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Numerical analysis of the suction pile behavior with different lateral loading locations

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ABSTRACT

Numerical analyses were performed to simulate the displacement and resistance behaviors of suction piles subjected with different lateral loads (i.e. tensile on top, middle, and bottom of the pile) and soil layer conditions (i.e. uniform clay, uniform sand, and multi composition of clay and sand). The simulation results show that lateral resistance is always maximized at lateral load applied at the middle point of piles, regardless of soil layer conditions. For a certain loading position, sand layer condition delivers relatively higher resistance compared to multi composition layers. Meanwhile, the amount of translation shows high dependency on both soil layer condition and lateral load locations, while pile rotation angle varies significantly with lateral loading locations rather than soil layer conditions.

Keywords: suction pile, lateral behavior, translation, rotation, numerical analysis, sand, clay

1 INTRODUCTION

Recently, development demands on offshore structures are rapidly growing in South Korea in the aim of land space expansion and renewable energy (e.g. offshore energy plants, subsea mineral mining, oil or gas platforms, etc.) development. Therefore, the importance of offshore foundations is also emphasized in the same manner. Among various offshore foundation prototypes, a suction pile is generally known to be a cost-effective foundation type according to its quick installation under deep sea conditions.

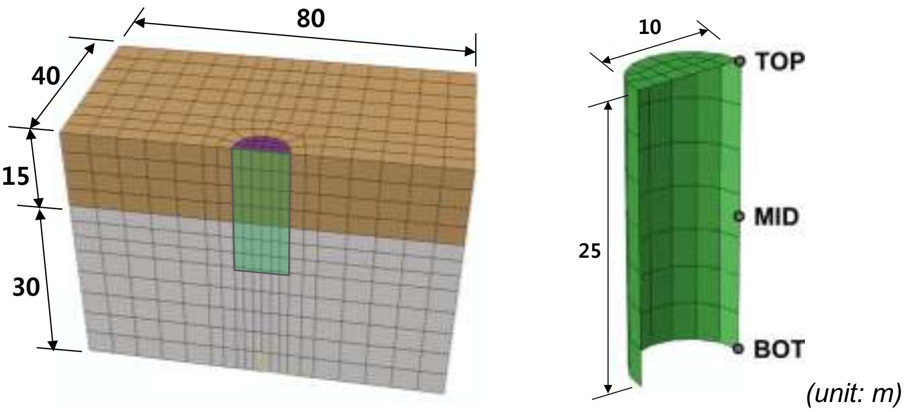
Under deep sea conditions (more than 50 m), several problems (size limits of construction equipments and working barges) restrict conventional foundation types such as driven piles or drilled shafts. Thus, new foundation types (e.g. drag anchors, suction piles) are recommended to be applied for deep sea conditions according to their cost efficiency and work effectiveness. Meanwhile, suction pile system is more effective for lateral behaviour prediction compared to drag anchors (Sukumaran 1998).

The typical shape of a suction pile is a cylindrical bell-shape which diameter to height ratio is less than 3.0. The installation procedure of a suction pile follows the sequences as: 1) initially embedded into subsea floor according to its self-weight, 2) negative suction pressure generated inside the closured pile, 3) pile driving into the ground according to the difference between inner and outer pressure.

Previous studies were attempted to characterize the behaviour of suction piles using analytical, experimental, and numerical approaches. 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. The mooring lines of floating structures are generally linked on the middle point of suction piles. Thus, Bang and Cho (2001) questioned whether the maximum resistance is mobilized at the middle point of the suction pile shafts or not. According to their studies, the mooring location for maximum lateral resistance varies with the geometries and soil layer characteristics (soil types and soil strengths). 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 piles with different length-to-diameter ratios for sand and clay 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. Lee et al. (2011) evaluated the suction pile behavior under lateral loads with various loading points along the suction pile shaft. Maniar (2004) developed a computational analysis on the suction pile behavior with axial and inclined loads.

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 modelled three dimensionally using platy shell element with 8 nodes. For the calculation of stresses and strains of the foundations 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.



(a) (b)

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

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 of West sea of South Korea. The properties of steel suction pile are assumed as follows: unit weight = 75 kN/m^3; Elastic modulus = 2 x 10^5 MPa; and Poisson's ratio at over-consolidated state = 0.3.

Table 1: Soil parameters for clay and sand models

Clay	Modified Cam Clay Model Parameters							
	γ_t (kN/m^3)	e	k	ν_{el}	λ	M	OCR	k (m/s)
	14	2.0	0.043	0.1	0.434	1.0	1	1×10^{-8}
Sand	Linear-Elastic Mohr-Coulomb Model Parameters							
	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, 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 horizontal and inclined loads are imposed on the three different locations (points shown in Fig. 1) of the suction pile boundary 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 relatively high stiffness compared with those of soils; therefore, it 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:

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

where m_x and m_y are the horizontal and vertical components of the translation; a, b, c, and d are the coefficients related to rigid body rotation and deformation of the suction pile. For the calculations of these six parameters, the coordinates of the 2D movements of the seven locations on the boundary of the suction pile shown in Figure 2(a) are analyzed through linear equations represented by the following matrix:

$$\begin{bmatrix} x_1' & y_1' \\ x_2' & y_2' \\ \vdots & \vdots \\ x_7' & y_7' \end{bmatrix} = \begin{bmatrix} 1 & x_1' & y_1' \\ 1 & x_2' & y_2' \\ \vdots & \vdots & \vdots \\ 1 & x_7' & y_7' \end{bmatrix} \begin{bmatrix} m_x & m_y \\ a & c \\ b & d \end{bmatrix} \quad (2)$$

where the subscripted numbers indicate the numbers of points.
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:

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

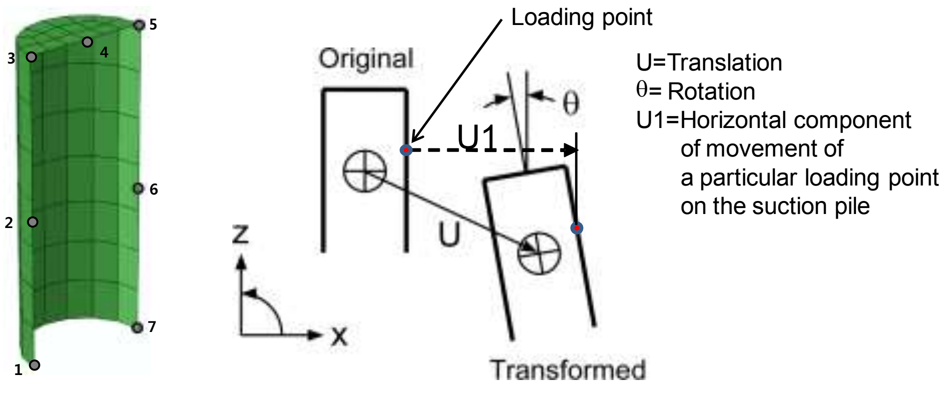
The matrix [H] can be decomposed into the following two matrices, the translation matrix $[H_t]$ and rotation matrix [R], using the polar decomposition technique (Shabana, 2010) as follows:

$$[H] = [R][H_t] \quad (4)$$

The rotation matrix [R] can be represented in terms of rotational angle θ defined in Figure 2(b) as follows:

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

The notations of translation (U), horizontal component of movement of a loading point (U1), and rotational angle (θ) of the suction piles can be represented as in Figure 2(b).



(a) (b)

Figure 2. Definition (a) Seven locations on the suction pile boundary and (b) U,U1 and θ

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 loading angles (α = 0°, 10°, and 20°) at each loading location. The loading angle α is the angle of loading direction from the horizontal. Typically, suction piles with mooring system do not have high loading angles α 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 loading inclination.

3.1 Lateral Resistance RF

The results of suction pile resistances RF against the horizontal and inclined loads with respect to the horizontal component (U1) of the suction piles' movements of the loading points are summarized in Fig. 3. The results show the change of RF within the U1 range of 0 – 1.0 m. Furthermore, the maximum RF with respect to load inclination angle α for three soil layer conditions and three loading locations are plotted separately in Fig. 4. To compare 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 suction pile movement of loading point increased. Most of the analyses were intended to evaluate the suction pile behavior until U1 reached 2.0m; however, there were several unstable cases which analyses stopped at different levels of U1; therefore, the authors decided to show the results for U1 ≤ 1.0 m. Although the authors have not exhausted finding the reason of the non-convergence (stoppage) of the analyses, the authors tentatively concluded that the non-convergence results from the fact that the plastic deformation zone expanded abruptly and exceeded the boundary of the foundation meshes.

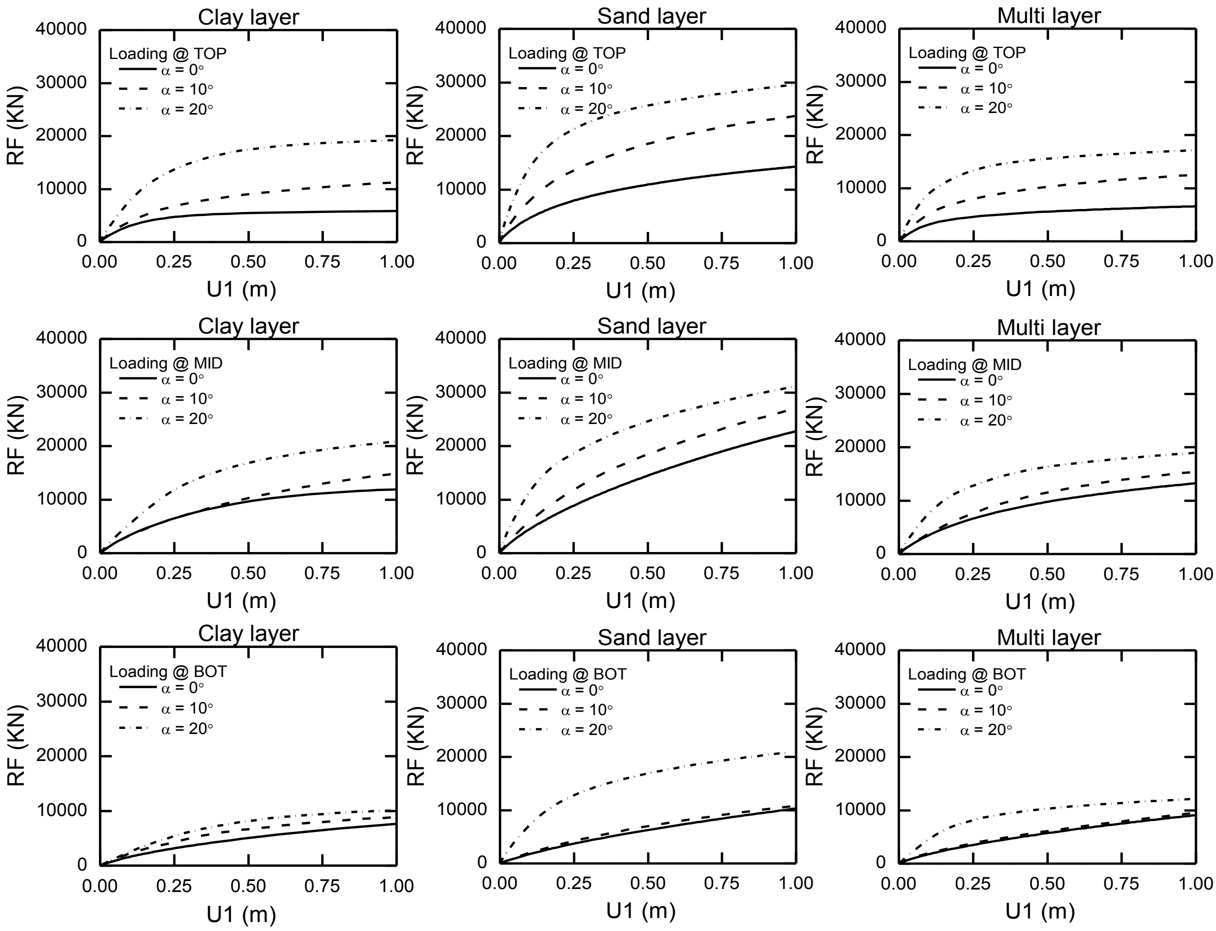


Figure 3. Resistance RF of the suction pile versus its horizontal component of movement of loading point U1

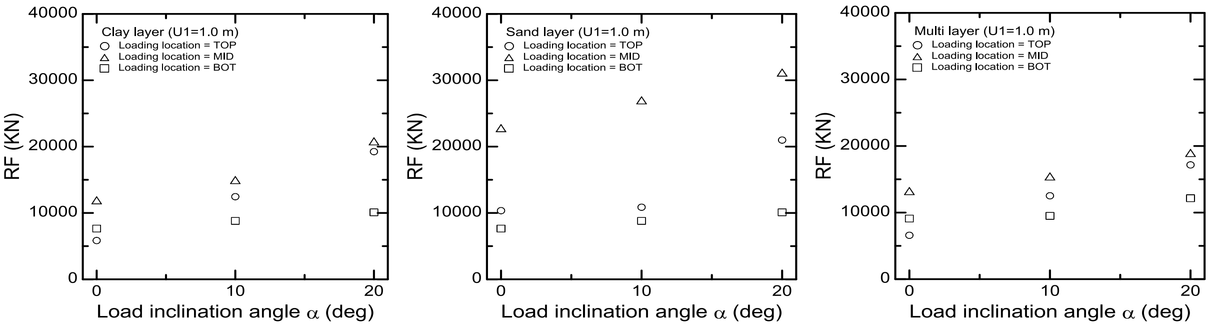


Figure 4. Resistance RF of the suction pile versus load inclination angle α for U1 = 1.0m

The maximum RF approximately ranged from 5 to 30 MN depending on the loading location and the load inclination angle α. Regardless of the soil layer conditions and the loading locations, the maximum RF increased with an increasing α as shown in Fig. 4. For the loading locations of TOP and MID, the RFs were highest for sand layer while the RF values for clay and multi layers were similar. Therefore, it is inferred that the RF values for the loading 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. For the loading location of BOT, the changes of RF values were pronounced for α = 20° while those were insignificant with respect to the changes of the soil layer condition and the α. Overall, for each soil layer condition and load 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 "MID" location, rather than the other locations (TOP or BOT).
The results of RF changes with an increasing α in the present paper are quite different from the results by Cho and Bang (2002) and Bang et al. (2011). Cho and Bang(2002) and Bang et al. (2011) insisted that the RF does not change significantly with an increasing load inclination α within a α range between 0° and 20°. Especially, if soils (both clay and sand) are weak in terms of strength, the change of RF with respect to α becomes more negligible for lower α values (α=0° - 20°). However, the results from the analyses in the present paper show that there exists a clear increase of RF with an increasing load inclination angle α (Fig. 4). In the each plot of Fig. 4, for the loading location of MID, the RF increased almost linearly with an increasing α. For the other loading locations, RF also increased with an increasing α 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 load inclination angle α. The method of translation calculation was explained earlier in this paper. The results are summarized in Fig. 5. As explained earlier, the translation U denotes the shortest distance from the centers of the suction pile before and after its transform.
Fig. 5 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 load 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 load inclination angle α increases the absolute translation quantity (i.e. regardless of the direction of the translation) also tend to increase. In addition, for the clay 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. 6. 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 loading angles α of 10° or 20° changed the rotation θ direction compared to those directions for α = 0°. 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.

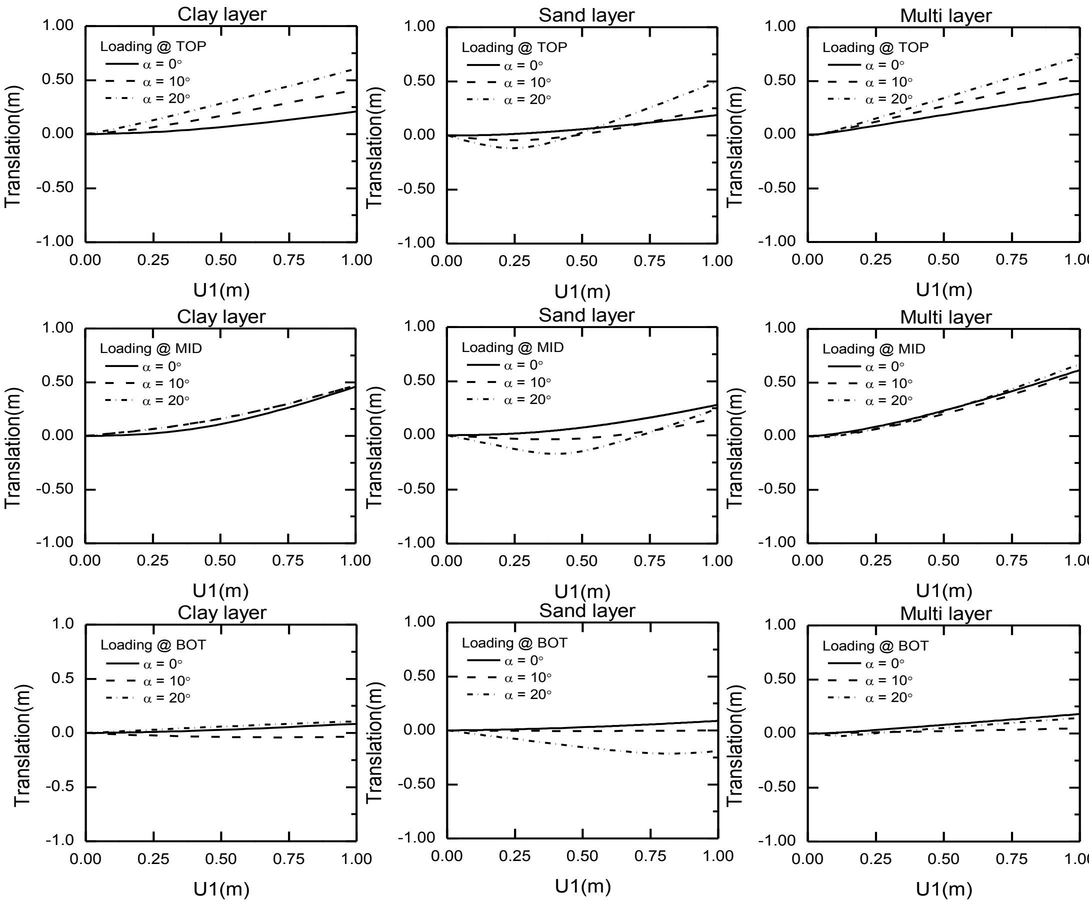
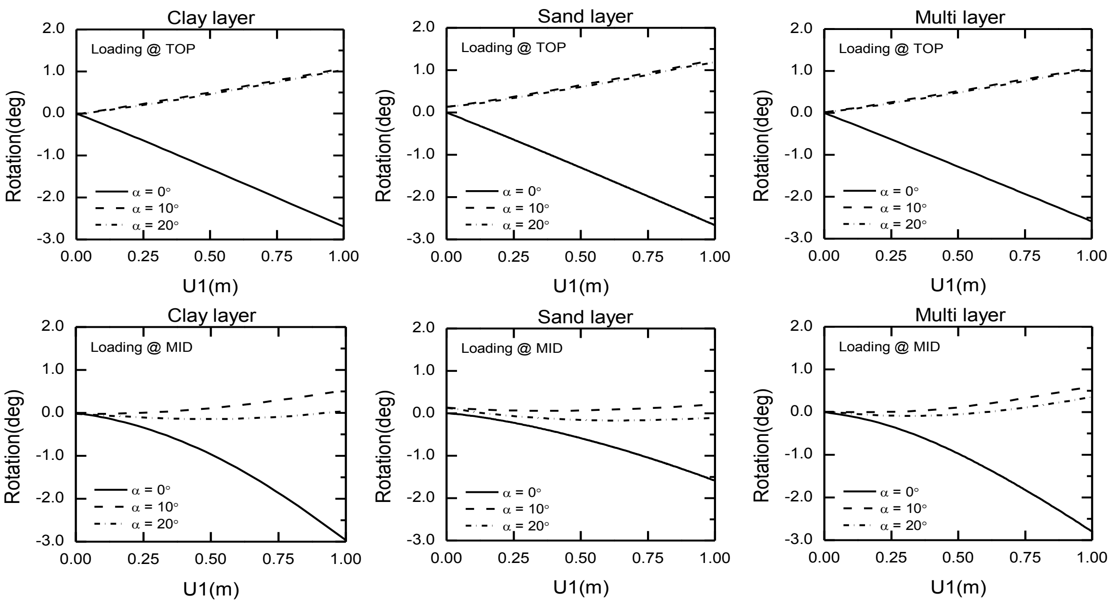


Figure 5. Translation U of the suction pile versus its horizontal component of movement of loading point U1



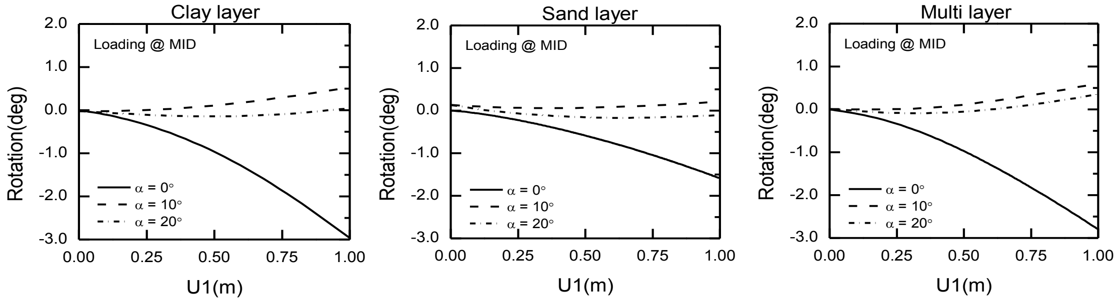


Figure 6. Rotation of the suction pile versus its horizontal component of movement of loading point U1

4 CONCLUSIONS

The primary goal of this paper is to evaluate resistances, translations, and rotations of the suction pile for different soil layer conditions, different loading locations, and different load inclination angles from the results of numerical analyses. The analyses are done until the horizontal component of movement of loading 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 load 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 loading 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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