Numerical Studies on Performance of Offshore Wind Turbine Composite Suction Pile in Sand Subjected to Combined Loading

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ABSTRACT: In order to increase the overall bearing capacity of a wind turbine foundation, a composite type of suction pile is proposed in this paper. Numerical studies on the performance of the proposed suction pile with enlarged lid size subjected to combined lateral and axial loading is presented in the paper. The numerical model is firstly validated by comparison with other numerical study results. The parametric analysis results prove a suction pile with enlarged lid size has better performance than a normal suction pile on both the overall bearing capacity and the stability of the foundation.

KEYWORDS: Composite suction piles, Combined loading, Numerical study

1. INTRODUCTION

A typical suction pile structure, or called suction bucket foundation, consists of a steel cylinder with diameter D, skirt length L and thickness t_s plus an upper steel lid with thickness t_l as shown in Figure 1. The suction pile was firstly used as the foundation of a 3MW wind turbine in Denmark in 2002. Since then, more suction piles have been adopted as the foundation of off-shore wind turbine. Designing of this type of foundation needs to consider large lateral loading and overturning moment. Under extreme condition, this type of foundation has to carry lateral loading up to 60% of its axial loading (Houlsby et al. 2005a).

The suction pile needs to be installed deeply enough in order to provide enough bearing capacity and stability. Hence, a suction or negative pressure is supplied inside the bucket to penetrate the pile bucket into desired depth. The relationship between the required suction and the penetration resistance of a suction bucket in sand was studied by Anderson et al. (2008) using the bearing capacity theory, the tri-axial shear test, the cone penetration test, and the laboratory model test. The research results showed that the penetration resistance decreases with increasing suction pressure. In addition, reducing the relative density of the sand inside the bucket increased the permeability of the sand. Since the higher inside permeability has higher gradients along the outside of the skirts and smaller gradients inside the skirt, the hydraulic gradient decreases the frictional resistance between the soil and the inside bucket wall.

In addition to study the bearing capacity of the suction pile by the upper bound limit method, a centrifuge test was also conducted by Zhang et al. (2010) to verify the accuracy of the used theoretical method.

Villalobos et al. (2005) used small scale model test to investigate the bending resistance of a suction pile installed in saturated dense sand under different installation methods. It was found that the bending resistance installed by suction is smaller than that by pushing method.

Villalobos et al. (2009) investigated the performance of the suction pile in dry sand, with length to diameter ratio of 0.5 and 1.0, subjected to composite loading. The work-hardening plasticity theory was used to interpret the experiment results. The shape of the yield surface and the post-yield behaviour of the foundation were also deduced in the paper.

Performance of a full scale and a small scale suction piles, installed in sand or in clay subjected to vertical loading or bending moment was studied by Kelly et al. (2006). Normalization procedures were proposed to allow laboratory tests and field trials of foundations to be compared in terms of both stiffness and capacity. The non-dimensional laboratory data from moment loading tests were similar to the field data in most cases. However, the non-dimensional data from vertically loaded caisson tests in the laboratory and in the field showed more significant differences.

Utilizing the centrifuge and the in-situ test results, a finite element method was used by Tran and Randolph (2008) to simulate the installation of a suction pile installed in sand. A linear relationship was found between the suction pressure and the installed depth. In addition, it was also found that the slope of the linear relationship is a function of the critical hydraulic gradient inside the bucket.

Performance of a laterally loaded suction pile installed in sand was studied by Achmus et al. (2013) using the finite element method. It was found that increasing of the lateral loading up to a certain magnitude will cause separation between the lid and the soil below the lid. Once the lateral loading or the rotation of the foundation up to a certain value, complete separation between the lid and the soil below may occur.

Uplift capacity of the suction pile in sand was studied by Houlsby et al. (2005b). A simplified uplift bearing capacity equation was also proposed by the authors.

Small scale tests of suction piles subjected to combined loading were conducted by Ibsen et al. (2014). It was found that the vertical bearing capacity of the suction pile was depending on the suction piles installed depth. Calibration of the failure criteria was also conducted using two methods. One of the methods assumed a frictional resistance between the soil and skirt (based on the Mohr-Coulomb model and stresses calculated at rest). The other method was related to the stress situation that accounted for the decreasing stresses close to the skirts in tension.

A series of small scale tests on the effects of suction installation and jacking installation on the interaction between suction pile and inside soil were carried out by Lian et al. (2014). Under $h/D<0.3$ (h= depth of bucket and D= diameter of the bucket), it was shown that the soil pressures either inside or outside the skirt have the same magnitude. However, when $h/D>0.3$, the inside soil pressure is larger than the outside pressure. If the suction pile is installed by suction, the inside soil pressure drops when the suction is steadily applied. The outside soil pressure increases immediately after application of the suction, and then drops to a steady condition.

In order to study the effects of wind or wave on performance of suction piles, laboratory tests on small scale suction piles subjected to cyclic lateral loading were conducted by Byrne and Houlsby (2004). The axial loading was considered as constant magnitude. The test result showed that the rate of cyclic lateral loading has no effect on the load vs displacement relationship of the tested suction pile.

Small scale tests were conducted by Zhu et al. (2013) to investigate the performance of a suction pile in loose sand subjected to 10,000 cycles of lateral loading. The main concerns were the accumulated rotation angle, settlement and stiffness of the foundation due to cyclic loading. The test results show that the settlement increases with increasing the loading cycle. However, the numbers of loading cycle have little effect on the foundation stiffness. It was also found that a cyclic loading regime intermediate between one-way and full two-way cycling produced the largest rotations.

Centrifuge was used again by Tran et al. (2007) to investigate the effect of a silty soil layer sandwiched between two sand layers on the penetration resistance of a suction pile. The results show that more suction was needed for the soil containing silt than that of sand only.

Dynamic and static full scale pullout tests of suction piles were conducted by Ravichandran et al. (2014). The in situ condition includes natural effects of wind, wave and current. The tested results show that the pullout capacity is affected by the geometry of the test pile, pullout angle and whether the loading was static or dynamic. It was also observed that the pullout angle has no effect on performance of the large diameter suction pile.

Installation of a suction pile does not need impact loading and ocean bed levelling. In addition, the suction pile can easily be removed after the wind turbine lost its function. Hence, overall construction of a suction pile is not only cheaper but also less time consuming compared to other types of wind turbine foundation. It satisfies both low cost and low environmental impact. However, one important concern of the suction pile is its overturning stability when subjected to lateral loading. Hence, a composite type of suction pile is proposed in this paper in order to increase the overall bearing capacity of the foundation. By increasing the diameter of the lid of a suction pile up to a certain size, such as D_l of Figure 1, the new type of composite foundation is expecting to have a more stable and a higher bearing capacity performance. This paper presents the numerical simulated results of suction piles with enlarged lid size for improving its bearing capacity and stability when subjected to combined lateral and axial loading.

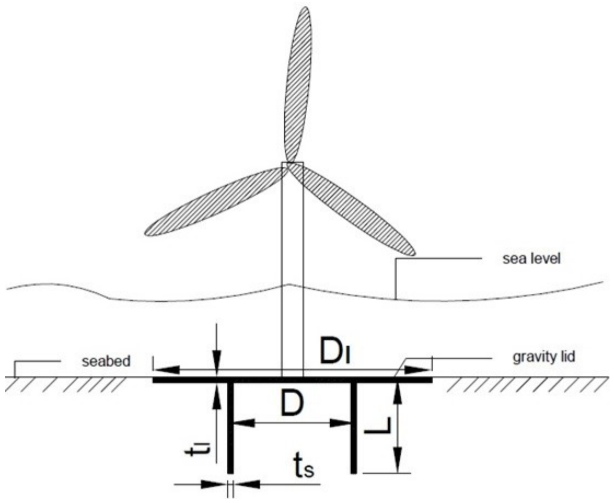


Figure 1 Composite suction foundation geometric model

2. FINITE ELEMENT MODEL

Performance of the proposed composite foundation is studied by using an available three dimensional finite element software, PLAXIS 3D (2013). A schematic illustration of a composite suction pile is shown in Figure 1. Once the lid size, D_l, is reduced to the diameter of the suction pile, the composite suction foundation becomes a usual suction pile. As suggested by Achmus et al. (2013), in order to reduce the size effect at the simulation boundary, the size of the finite element mesh is assumed to reach the boundary at 6.67 times the diameter of the lid as shown in Figure 2. Also, the boundary at the bottom is set at 3 times of the bucket depth.

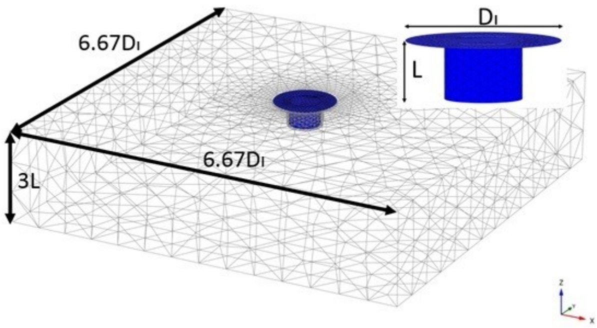


Figure 2 The boundary of the finite element model

The Mohr-Coulomb model is used to simulate the behavior of the soil. The interface element is used to simulate the interaction between the soil and the foundation structure. The parameter, R_{inter} , is set as 0.67 as the criterion to control the relative displacement between the soil and the structure. Hence, the strength at the soil/structure interface can be expressed as $C_{inter} = R_{inter} \times C_{soil}$ and $\tan\psi_{inter} = R_{inter} \times \tan\psi_{soil}$, in which C_{inter} and ψ_{inter} are the cohesion and the friction angle at the soil-structure interface.

Two different densities of the sandy soil are used for analyses. Drained condition is considered for both soils. For dense sand and medium dense sand, the parameters were shown in Table 1.

Table 1 Soil parameter

	Dense sand	Medium dense sand
buoyant unit weight , γ' (kN/m^3)	10.2	9
Poisson's ratio , ν (deg.)	0.25	0.25
internal friction angle , ϕ (deg.)	40	35
dilatancy angle , ψ	10	5
cohesion , c (kN/m^2)	0.1	
R_{inter}	0.67	

The geometry and material properties of the simulated composite suction pile is given in Figure 1 and Table 2. In order to simulate the lid as a substantial rigid plate, the elastic modulus of the rigid plate is assumed as 10^9 GPa.

Table 2 Composite suction foundation parameter definition

Diameter of the upper lid, D_l (m)	**12, 16, 20, 24**		
Material	Steel		
Buoyant unit weight (kN/m³)	68		
Elasticity Modulus of lid, E (GPa)	10^9		
Elasticity Modulus of skirt, E (GPa)	210		
Diameter of the suction pile, D (m)	12		
Skirt length, L(m)	6	9	12
L/D	0.5	0.75	1
Skirt thickness, t_s (m)	0.03		
Lid thickness, t_l (m)	0.1		

The finite element analysis includes three stages. The initial stage considers the self-weight of the soil mass itself. The at-rest earth pressure coefficient $K_0 = 1 - \sin \phi$ (Jaky, 1944) is used. Subsequently, applying the self-weight of the foundation structure and then finally the external load application. The external load includes axial loading, V, lateral loading, H, and overturning moment, M. The applied loads are applied at the center of the lid with the coordinates of (0, 0, 0). Assuming the simulating weight were a 5MW wind turbine, the axial loading is fixed as10MN in the analysis. The moment is controlled by the lateral load, H, and the eccentricity, h, as shown in Figure 3.

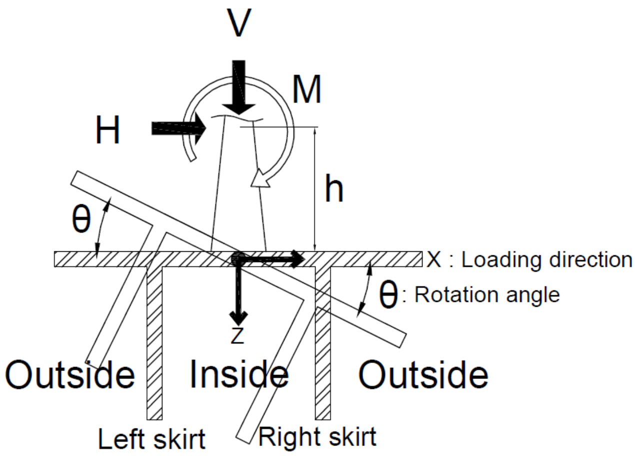


Figure 3 Definitions of external loads on composite suction foundation

3. VERIFICATION OF THE FINITE ELEMENT MODEL

The load-bearing behaviour of a suction pile foundation in sand studied using different finite element code, ABAQUS, by Achmus et al. (2013) is used to verify the model of the finite element code in this paper. The parameters used for numerical analyses are also followed the assumptions made by Achmus et al. (2013). Comparison on the results analyzed by ABAQUS and PLAXIS of a suction bucket with length/diameter ratio L/D=0.75 subjected to axial loading V=10MN under different eccentricity (h=0m, h=20m and h=30m) is shown in Figure 4. Good correlation on the relationships between horizontal load vs displacement obtained from both methods is shown in the figure.

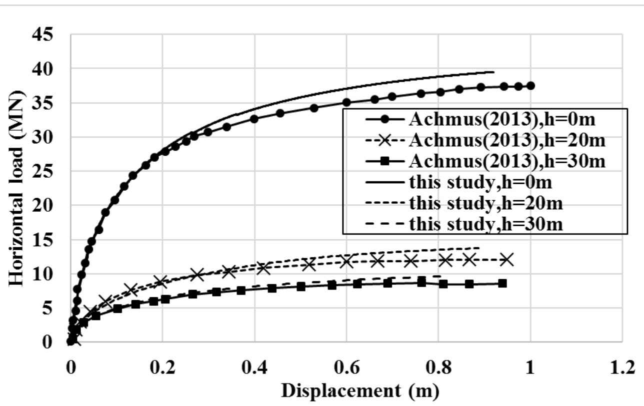


Figure 4 Verification with Achmus (2013) when L/D=0.75,vertical load V=10MN with different load eccentricities

4. NUMERICAL SIMULATION

Sandy soil with two different densities, dense and medium dense sand, are considered in the following parametric numerical simulations. The geometry of the composite foundation is assumed to be the combination of various lid diameters (D_l = 12m, 16m, 20m, or 24m) with bucket lengths (L= 6m, 9m, or 12m under fixed value of D= 12m). Assumed material properties of the suction bucket for analysis are given in Table 1. A vertical loading of 10MN is applied to simulate the weight of a 5MW wind turbine. In addition, lateral loading is assumed to have eccentricity h= 0m, 30m, 70m, and100m.

If a wind turbine foundation is assumed to have lid diameter D_l= 20m and L/D= 0.75 (L=9m and D=12m) and to be installed in dense sand, the relationships of lateral load versus displacement and moment versus rotation relationship under eccentricity h=0m, 30m, 70m, and 100m are shown in Figure 5(a) and Figure 5(b), respectively. The rotation angle is referred to Fig. 3. As shown in the figures, the lateral capacity of the suction bucket decreases with increasing of eccentricity. When there has no eccentricity, i.e. h= 0m, the maximum lateral capacity matches to the results by Achmus (2013).

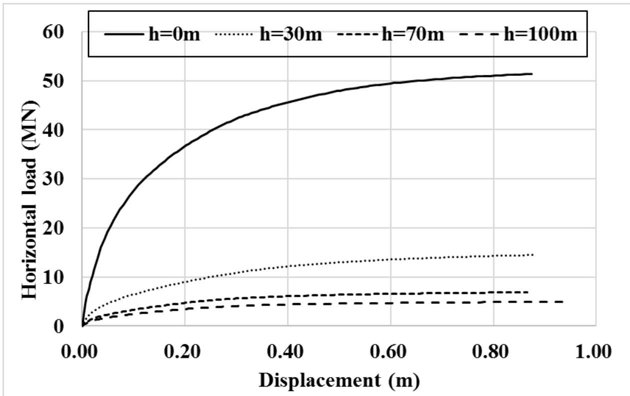


Figure 5(a) Horizontal load – displacement interaction diagram (upper lid diameter D_l=20m, L/D=0.75, with different load eccentricity h in dense sand)

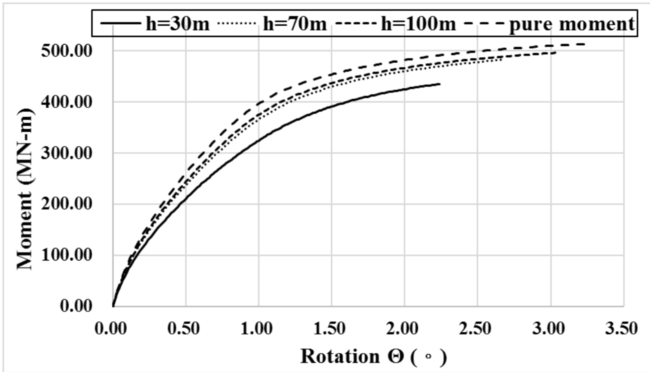
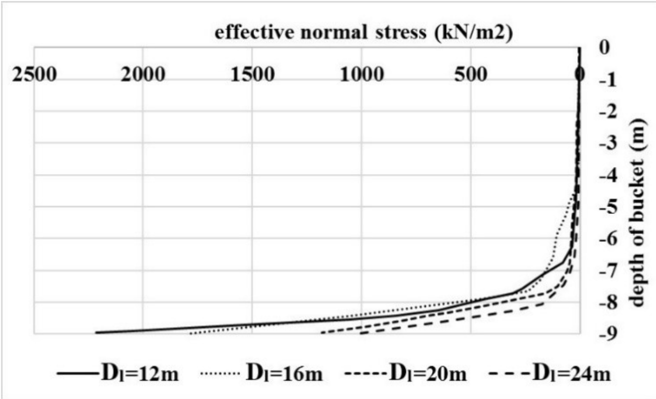


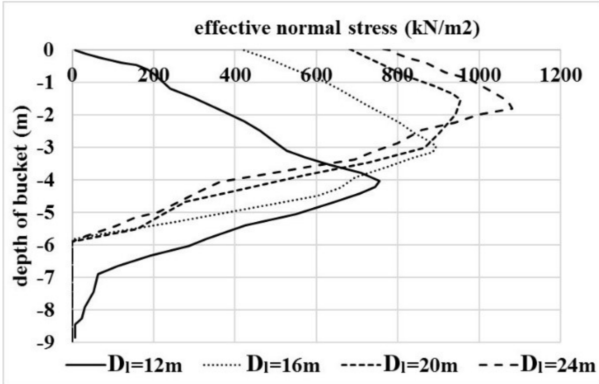
Figure 5(b) Moment – rotation interaction diagram (upper lid diameter D_l=20m, L/D=0.75, with different load eccentricities h in dense sand)

Considering four different lid sizes, with fixed skirt length of 9m and eccentricity of 30m, the normal stress distribution outside and inside the bucket skirt is shown in Figure 6. The effective normal stress on the right skirt increases with increasing of D1. Comparison between Figure 6(a) and Figure 6(d), we can find that the normal stress inside the right skirt is smaller than that of the outside skirt. From comparison between Figure 6(a) and Figure 6(c) we can find that the normal stress below the rotating center is much higher due to the effect of passive earth pressure. In addition, Figure 6(b) also shows that the rotating center is higher under larger lid size, D1.

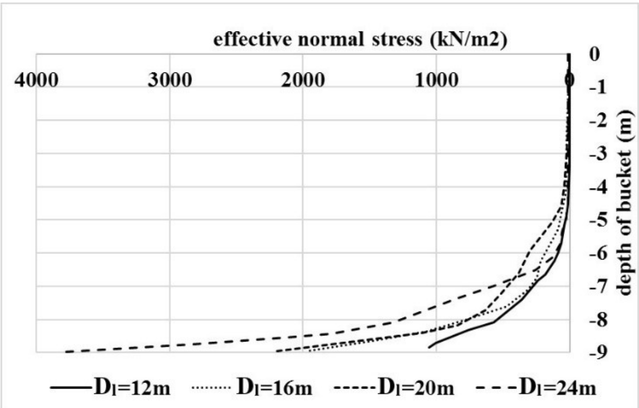
Hence, increasing the lid size appears to have higher bending moment resistance.



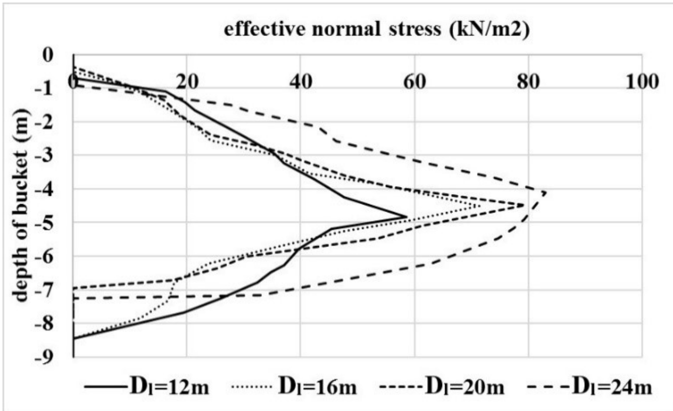
(a) right skirt (inside)



(b) right skirt (outside)



(c) left skirt (outside)



(d) left skirt (inside)

Figure 6 Composite suction foundation with different D_l (when bucket length L=9m , load eccentricity h=30m), bucket skirt effective normal stress distribution

The failure modes of the composite suction caisson with lid size D_l=12m and D1=24m are shown in Figure 7. As shown in Figure 7(a) for the case with D_l=12m and L/D=0.5, inclination of the bucket also induces the passive failure on the right skirt and the separation between the bucket and the soil on the left skirt. A rotating center at right bottom corner is observed from Figure 7(b) and Figure 7(c). Passive failure mode is observed for the skirt above the respective rotating centre.

For the larger lid size of D_l=24m and L/D=0.5, the numerical study results show that the uplifting of the soil on top of the right side lid as shown in Fig. 7(d). In addition, a passive failure is observed on the left skirt. Observation from Figures 7(e) and 7(f) we can also find larger D_l caused higher rotating centre.

Assuming h=30m and D1=20m, variation of lateral capacity under different bucket lengths (L=6m, 9m, and12m; and L/D=0.5, 0.75, and 1.0) is shown in Figure 8. Whether the soil condition is dense or medium dense, we can find the lateral capacity increases with increasing of bucket length. At the displacement 0.8m, the lateral capacity increases about 63.5%~72.9% when the bucket length increases from 6m to 9m. For the case of increasing the bucket length from 9m to 12m, the capacity increases about 44.1%~46.9%.

Assuming h=30m and L=9m, variation of lateral capacity under different lid diameters (D_l=12m, 16m, 20m, and 24m) is shown in Figure 9. As shown in the figure, the lateral capacity increases with increasing of lid size. At the displacement 0.8m, the lateral capacity increases about 25.8% (in dense sand) and 49.7% (in medium dense sand) when the lid diameter increases from 12m to 16m.

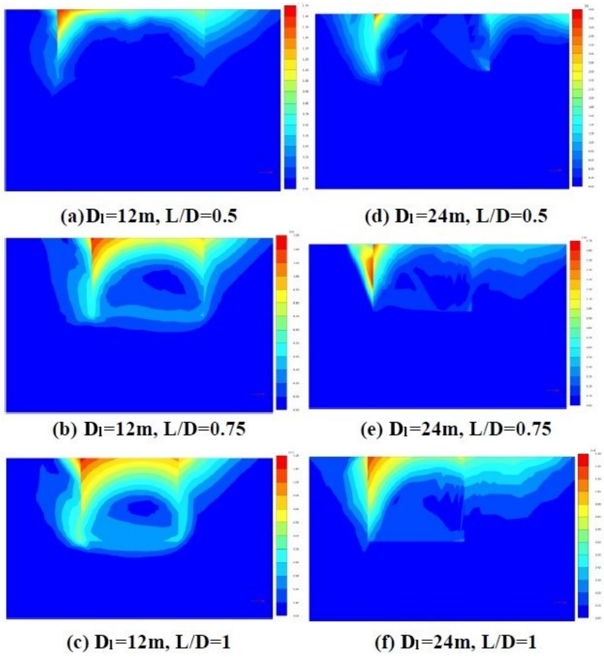
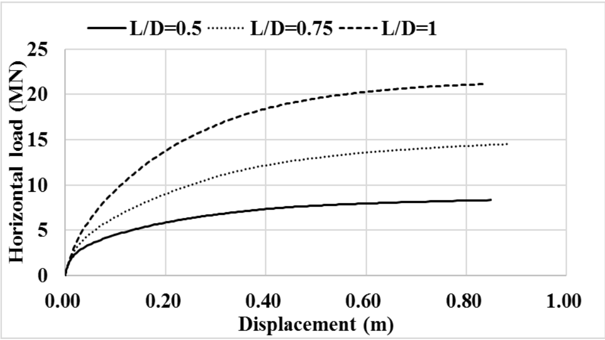
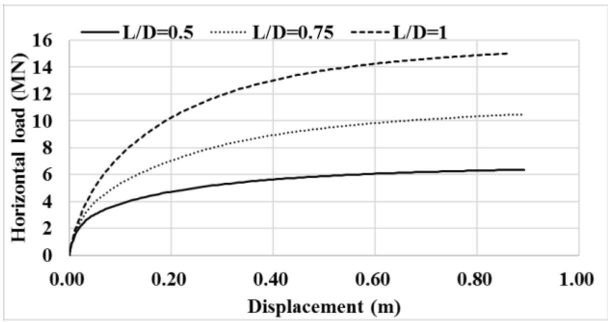


Figure 7 Comparison to the displacement of the composite suction foundation upper lid diameter D_l=12m, 24m with different bucket L/D when load eccentricity h=70m in dense sand



(a) in dense sand



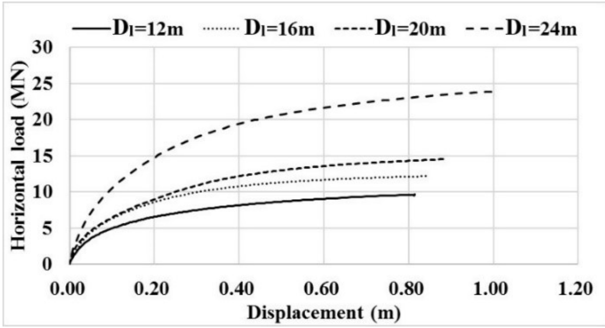
(b) in medium dense sand

Figure 8 Horizontal load – displacement interaction diagram (upper lid diameter D_l=20m, load eccentricity h=30m, with different bucket length)

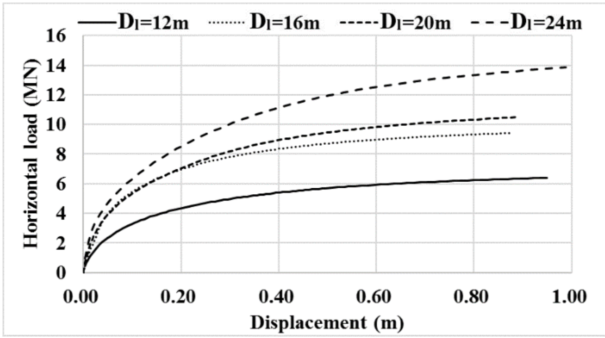
If we assume h=30m and D_l=20m, the overturing moment versus rotation relationships under different bucket lengths (L=6m, 9m, and 12m; and L/D=0.5, 0.75, and 1) are shown in Figure 10. Increasing the bucket length also increases the rotational resistance of the bucket. For example, under a given overturning moment (M=150MN-m) in dense sand, the rotation angles under bucket lengths of L=6m, L=9m, and L=12m are 0.6^{θ}, 0.3^{θ} and 0.14^{θ} degrees, respectively. In addition, under the same overturning moment, the rotation angle decreases with increasing the bucket length, either in dense sand or in medium dense sand.

The relationships of moment versus rotation of the foundation with h=30m and L=9m under various lid size (D_l=12m,16m, 20m, and 24m) are shown in Figure 11. The figures show that the rotation resistance of the foundation increases with increasing of the lid size, whether in medium dense sand or in dense sand. Based on Figure 10 and Figure 11 we can find that the rotation resistance of the foundation is improved by increasing the size of the lid or the length of the bucket.

The effectiveness by increasing the length of the bucket or by increasing the size of the lid are summarized in Table 3 and Table 4, respectively, for comparison. As shown in Table 3 and Figure 10, if the bucket were installed in the dense sand, the moment capacity increases 92.6％ by increasing the length from 6m to 9m. In addition, the moment capacity increases 47.04％ by increasing the length from 9m to 12m. For the case in medium dense sand as shown in Table 4 and Figure 11, the moment capacity increases 38％ by increasing the lid size from 12m to 16m. Again, the moment capacity increases 41.3％ and 68.97％ by increasing the lid size from 16m to 20m and from 20m to 24m, respectively. Although increasing the length of the bucket can also improve the performance of the suction pile, it may cause additional difficulty for installation.

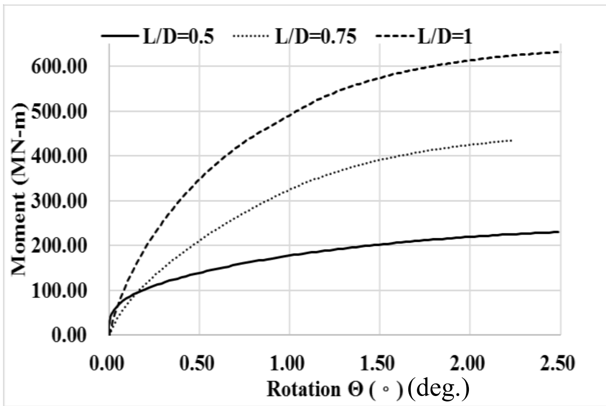


(a) in dense sand

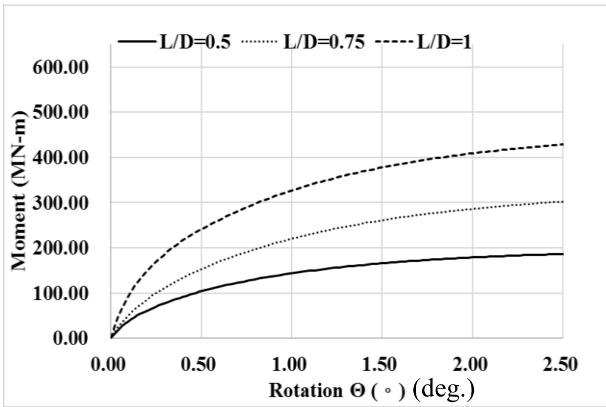


(b) in medium dense sand

Figure 9 Horizontal load – displacement interaction diagram (L/D=0.75, load eccentricity h=30m, with different upper lid diameter D_l)



(a) in dense sand



(b) in medium dense sand

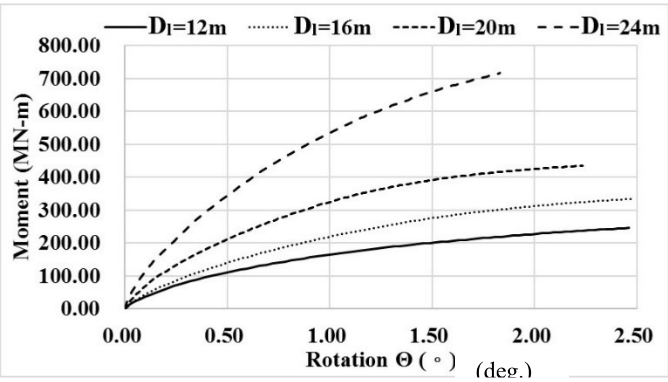
Figure 10 Overturning moment – rotation interaction diagram (upper lid diameter D_l=20m, load eccentricity h=30m, with different bucket lengths)

Table 3 The effect by increasing the length of the bucket

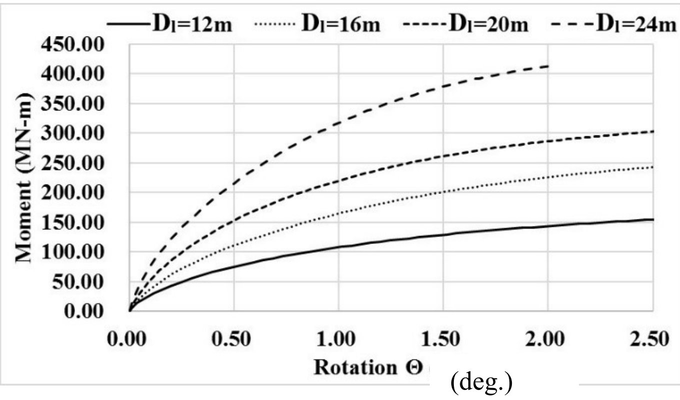
L (D_l=20m, h=30m)		**6m**	**9m**	**12m**
dense sand	**Rotation angle (deg.θ)** (M=150MN-m)	0.6	0.3	0.14
	Resistance moment (MN-m) (at rotation angle =1.5 **deg.**°)	203	391	575
medium dense sand	**Rotation angle (deg.θ)** (M=150MN-m)	1.1	0.48	0.2
	Resistance moment (MN-m) (at rotation angle =1.5 **deg.**°)	166	262	378

Table 4 The effect by increasing the size of the lid

D_l (L=9m, h=30m)		**12m**	**16m**	**20m**	**24m**
dense sand	**Rotation angle (deg.θ)** (M=150MN-m)	0.84	0.55	0.3	0.15
	Resistance moment (MN-m) (at rotation angle =1.5 **deg.**°)	200	276	391	659
medium dense sand	**Rotation angle (deg.θ)** (M=150MN-m)	2.28	0.85	0.48	0.28
	Resistance moment (MN-m) (at rotation angle =1.5 **deg.**°)	128	201	262	378



(a) in dense sand



(b) in medium dense sand

Figure 11 Moment – rotation interaction diagram (L/D=0.75, load eccentricity h=30m, with different upper lid diameter D_l)

For studied sizes of the suction pile in the paper, the effectiveness of increasing the length of the bucket or increasing the size of the lid are also presented in Figure 12 and 13 for comparison. Whether the suction pile is installed in medium or dense sand, either the moment resistance increases or rotation angle decreases. However, too large lid size may cause difficulty of installation and may not be economic. In addition, increasing the bucket length also cause the difficulty of installation. Once the bucket length is too long, it is more like a monopole, which is in general installed by driving.

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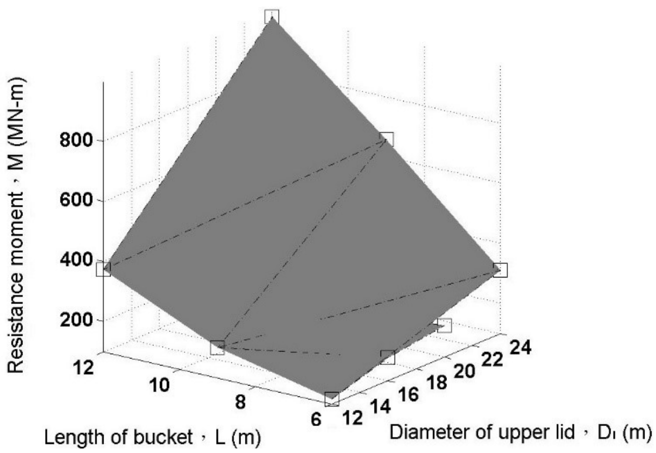
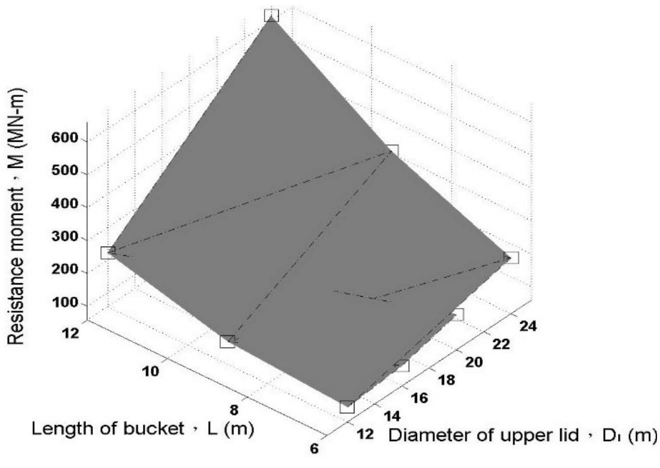
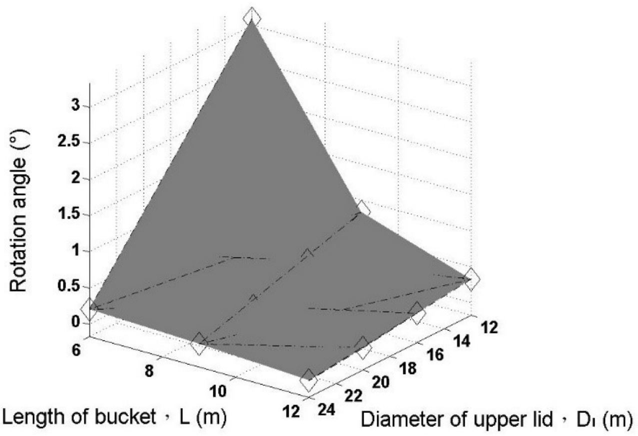


(a) in dense sand

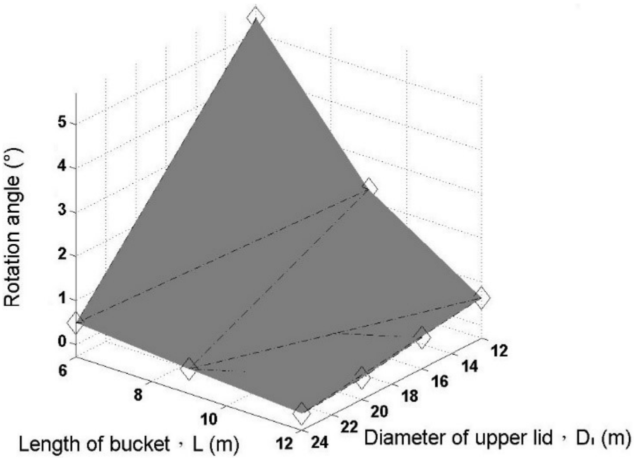


(b) in medium dense sand

Figure 12 Moment – upper lid size - bucket length relation diagram (when load eccentricity h=30m, rotation angle =1.5°)



(a) in dense sand



(b) in medium dense sand

Figure 13 rotation angle – upper lid size - bucket length relation diagram (when load eccentricity h=30m, M=150MN-m).

5. CONCLUSIONS

Numerical studies on performance of a proposed composite type suction pile foundation in medium dense sand or in dense sand subjected to combined axial and lateral loading was presented in the paper. The following conclusions can be drawn from the results:

1. The parametric analysis results showed that a suction pile with enlarged lid size has better performance than a normal bucket on both the overall bearing capacity and the stability of the foundation.
2. The results of the numerical study showed the ultimate load of a suction pile is dependent on the size of the lid, the length of the bucket and the relative density of the sand.
3. Although increasing the bucket length can also improve the performance of a suction pile, it may cause additional difficulty for installation.

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