STUDY ON INSTALLATION AND PULLOUT OF SUCTION CAISSON FOUNDATION FOR OFFSHORE WIND TURBINES

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ABSTRACT

Suction caisson is being adopted as an alternative solution for the foundation of offshore wind turbines at shallow water depths. The design of foundations for offshore wind turbine is challenging. There are several options for the foundation system: gravity base, mono pile, tripod or tetrapod piles, and suction caisson foundations. Two types of structural configuration of suction caisson foundation are: a single large caisson as monopod foundation, and three or four smaller caissons as tripod/tetrapod foundation. The installation process includes self-weight penetration and penetration under the influence of applied suction. In the case of monopod, the most unfavourable loading is the large overturning moment whereas in the case of tripod/tetrapod foundation, it is transient uplift loading in the upwind legs. The uplift capacity is a critical issue regarding the design. This paper presents the installation and pullout behaviour of suction caisson foundation. For the calculation of pullout capacity, reliable methods have been explained.

***Key words*:** Wind turbine, Suction caisson, Monopod, Tripod/tetrapod, Pullout.

1. INTRODUCTION

Offshore wind farms are becoming very popular as an alternative for renewable source of energy these days. These have been installed in shallower water depth (up to 30 m). The cost of foundation for offshore wind turbines including installation is a significant fraction of the total cost. There are several options for foundation system like gravity base, monopile, tripod and suction caisson.

Among these suction caisson foundation is a more economical and attractive alternative [1]. It is a skirted shallow foundation open at bottom and closed at the top. Installation is done by creating suction beneath the caisson by pumping out the water from the hollow compartment. This pumping out of water creates a differential pressure beneath the caisson which forces the caisson into the soil. The installation process is faster and simpler than that of other alternative. Suction caisson foundation can be adapted flexibility to a variety of structural forms which makes it accessibility by boat [2]. The overall installation is independent of weather condition. At the end of wind turbine life, suction caisson can be removed completely from seabed.

Suction caisson foundations have been widely used in oil and gas offshore structures. Recently they have been considered as a possible alternative for the foundation system for offshore wind turbines [3]. Offshore wind turbines vary in different way from oil and gas industries structures. These structures are likely to be found in shallower water depth. Vertical loading is much smaller than that of horizontal loading which leads to relatively large overturning moments. Also relatively small and multiple installation of economical foundations are required for development of wind farms rather than larger one-off foundation of oil and gas industries.

Suction caisson foundation is of two types: monopod and tripod/tetrapod. For tripod/tetrapod the caisson design must take the account of involvement of transient tensile loading in the upwind leg. In case of monopod the most unfavourable loading condition is large overturning moments. In both case the design of foundation is not usually governed by considering the ultimate capacity, but the accumulated deformation under cycling loading. The design of foundation mainly depends on installation and it's in service performance. In this paper we will discuss the installation and vertical pullout behaviour of suction caisson foundation.

2. INSTALLATION BEHAVIOUR

The installation of suction caisson foundation is performed in two steps. (a) self- weight penetration and (b) suction assisted penetration. During self-weight penetration, the foundation is kept on the soil and allowed to penetrate under its own weight for some time. When self-weight penetration is over, a seal is formed around the bottom skirt of foundation and now it is ready for the second stage penetration. The water is pumped out through the provison provided at the top of caisson generating suction beneath the foundation which allows the caisson foundation to penetrate to desired depth.

Fig. 1 shows typical outline of suction caisson foundation during installation both in sandy and clayey soils [4,5]. The resistance against penetration is calculated as simple pile capacity analysis in which resistance to penetration is calculated as the sum of end bearing on the annulus and friction inside and outside the caisson wall.

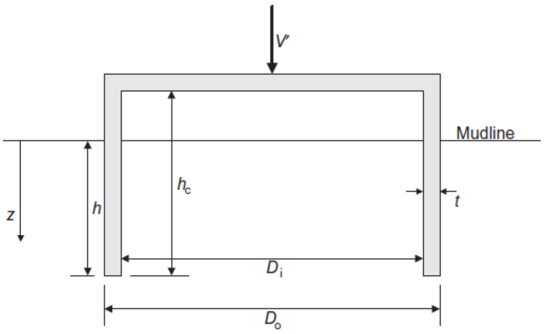

Figure 1: Suction caisson foundation outline

Installation in sandy soils

In case of sandy soils [4], the vertical load on caisson during self-weight penetration in absence of suction is given as

$$V' = \frac{\gamma' h^2}{2}(K\tan\delta)_o(\pi D_o) + \frac{\gamma' h^2}{2}(K\tan\delta)_i(\pi D_i) + \left(\gamma' h N_q + \gamma' \frac{t}{2} N_\gamma\right)(\pi D t) \qquad (1)$$

where, δ is mobilised angle of friction between the caisson wall and soil, N_q and N_γ are end bearing factors, D is caisson mean diameter and K is horizontal earth pressure constant.

When suction s is applied, the penetration resistance is expressed as

$$V' + s\left(\frac{\pi D_i^2}{4}\right) = \int_0^h \sigma'_{vo}dz(K\tan\delta)_o(\pi D_o) + \int_0^h \sigma'_{vi}dz(K\tan\delta)_i(\pi D_i) + \left(\sigma'_{vi}N_q + \gamma' t N_\gamma\right)(\pi D t) \qquad (2)$$

To study the installation behaviour, data of actual offshore platforms have been used as listed in Table 1 [4]. Using this data, initially the penetration depth under self-weight is calculated. Thereafter, suction is applied and the suction required up to full depth penetration is calculated and plotted in Fig. 2. Overall calculation results obtained are listed in Table 2.

Table 1: Data of caissons used for offshore platforms in sandy soils

	Sand Haven platform	**Draupner E platform**	**Sleipner T platform**
D (m)	4	12	15
L (m)	2.5	6	5
t (mm)	20	45	45
V' (kN)	100	6622	12000
Ø (deg)	40	44	45
γ' (kN/m^3)	8.5	8.5	8.5
*K*tan*δ*	0.48	0.63	0.8
K_i/K_o	2	3	3

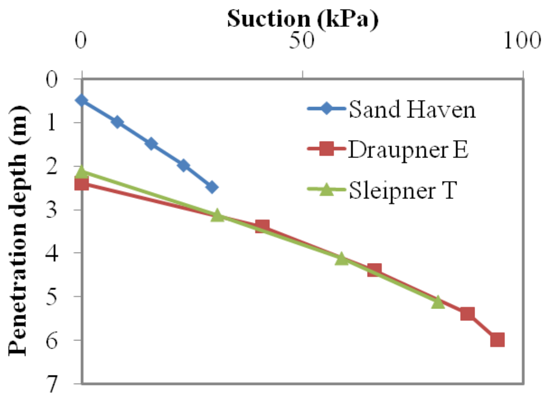

Figure 2: Required suction for penetration of caissons in sandy soils

Table 2: Calculated data during installation in sandy soils

	Sand Haven platform	Draupner T platform	Sleipner E platform
Self-weight penetration depth (m)	0.49	2.401	2.92
Suction for full depth penetration (kPa)	23.08	84.18	76.9

Installation in clayey soils

In case of clayey soils, the installation resistance is the sum of adhesion on the caisson wall and the end bearing on annular ring [5].

$$V' = h\alpha_o s_{u1}(\pi D_o) + h\alpha_i s_{u1}(\pi D_i) + \left(\gamma' h N_q + s_{u2}N_c\right)(\pi D t) \qquad (3)$$

where s_{u1} is average undrained shear strength between mudline and depth h, s_{u2} is undrained shear strength at depth h, α_o and α_i are adhesion factors outside and inside the caisson. When suction is applied, the penetration resistance is expressed as

$$V' + s\left(\frac{\pi D_i^2}{4}\right) = h\alpha_o s_{u1}(\pi D_o) + h\alpha_i s_{u1}(\pi D_i) + \left(\gamma' h - s + s_{u2}N_c\right)(\pi D t) \qquad (4)$$

The study of installation in clay has been done by using data of Table 3 [5]. The overall suction required for further penetration up to full depth are plotted in Fig. 3. The results obtained during self-weight penetration and suction required for penetration are presented in Table 4.

Table 3: Data for caisson installation in clayey soils

	Centrifuge test	Design data	Nkossa field test
D (m)	0.03	12	15
t (m)	0.0005	6	5
L (mm)	0.12	45	45
$S_{u,o}$ (kPa)	0	20	5
ρ (kPa/m)	144< 0.067m 204>0.067m	2.5>2m	1< 5m 1.67>5m
V' (kN)	0.0153	1000	350
γ′ (kN/m^3)	792	6	6
$\alpha_i = \alpha_o$	0.5	0.6	0.3
N_c	9	9	9

Table 4: Calculated data during installation in clayey soils

	Design data	Nkossa field test
Self-weight penetration depth (m)	0.83	4.57
Suction for full depth penetration (kPa)	50	117

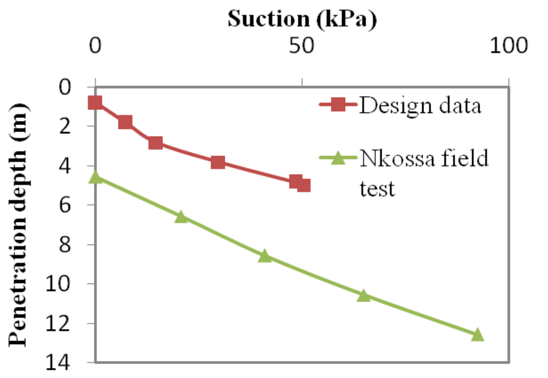

Figure 3: Required suction during penetration in clayey soils

3. PULLOUT BEHAVIOUR

Pullout capacity is one of the main criteria to design the suction caisson foundation. The vertical pullout capacity of suction caisson depends on many factors like Caisson submersed weight, Skin friction on caisson wall, Soil plug inside the caisson, Soil tensile strength at the caisson base and suction pressure developed due to tensile loading across the caisson.

Failure mechanisms

Depending on the load velocity and drainage condition three different failure mechanisms have been given for the pullout failure of suction caisson: reverse bearing failure, sliding failure and tensile failure [6, 7].

Sliding failure mechanism occurs in case of drained condition. During failure soil plug remain at its place and the pullout resistance is calculated as the sum of internal and external skin friction of the caisson wall.

Bottom resistance failure mechanism is considered in semi drainage condition. In this failure mechanism soil plug inside the caisson moves along the caisson during failure. The pullout resistance is calculated by considering the outside friction on caisson wall and taking account for the weight of soil plug and caisson.

Reverse bearing capacity mechanism is considered in case of undrained condition. It is similar to bottom resistance failure mechanism. Only difference is that soil failure capacity under caisson is deduced from the bearing capacity formula with reverse mechanism. The overall pullout capacity is calculated as sum of external wall friction and bearing capacity load of caisson.

Ultimate pullout capacity

The ultimate pullout capacity of suction caisson foundation can be calculated on the basis of equilibrium of forces acting on the caisson during pullout. In undrained condition [8] it can be expressed as

$$P_{u,undrained} = P_b + P_{f,ext} + P_c + P_s \quad (5)$$

where, P_b is bearing capacity of suction caisson, $P_{f,ext}$ is friction resistance on external caisson wall, P_c is the weight of caisson and P_s is the soil plug weight. In drained drained condition the ultimate pullout capacity [8] of caisson foundation can be expressed as

$$P_{u,drained} = P_{f,ext} + P_{f,int} + P_c \quad (6) \qquad (6)$$

Some other methods are also given by different researchers to evaluate the pullout capacity of suction caisson foundation. All the methods are based on equilibrium of forces. The methods of Deng and Carter and Christensen et al. as elaborated by Thorel et al. [6] and that of Iskander et al. [9] are used in the computations.

Ultimate pullout capacity for suction caisson data (Table 5) and for different aspect ratios up to 3 has been calculated using these methods and the results are compared with those obtained from PLAXIS 2D analysis. PLAXIS analysis has been done by choosing axisymmetric model. 15-node triangular elements are used to model the soil and other volume cluster. Mohr-coulomb model has been used to analyze the materials.

From Fig. 4, it is clear the pullout capacity obtained by PLAXIS is showing higher value that of by Iskander et al. and Christensen et al. while it is lower than that of Deng and Carter result.

Table 5: Data used for pullout calculations

D (m)	*t* (m)	*μ* (Caisson)	*γ′* (kN/m^3)	*Ø* (°)	S_u (kPa/m)
20	0.03	0.25	11	24	1.5

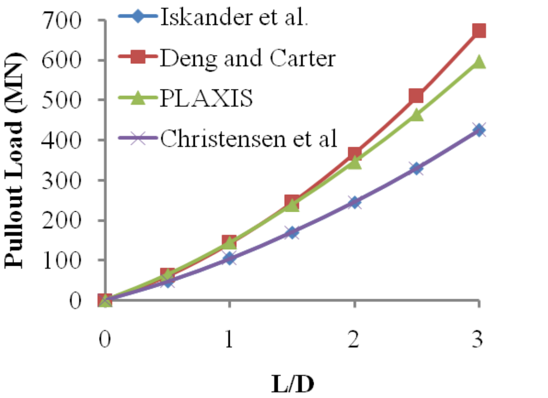

Figure 4: Comparison between pullout results of different methods and PLAXIS analysis

4. CONCLUSIONS

The overall design of suction caisson foundation for offshore wind turbines depends on its installation and pullout capacity. Installation capacity depends mainly on frictional resistance and end bearing at caisson tip. It is calculated by using conventional pile capacity analysis method. The pullout of caisson mainly depends on the drainage condition, caisson submersed weight, skin friction on caisson wall, and soil plug weight. The ultimate pullout capacity is calculated by using equilibrium of forces at the time of pullout. PLAXIS 2D results are showing reasonable good agreement with other methods and can be used to find ultimate pullout load.

5. REFERENCES

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