the suction pile resistances were highest for sand layer. For each soil layer condition, the maximum resistance was mobilized at the loading location of the middle along the suction pile shaft. The translation and rotations were not significant until the horizontal component of movement of displacement controlled point reached 1.0 m. However, it should be reminded that the patterns of the changes of resistances, translations, and rotations of the suction pile presented in this paper may not be typical because these patterns vary site to site. In addition, our analysis results are planned to be verified by performing suction pile model test in the future. More findings may be available after the experiment.

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References

H.K.S. (1997), *ABAQUS 5.2 User's manual*, Hibbitt, Kartsson & Sorensen Inc.

Bang, S. and Cho, Y. (2000), *Use of suction piles for mooring of mobile offshore bases- task 3. Analysis and design methods of suction piles*, Report prepared for the Naval Facilities Engineering Service Center.

Bang, S. and Cho, Y. (2001), “Ultimate horizontal loading capacity of suction piles”, *Proceedings of the 11th International Offshore and Polar Engineering Conference*, Stavanger, Norway.

Bang, S., Jones, K.D., Kim, K.O., Kim, Y.S. and Cho, Y. (2011), “Inclined loading capacity of suction piles in sand”, *Ocean Eng*., **38**(7), 915-924.

Bransby, M.F. and Randolph, M.F. (1999), “The effect of skirted foundation shape on response to combined VM-H loading”, *Int. J. Offshore Polar*, **9**(3).

Chen, W. and Randolph, M.F. (2007), “Uplift capacity of suction caissons under sustained and cyclic loading in soft clay”, *J. Geotech. Geoenviron*., **133**(11), 1352-1363.

Cho, Y. and Bang, S. (2002), “Inclined loading capacity of suction piles”, *Proceedings of 12th International Offshore and Polar Engineering Conference*, Kitakyushu, Japan.

Clukey, E.C., Aubeny, C.P. and Murff, J.D. (2003), “Comparison of analytical and centrifuge model tests for suction caisson subjected to combined loads", *Proceedings of the 22nd International Conference on Offshore Mechanics and Arctic Engineering*, Cancun, Mexico.

Hogervorst, J.R. (1980), "Field trails with large diameter suction piles", *Proceedings of the 12th annual Offshore Technology Conference*, Houston, Texas.

Larsen, P. (1989), "Suction anchors as an anchoring system for floating offshore constructions", *Proceedings of the 21st annual Offshore Technology Conference*, Houston, Texas.

Lee, J.H., Kim, D., Chung, M.K., Kwak, K.S. and Jung, Y.H. (2011), "Numerical analysis of the suction pile behavior with different lateral loading locations", *J. Korean Geotech. Soc*., **27**(4), 67-76, in Korean.

Maniar, D.R. (2004), *A computational procedure for simulation of suction caisson behavior under axial and inclined loads*, Ph.D. thesis, University of Texas at Austin.

Sukumaran, B. (1998), "Suction caisson foundations - A better option for deep water applications", *Proceedings of the SWE Annual Conference*, Houston, TX.

Shabana, A.A. (2010), *Computational continuum mechanics*, Cambridge University Press, New York.

Zhang, J.H., Zhang, L.M. and Lu, X.B. (2007), "Centrifuge modeling of suction bucket foundations for platforms under ice-sheet-induced cyclic lateral loadings", *Ocean Eng*., **34**(8-9), 1069-1079.