Investigating the monotonic behaviour of hybrid tripod suction bucket foundations for offshore wind towers in sand

Faizi, Koohyar; Faramarzi, Asaad; Dirar, Samir; Chapman, David

DOI:
10.1016/j.apor.2019.05.018

Investigating the Monotonic Behaviour of Hybrid Tripod Suction Bucket Foundations for Offshore Wind Towers in Sand

Koohyar Faizi[1], Asaad Faramarzi[2], Samir Dirar[3], David Chapman[4]

[1]PhD student, School of Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK, K.Faizi@pgr.bham.ac.uk

[2]Assistant Professor, School of Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK, A.Faramarzi@bham.ac.uk

[3]Associate Professor, School of Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK, S.M.O.H.Dirar@bham.ac.uk

[4]Professor, School of Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK, d.n.chapman@bham.ac.uk

Abstract: Existing tripod suction bucket foundations, utilised for offshore wind turbines, are required to resist significant lateral loads and overturning moments generated by wind and currents. This paper presents an innovative type of tripod bucket foundation, 'hybrid tripod bucket foundation', for foundations of offshore wind turbines, which has the ability to provide a larger overturning capacity compared with conventional tripod buckets. The proposed foundation consists of a conventional tripod bucket combined with three large circular mats attached to each bucket. A series of experiments were conducted on small-scale models of the proposed foundation subjected to overturning moment under 1g conditions in loose sand. Different circular mat diameter sizes with various bucket spacings were considered and the results were compared with conventional tripod bucket foundation. Finite element models of the proposed foundation were developed and validated using experimental results and were used to conduct a parametric study to understand the behaviour of the hybrid tripod bucket foundation. The results showed that there is a significant increase in overturning capacity provided by the novel foundation. The results of this work can significantly improve lowering the costs associated with installation of foundations to support offshore wind turbines.

Keywords: Overturning capacity; Hybrid tripod bucket foundations; Sand; Finite element models

1. Introduction

Large horizontal and overturning bearing capacities are generally the key design requirements for offshore shallow foundations [1].

Suction bucket foundations (monopod bucket), also known as a skirted shallow foundations [2], have recently been considered for offshore wind turbines (OWTs) as a cost effective alternative to conventional foundations [3]. As future generations of offshore wind turbines are likely to have taller towers and be located further away from the coast, the standard monopod foundations may become uneconomic and tripod suction buckets may be more suitable [4].

Tripod bucket foundations are a standard three-legged structure made of cylindrical bucket foundations. The central steel shaft of the tripod is attached to the turbine tower by tubular space frames. This type of foundation is a popular design due to the smaller diameter buckets, which reduces the probability of structural failure and easier installation, [5] and provides higher bearing capacity for the foundations of OWTs compared with single leg foundations [6, 7].

In case of single bucket foundation, as used in OWTs, the most unfavourable loading condition is large overturning moments due to its low embedment depth [8]. A large penetration to diameter ratio (>1) of the bucket typically has been recommended to obtain satisfactory overturning capacities [9]. Using large buckets is another way to increase capacities. However, as suction buckets are sensitive to structural buckling during the installation process due to the profile characteristics (thin-walled structures) [10, 11], installation of a very large thin wall bucket involves significant risks of buckling. A large diameter suction bucket therefore requires a significant number of stiffeners to prevent skirt buckling during installation. However, any additional stiffeners may adversely impact the installation process [12].

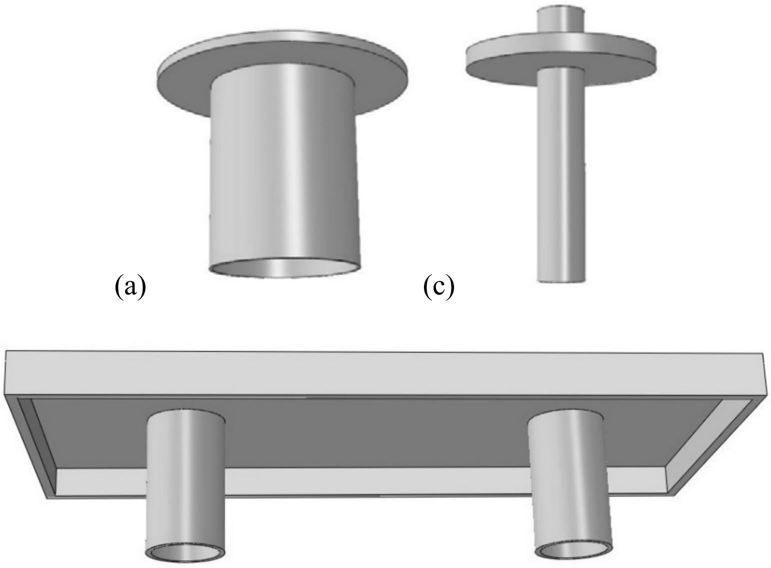
Apart from the shape, the load transfer mechanism from the foundation to the soil is the main difference between the mono and tripod bucket foundations [7]. The large overturning moment can be resisted by a combination of tension and compression on the windward and leeward legs in a tripod foundation, while a single bucket only transfers the loading moment by the individual bucket surface interfaces with surrounding soil [2, 13]. The installation process of the tripod bucket foundation into the seabed is similar to that of the single suction bucket foundation (monopod). After an initial penetration of the bucket into the seabed caused by self-weight, further penetration is achieved by pumping air and water out of the bucket [14-17].

The bearing capacity of the single suction bucket foundations has been extensively studied in different soil types [15, 18-20], whereas only a few studies have examined the behaviour of tripod suction bucket foundations under lateral loading [21-23]. Various bucket and soil parameters have a direct influence on the bearing capacity of the tripod bucket foundation, such as the ratio of the bucket spacing to the bucket diameter (*S/D)*, the embedment depth of the bucket (*L*), the soil–bucket friction angle (δ) and the unit weight (γ) of the soil [21, 24, 25].

Although the increased capacity of tripod buckets has been demonstrated by increasing the spacing of the buckets [22, 24], this will impose significant additional costs to the structure of the space frames, thereby reducing the cost-effectiveness of tripod foundations. This paper proposes a novel tripod foundation taking advantage of combining tripods with circular mats as additional supporting structural elements. Hereafter, this is referred to as a hybrid tripod bucket foundation. The hybrid tripod bucket foundation aims to provide additional horizontal and moment capacity by optimising the bucket spacing and consequently minimise the construction and installation costs associated with large diameter skirted foundations.

The hybrid foundation concept has been considered in past studies for OWTs, for example these can be a combination of single suction buckets (Fig. 1a), multiple suction buckets [26-28] (Fig. 1b) or mono-pile foundations (Fig. 1c) [29, 30] fitted on a mat foundation, in which the mat contributes to enhancing the load capacity. A hybrid single bucket foundation, which is a combination of a circular mat and a suction bucket, was shown to provide a higher bearing capacity compared to a conventional caisson in a study by [31]. However, the combination of a circular mat foundation and a conventional tripod bucket foundation to improve the overturning capacity has not been considered previously.

This study aimed to investigate the influence of including large mats to the tripod suction bucket in loose sand subjected to horizontal loading by means of numerical and experimental modelling.



(a) (c)

(b)

Fig. 1. Some proposed hybrid foundations concepts from previous research studies, (a) a modified suction bucket, (b) a skirted mat with suction buckets, (c) a hybrid mono-pile foundation.

2. Methodology

The proposed hybrid foundation consists of three single bucket foundations combined with three large circular mats attached to each bucket foundation. The general concept is shown in Fig. 2. In the conventional tripod bucket foundation, the bearing capacity is provided by three rigidly connected bucket foundations, while in this proposed hybrid foundation, the resistance is offered by a combination of the buckets and the circular mats. In the proposed hybrid foundation the circular mats are in complete contact with the soil surface providing greater resistance against the overturning moments.

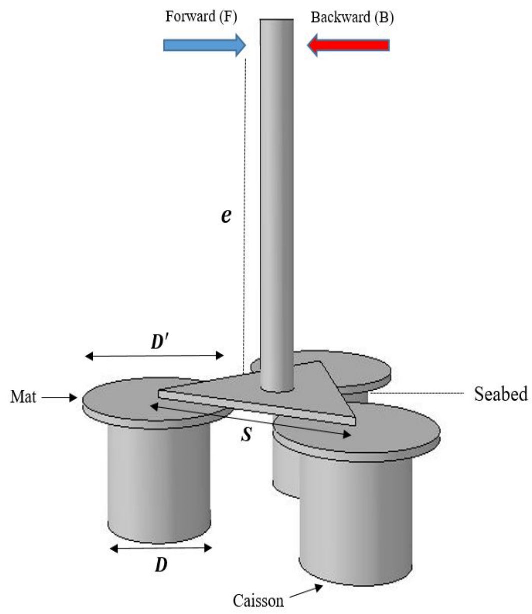


Fig. 2. Schematic of the hybrid three suction bucket and mat foundation. The key dimensions and loading condition are also shown

The experiments were conducted at small-scale under 1-g condition. Different bucket spacing (S) and loading directions (backward and forward) were evaluated on the basis of overturning resistance of the conventional and hybrid tripod bucket foundations. In particular, forward and backward titles are given to the models with respect to the loading direction, i.e. backward used where the loading direction is towards a single bucket of a tripod foundation and the other two buckets are being rotated out of the seabed (Fig. 2).

Numerical analyses were conducted of the experiments for both the conventional and hybrid tripod bucket models using the finite-element (FE) method software, ABAQUS. The results of the experiments have been used to develop and validate FE models of the proposed system in order to understand the behaviour and the mechanisms in which the proposed hybrid system in a tripod foundation contribute to resistance against overturning moment. The effect of the circular mat diameter was also investigated using the validated FE model on the overturning resistance of the hybrid tripod bucket foundation.

3. Experimental Procedure

3.1 Materials and model preparation

The prototype was scaled down to 1/100, and a bucket embedment depth ratio (L/D) of 1 and a skirt width to bucket diameter ratio (t/D) = 0.02, were considered. The distance between the buckets is expressed by the spacing ratio S/D, where S is the axial distance between the circular buckets and D is their diameter (Fig.1). Experiments were performed using various normalised spacings, S/D, ranging from 1.13 to 3.13.

The three conventional buckets with the external diameter (D) and embedment depth (L) of 75 mm were connected with an adjustable plate. The caisson specimens were fabricated from a smooth stainless steel tube with a wall thickness (t) of 1.2 mm. The adjustable mechanism consisted of an equilateral triangular plastic plate (200 mm long and 5 mm thick) with three linear holes in each angle. The three buckets were connected to the adjustable mechanism by screws. By adjusting the distance between the buckets, three different configurations could be created (more details are provided in section 5.2). Three circular mats with a diameter of 120 mm, made of plastic, were used to replace the conventional suction bucket caps and help to create the hybrid tripod foundation (Fig. 3).

Fig. 3. Hybrid foundation model used in the experiments, with $D' = 120\ mm$ and $S = 165\ mm$

The horizontal load was applied to an extension rod (tower with 230 mm tall) that was rigidly connected to the top of the centre of the base (triangular plate). Reinforcement bracing between the top cap and the tower in the prototype were omitted in the model for simplification. The circular mats and the towers made of plastic to reduce the effects of additional weight affecting the bearing capacity.

Tests were conducted in a strong cylindrical container. The container had an inner diameter of 550mm, with a thickness of 30mm and a height of 600mm, and was filled with dry Redhill 110 silica sand. The particle size distribution of the Redhill 110 silica sand is shown in Fig. 4. A 100 mm thick layer of gravel was placed uniformly at the base of the tank to provide a stiff layer underneath the sand layer. The sand layer was prepared using a pluviation method to achieve the targeted density (Dr =23%). The model buckets were installed in the dry sand by pushing rather than by suction. The pushing process was carried out very gently to avoid any major disruption to the soil density. Previous studies showed that the effect of the installation technique on the subsequent behaviour of a single bucket is negligible [32].

The models were installed into the soil at a rate of 0.1 mm/s until the lid made complete contact with the top of the sand. The tests were carried out under drained soil conditions to explore the drained response of the model foundation with a loading rate of 0.1mm/s. The properties of the Redhill 110 silica sand used in this study (Table 1) were obtained from the study conducted by Kelly et al.[33] and Villalobos et al. [34, 35].

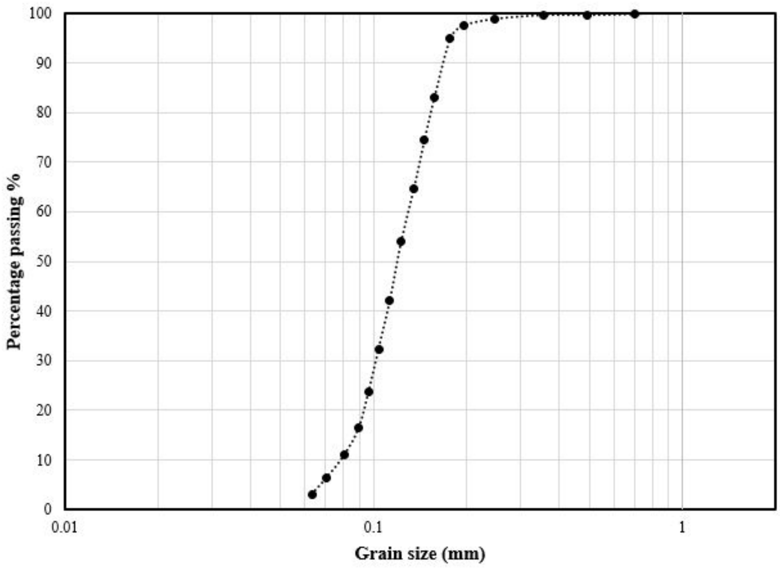


Fig. 4. Particle size distribution curves for Redhill 110

Table 1. Physical properties of sand used in the model tests, Redhill 110

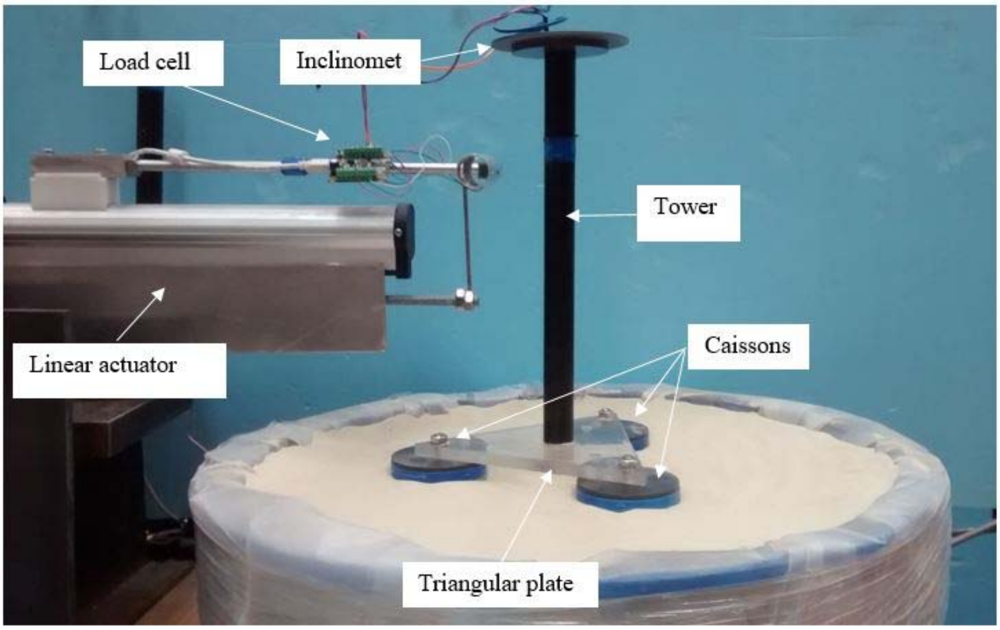
Properties	Value
$d_{10}, d_{30}, d_{50}, d_{60}$ (mm)	0.08, 0.10, 0.12, 0.13
Coefficients of uniformity, C_u and curvature C_c	1.63, 0.96
Specific gravity, G_s	2.65
Minimum dry density, γ_{min} (kN/m^3)	12.76
Maximum dry density, γ_{max} (kN/m^3)	16.80
Angle of friction of the soil, $\emptyset$	36º
Permeability (m/s)	3.8×10^{-4}

3.2 Test procedure

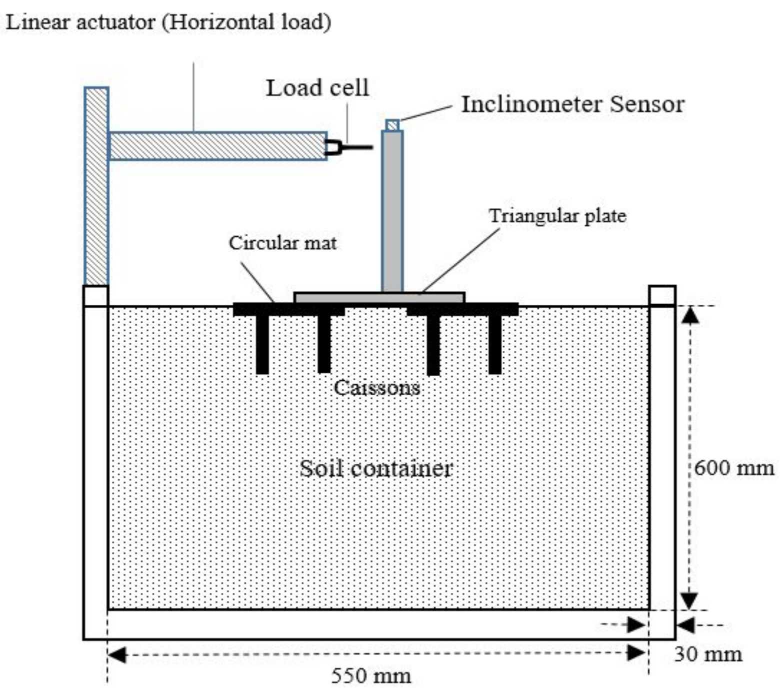
For all the models, to create a moment, M, a horizontal load H' was applied using an electric actuator at a certain height (230 mm) above the cap of the tripod bucket. An eccentricity ratio (i.e. $M/(H'D)$)) equal to 2.9 was used in this study, which corresponds to tall wind turbine towers (>100 m). A load cell was attached to the actuator to measure the applied force. The rotation of the foundation was recorded using an inclinometer sensor placed on the top of the tower (as shown in Fig. 5).

Fig. 5(b) shows the plan view of the experimental set up and the loading system. As illustrated, the model tripod foundations were placed in the middle of the model container. The model tests were carried out in the central part of the container to ensure minimal influence due to the wall boundary conditions.

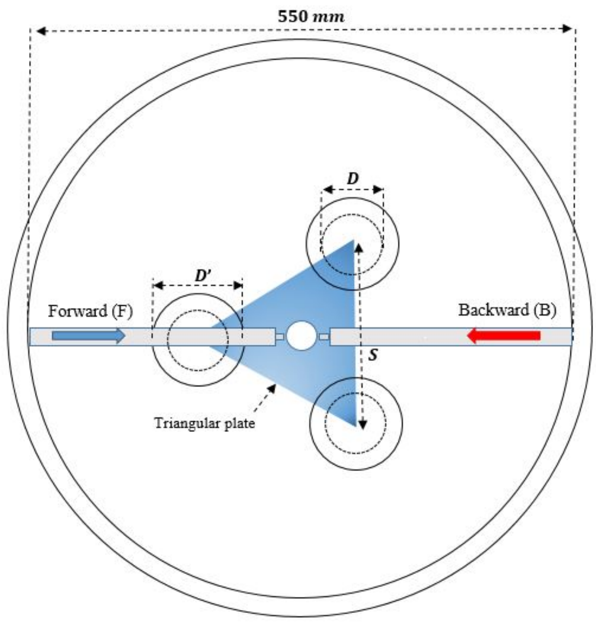
All the information related to the models and tests are summarised in Table 2; in this table the conventional tripod bucket foundations and the hybrid tripod bucket foundations are denoted C and H, respectively. The results from the experiments are presented in section 5, where they have been used to validate the results of the numerical models.



(a)



(b)



(c)

Fig. 5. Testing system with loading actuator and tripod model (a) overview of the experimental setup; (b) schematic of elevation view; (c) schematic of setup plan view

Table 2. Summary of the physical tests and numerical model analyses

Test ID	S (mm)	Forward (F)/ Backward (B) **	Caisson (D) and Circular mat (D') diameters (mm)	EXP/FEM***
C1*	95	F	D = 75	EXP/FEM
C2*	95	B	D = 75	EXP/FEM
C3*	130	F	D = 75	EXP/FEM
C4*	130	B	D = 75	EXP/FEM
C5*	165	F	D = 75	EXP/FEM
C6*	165	B	D = 75	EXP/FEM
C7	200	F	D = 75	FEM
C8	200	B	D = 75	FEM
C9	235	F	D = 75	FEM
C10	235	B	D = 75	FEM
H1*	130	F	D' =120	EXP/FEM
H2*	130	B	D' =120	EXP/FEM
H3*	165	F	D' =120	EXP/FEM
H4*	165	B	D' =120	EXP/FEM
H5	200	F	D' =120	FEM
H6	200	B	D' =120	FEM
H7	235	F	D' =120	FEM
H8	235	B	D' =120	FEM
H9	235	F	D' =120	FEM
H10	235	B	D' =120	FEM
H11	235	F	D' =142.5	FEM
H12	235	B	D' =142.5	FEM
H13	235	F	D' =180	FEM
H14	235	B	D' =180	FEM

*Reference tests
**F=Forward
B=Backward
*** EXP= Experiment
FEM= Finite element method

4. Numerical Simulation

To estimate the bearing capacity of the hybrid tripod bucket foundations in drained sandy soils, three-dimensional (3D) finite element (FE) models were developed using the commercial software ABAQUS; to reduce the computation time, only a half of the foundation and the ground were modelled taking advantage of the symmetry within the problem.

FE analysis was adopted to model the 3D geometry of the conventional and hybrid tripod bucket foundations, and the appropriate soil–foundation interaction. Figs. 6a and 6b show a schematic of the conventional and hybrid tripod bucket foundation problem in the FE model, respectively. To model the sand behaviour, a Drucker-Prager material model with assumption of soil in elastic-perfectly plastic behavior and follows an associated flow rule (dilatancy angle ψ equal to friction angle $\emptyset$) was used with material parameters of β =44.5 and d =135. Terms β and d represent parameters of the material model which can be calculated indirectly using parameters of the Mohr-Coulomb model derived from Ciampi [36].

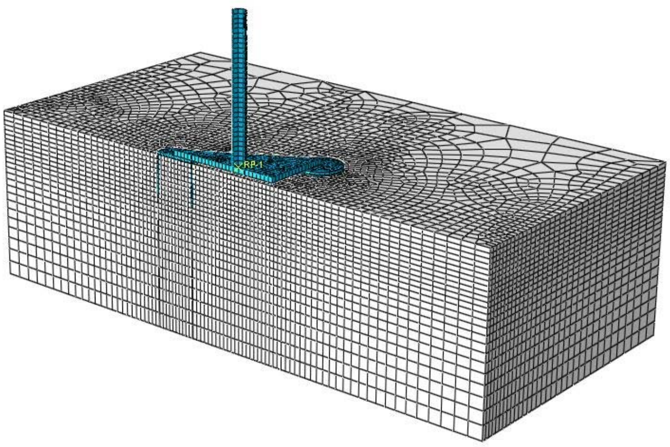
The 'Small Sliding' contact in ABAQUS was used to simulate the interaction between the soil and the buckets/mats. This type of interaction is used to simulate contact between two deformable bodies or a deformable body and a rigid body in 3D. The soil and the bucket were modelled using the C3D8R solid homogeneous elements available in the ABAQUS element library, which are 8-noded linear brick elements with reduced integration and hourglass control (an option for reduced-integration elements in ABAQUS/Standard). The interaction between the sand and the caissons was modeled by defining tangential and normal contact behavior in the FE model. Normal interaction between mat-soil was simulated by a "hard" contact. Allowed separation after contact was also used for interfaces of soil-caisson and mat-soil.

Fig. 6 shows a half model cutting through a diametrical plane of the tripod hybrid bucket foundation with $L/D = 1$. The mesh dimensions were varied depending on the bucket diameter and spacing. A relatively fine mesh was used around the bucket and the mats, and becoming coarser further away from the bucket. In the FE analyses, the foundations were modelled as "wished in place", assuming that installation effects had a negligible impact on the bearing capacity. The initial soil condition prior to loading of the model foundation was generated considering a lateral earth pressure coefficient $K_0 = 1 - \sin\phi$ [37].

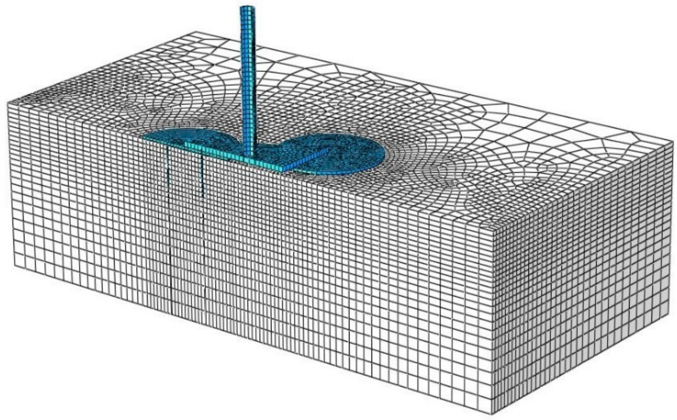
To simulate the overturning behaviour of the tripod foundation, a load-controlled FE model was created. A 'Contact pair' interface was used to capture the nonlinear behaviour of the soil-bucket interaction. The bucket outer surface was chosen as the 'master surface' and the soil surface in contact with the skirt of the bucket as the 'slave surface'. The frictional force between these surfaces is dependent on a coefficient of friction ?? [38]. In the numerical simulations presented here the friction coefficient was calculated using $\tan(\delta)$, where δ is interface friction angle and assumed to be $2/3\phi$ [39]. The mats and the buckets were considered as linear elastic materials (E=200 GPa) [40]. Elasticity modulus of sand is also calculated based on the formula proposed by Seed and Idriss [41] and considered approximately 8000 kPa for the sand with relative density of 23%.

$$G_{max} = 765.8(Dr)^{2/3} P_a (\frac{\sigma'_m}{P_a})^{0.5}$$

Where σ'_m is mean principal effective stress, and P_a is the atmospheric pressure in the same units as σ'_m.



(a)



(b)

Fig. 6. Finite element model of the a) conventional and b) hybrid tripod bucket foundations used to analyse the laterally loading behaviour

Based on the results of the FE analyses, the moment-rotation curves ($M - \theta$) of the foundations were constructed to obtain the ultimate overturning capacity. The curves are inherently nonlinear being controlled by the "elastic" stiffness at small rotations and the moment capacity of the foundation at larger rotations. The ultimate moment capacity of the foundation has been defined as the moment corresponding to the yield point. To define the yield point, the method described by Villalobos [32] was used. In this method, straight lines were fitted to the initial stiff elastic section and the plastic section, as shown in Fig. 7. A horizontal line is then drawn from the intersection point of the two fitted lines to the load-rotation angle curve. This line will be extended until it cuts the moment-rotation curve, the intersection between the horizontal line and the curve was defined as the ultimate moment, denoted as M_u.

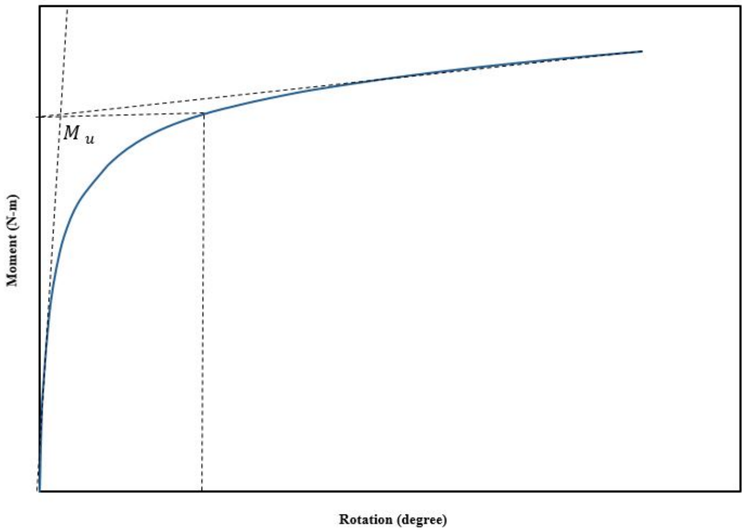


Fig. 7. Tangent intersection method for determining the yield point and hence the ultimate bearing capacity of the foundation (M_u)

5. Results and Analysis

The experiments using the convention foundations in the C1-C6 series (as listed in Table 2) were conducted under identical test conditions, including soil density, bucket aspect ratio (L/D=1) and type of loading, although bucket spacing (S) was varied from 90 mm to 165mm (see Table 2). The experiments H1-H4 were carried out on the hybrid tripod bucket foundations with circular mats of diameter 1.6 times larger than the bucket diameter (D'=120 mm) in the same sequence and under the same experimental conditions as the C1-C6 experiments. The remaining models in Table 2 (i.e. C7-C10, and H5-H14) refer to FE models that were created to identify the effect of different spacing and different mat size beyond those used in the experiments. All the experiments assigned odd numbers within the test IDs (e.g. C1, C3, H1, H3) are for models subjected to a forward loading direction, while the even numbers (e.g. C2, C4, H2, H4) are for the models loaded in the backward direction.

The tripod foundation resists the overturning moment with the reaction generated in the windward and leeward bucket foundations acting in tension and compression, respectively [42, 43]. Based on the deformation mechanisms, observed in Fig. 8, the overturning moment is resisted by a combination of tension and compression on the windward and leeward in both conventional and hybrid tripod foundations.

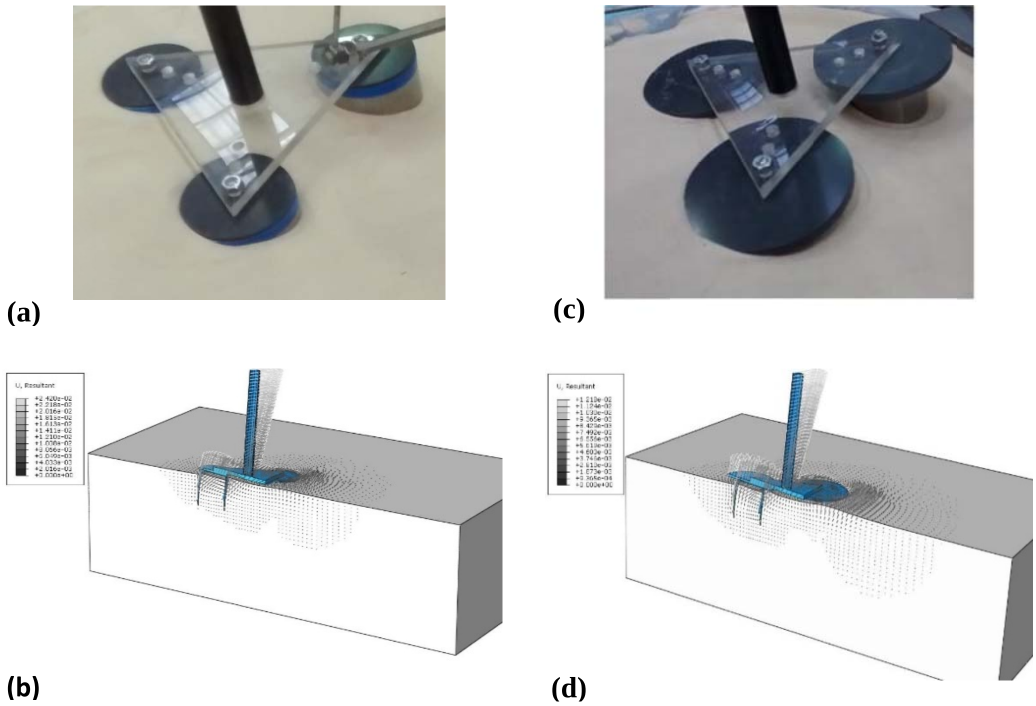


Fig. 8. Failure mechanism due to an overturning moment in the forward direction, (a) EXP conventional foundation, (b) FEM conventional foundation, (c) EXP hybrid foundation, (d) FEM hybrid foundation

5.1 The effect of bucket spacing and loading direction on the capacity of conventional foundation (Finite Element and Experimental Modelling)

Initially, the impact of the bucket spacing on the overturning moment capacity of the conventional and hybrid tripod bucket foundations are examined. The experiments were performed by applying a monotonic horizontal load at the top of the tower, with an eccentricity from the top of the foundations (e = 230 mm). This load was applied until failure was reached. The numerical and experimental results have been compared based on the direction of the load and bucket spacing of both the conventional and hybrid tripod foundations. The comparison demonstrated that the numerical simulations provide very close results (<10% average error) to the experimental data (Figs. 9-13). As can be seen in Figures 9-13, the bearing capacity of the conventional tripod due to an overturning moment is higher when the foundations are subjected to the backward loading direction, i.e. the foundation with S=95 mm maintained an almost 18% higher capacity under backward loading compared with the experiments loaded in the forward direction (Fig. 9).

The horizontal resistance of a tripod depends on the loading direction due to the asymmetry of the foundations [44]. Previous studies have revealed that the capacity of tripod systems is primarily governed by the pull-out capacity of the windward bucket [43, 44]. It should also be noted, however, that the capacity of single suction buckets under pull-out is lower than in compression [45]. Hence, the number of windward buckets in the tripod foundation could control the overall capacity. Accordingly, the two windward buckets provide a higher capacity compared with the scenario where two buckets are in compression. Therefore, the most critical loading condition for tripods is when the horizontal loading is imposed in the forward direction (F), i.e. where one bucket of the tripod resists pull-out load, as shown in Fig. 8. This observation for conventional tripod foundations is similar to that reported by Kim et al. [44].

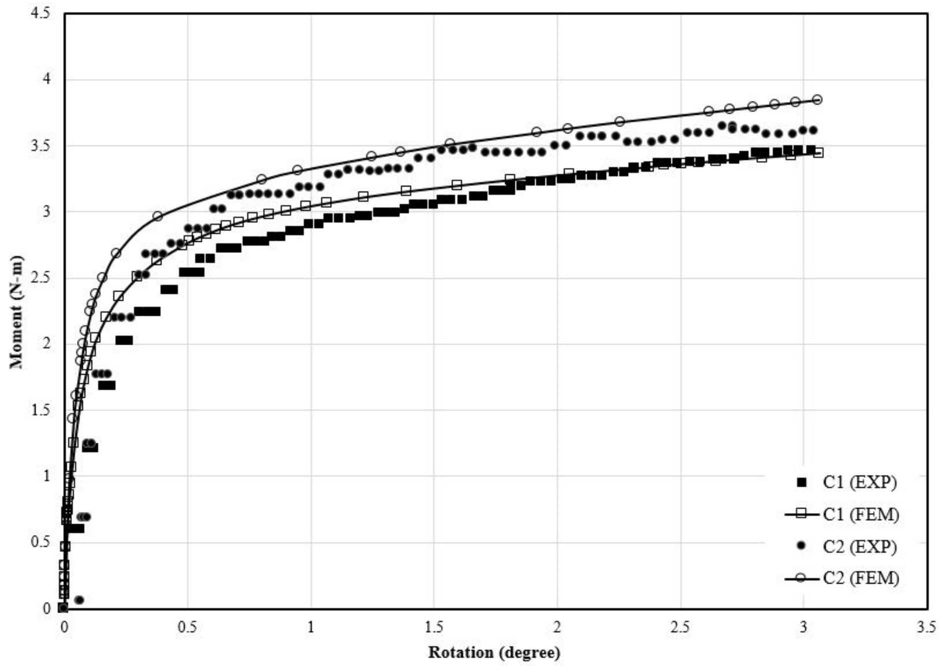


Fig. 9. Moment-rotation plot for the conventional foundation system with a spacing dimension of 95 mm (EXP and FEM)

5.2 The effect of the hybrid system on the capacity improvement of tripod bucket foundations

The impact of using a hybrid system on the overturning capacity of a tripod bucket foundation is presented by means of a series of laboratory tests and numerical modelling. Comparing Figs. 10 and 11, it is clear that there is a significant increase in the overturning capacity provided by the hybrid tripod foundation. The test results show that the overturning capacity of the tripod bucket foundation, under the forward loading direction, was increased by approximately 47% and 45%, for bucket spacings of 130 mm and 165 mm, respectively (Figs. 10 and 11). For the same spacing, the ultimate overturning bearing capacity increased by approximately 43% and 38%, for the models under the backward loading direction.

Based on the results, it is evident that attaching circular mats can provide additional resistance compared to the original tripod foundation. The contact surfaces between the circular mats and the seabed and the development of bearing stress beneath the mats provides a larger restoring moment to withstand the rotation. Moreover, the circular mats induce additional vertical stresses in the soil beneath the foundation, thereby helping to increase the shear resistance of the soil and further resisting rotation.

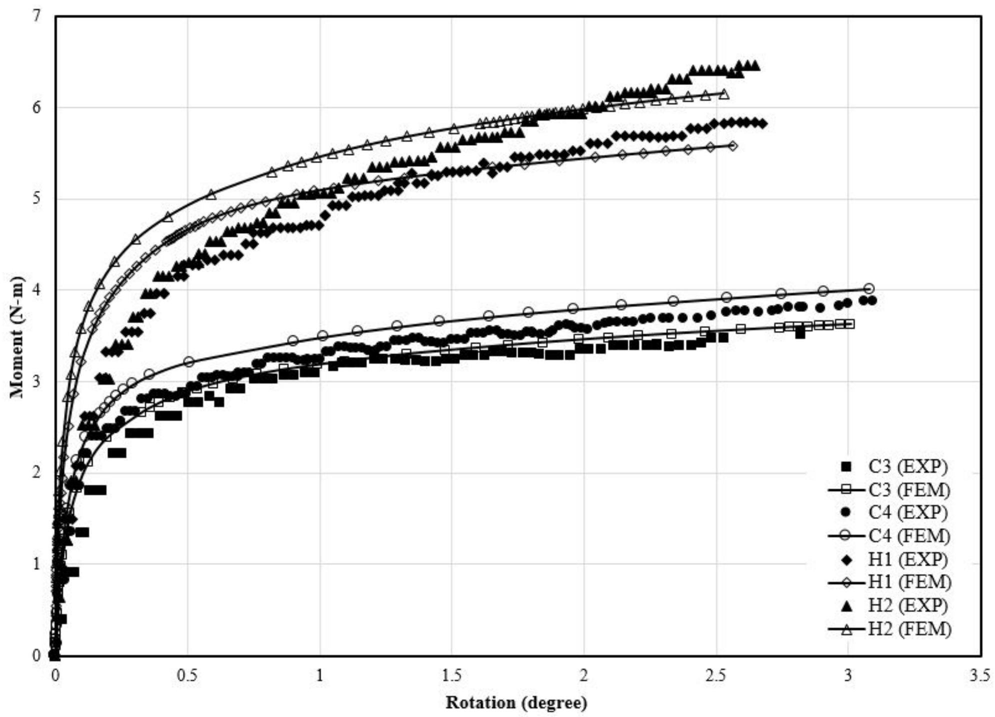


Fig. 10. Moment-rotation plot for conventional and hybrid foundation systems with a bucket spacing of 130 mm (EXP and FEM)

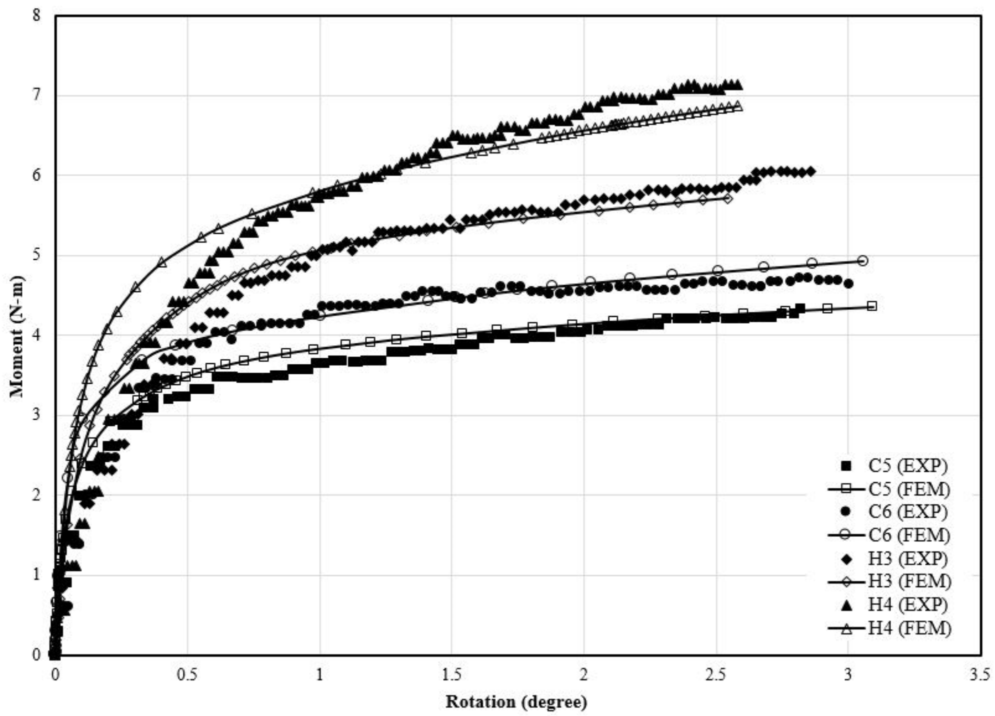


Fig. 11. Moment-rotation plot for conventional and hybrid foundation systems with a bucket spacing of 165 mm (EXP and FEM)

5.3 The effect of bucket spacing size and mat diameter on the improvement of capacity of hybrid system (FEM)

The results from the three-dimensional finite element analyses (FEM) for the two tripod foundation models (with and without circular mats) are presented in Figs. 12-14 in terms of the moment and rotation with varying circular mat diameters and bucket spacing.

A series of numerical models (C7, C8, H5 and H6) were performed in which the mat diameter was kept the same as those used in the previous models ($D' = 120\ mm$) while the bucket spacing was changed to $S = 200$ mm in order to evaluate the effect of higher spacing on the overturning moment resistance of the conventional and hybrid tripod foundations.

The moment-rotation ($M - \theta$) curves for the conventional and hybrid tripod models with diameter $D' = 120\ mm$ and spacing $S = 200$ mm installed in loose sand with relative density of Dr =23% are presented in Fig. 12. The results from the FEM indicated that the mats used in the proposed foundation have a significant impact on improving the overturning capacity. The mat aids the resisting force against the external load by extending the contact area. The results also showed that the overturning capacity of the tripod bucket foundation was increased by approximately 53%, and 47% for the hybrid bucket foundation, under F and B load conditions.

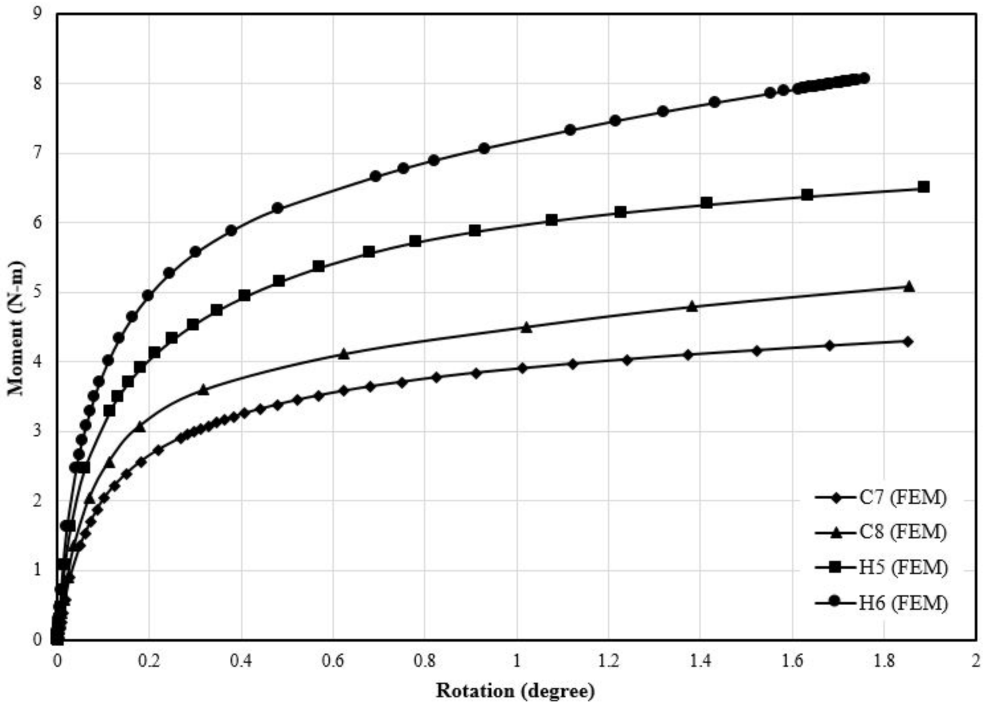


Fig. 12. Comparison of the moment-rotation plots for conventional and hybrid foundations with a bucket spacing of 200 mm (FEM)

A FEM was also developed to investigate the effects of the mat diameter to improve the capacity of the hybrid tripod bucket foundations. The models C9, C10, H7, H8, H11, H12, H13 and H14 were selected with mat sizes both smaller and larger than those used in the reference models ($D' = 120\ mm$). When $\frac{S}{D}$ equals 3.13, the ultimate overturning bearing capacity increased by approximately 18%, 36% and 80% for hybrid tripod models under a backward loading system with mat diameter ratios ($\frac{D'}{D}$) equal to 1.3, 1.9 and 2.4, respectively (see Fig. 13). However, it is worth noting that combining circular mats with the buckets results in a slightly better overturning capacity under forward loading compared with backward loading. When $\frac{S}{D}$ equals 3.13, the ultimate overturning capacity increased by approximately 25%, 50%, and 100% for hybrid tripod models with mat diameter ratios ($\frac{D'}{D}$) of approximately 1.3, 1.9, and 2.4, respectively (Fig.14). Given the most unstable loading scenario is when the horizontal loading is imposed in the forward direction (F) [44], two circular mats attached to the two buckets at the leeward side provides higher resistance against overturning moments. This resistance corresponds to the larger contact surface areas between the circular mats, attached to the leeward buckets, and the seabed during the loading. In the forward direction, only the mat attached to the bucket at the leeward resists the horizontal load because the two other mats on the windward side are lifted from the soil surface when the whole foundation is rotating.

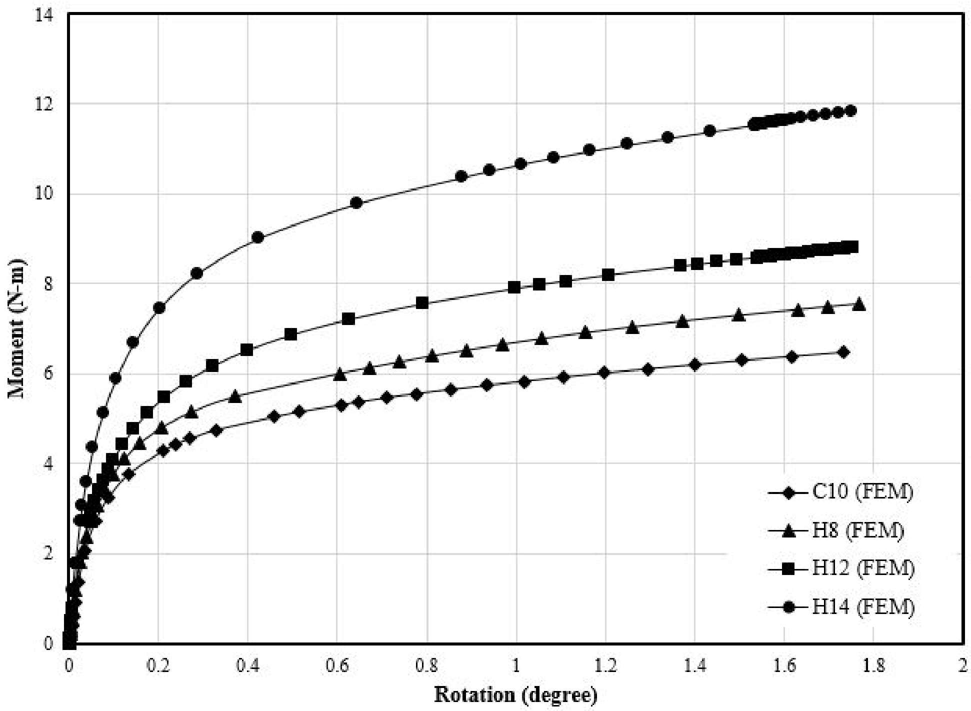


Fig. 13. Comparison of the moment-rotation plots for conventional and hybrid foundations with a bucket spacing of 235 mm and varying circular mat sizes, due to a backward loading direction (FEM)

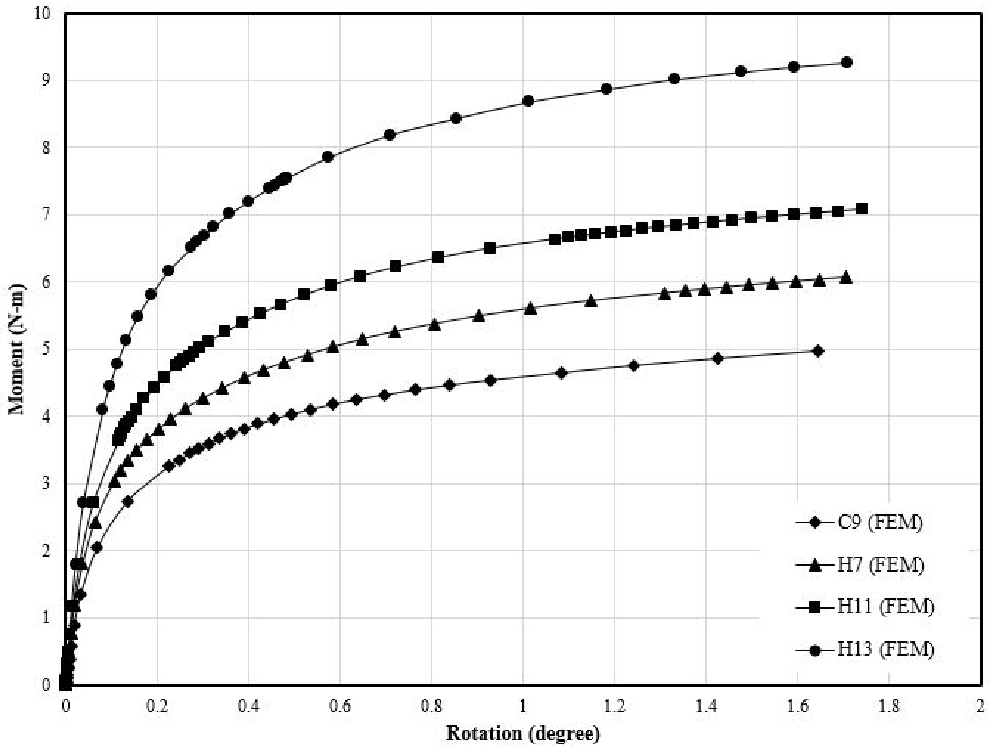


Fig. 14. Comparison of the moment-rotation plots for conventional and hybrid foundations with a bucket spacing of 235 mm and varying circular mat sizes, due to a forward loading direction (FEM)

Fig. 15 illustrates the variation in M_u with the normalized footing spacing S/D for the conventional and hybrid tripod foundations under the forward and backward loading directions. The hybrid models are enhanced with the circular mat diameter of 120 mm. As expected, M_u increases significantly as S/D increases, which is due to the increase in the lever arm length with an increase in S/D. The bearing capacity of tripod bucket foundations is influenced by the spacing between the buckets because of their mutual interaction [21].

In general, the interactions in a hybrid tripod bucket foundation can be classified into two categories: the interaction between buckets (bucket–soil–bucket) and the interaction between mat and bucket (mat–soil–bucket). A close spacing between individual caissons in a tripod caisson results in overlapping stress zones.

Due to the larger surface area between the soil and the circular mats in the hybrid foundation, relatively large stress zones occur along the contact interface when the foundation system is subjected to an overturning moment. For hybrid tripod foundations, the overlap of the stress zones are even larger due to the presence of the mats. The intensity of the stresses will be affected by the centre-to-centre spacing of the buckets (Fig. 16). In ABAQUS, PEMAG refers to the plastic strain magnitude.

Therefore, it can be concluded that the divergences in Fig. 15 are due to the different overlapping stress zones, which can influence the capacity of the foundations.

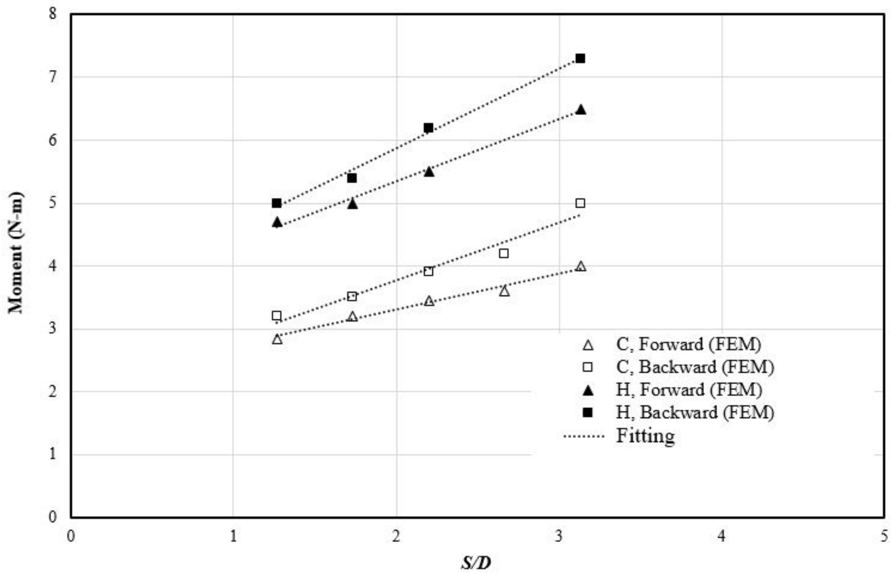


Fig. 15. Variation of M_u with S/D for loading directions F and B (FEM)

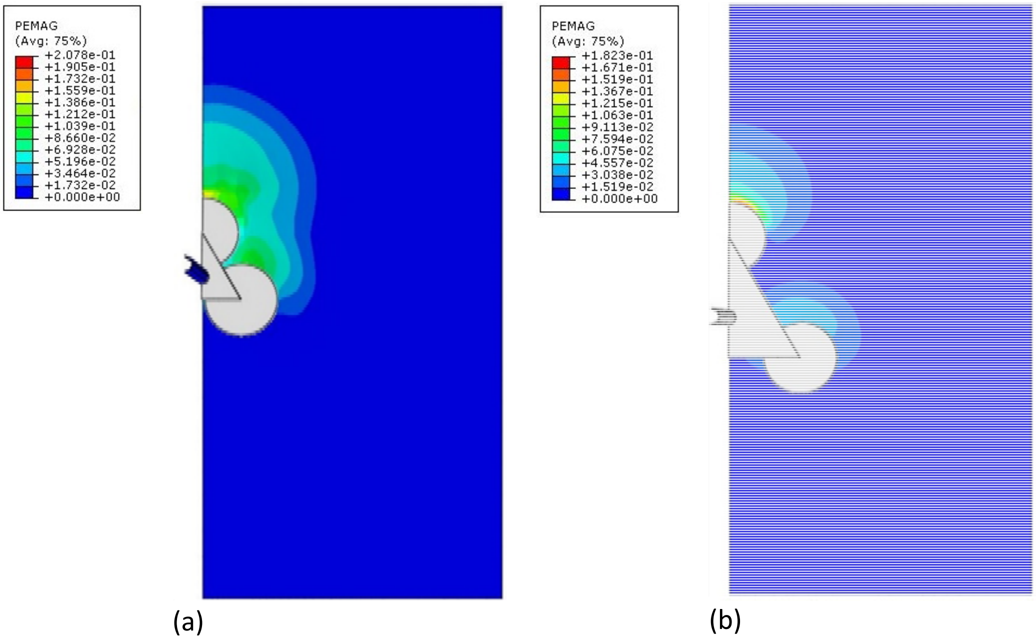


Fig. 16. Plan view of the shear zone formation in hybrid tripod foundations from the FEM results, (a) H2, (b) H10.

5.4 Large-Scale Numerical Modelling

5.4.1 Validation of finite element modelling against large-scale field trials

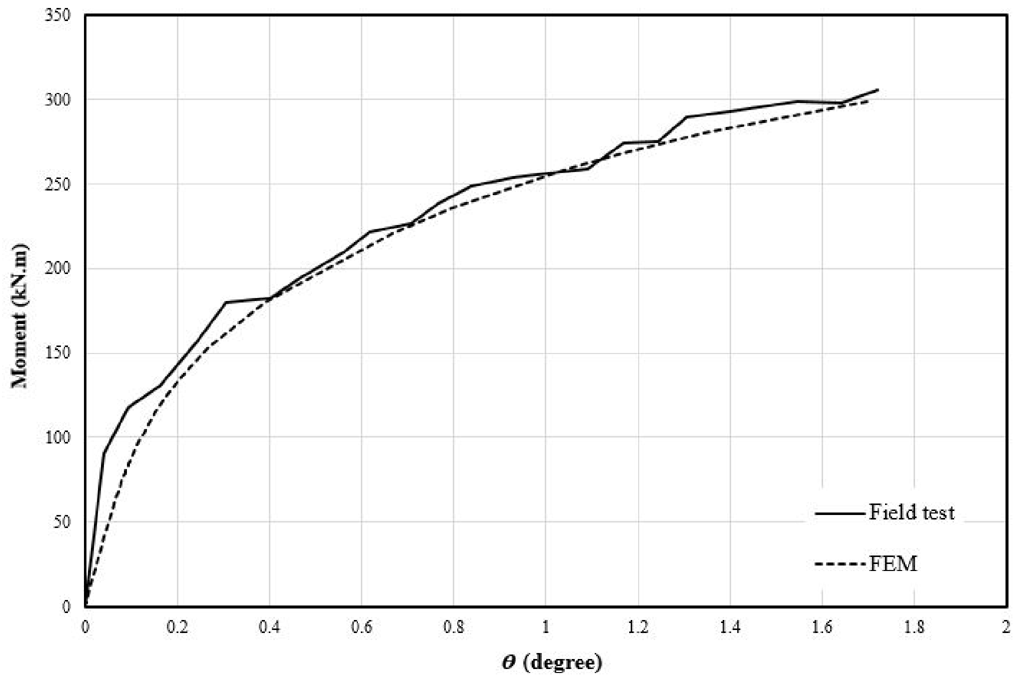
To understand the large-scale behaviour of the proposed tripod foundation, a series of FE models were developed to study their behaviour in field conditions. Initially, validation against two large-scale field trials on single suction caisson foundations available from literature were carried out to ensure the accuracy of our FE modelling. The FE models were then developed to predict the overturning capacity of the conventional and hybrid tripod foundations.

Of the available data in literature, two field tests were chosen to validate our FE models. The field tests were originally reported by Houlsby and Byrne [46] and Houlsby et al. [4] at the Sandy Haven and Frederikshavn test sites, respectively. The parameters used in the FEM simulations are given in Table 3. Both sites comprised of predominantly sandy soil. In the FE, the loading was simulated as drained to replicate the site condition.

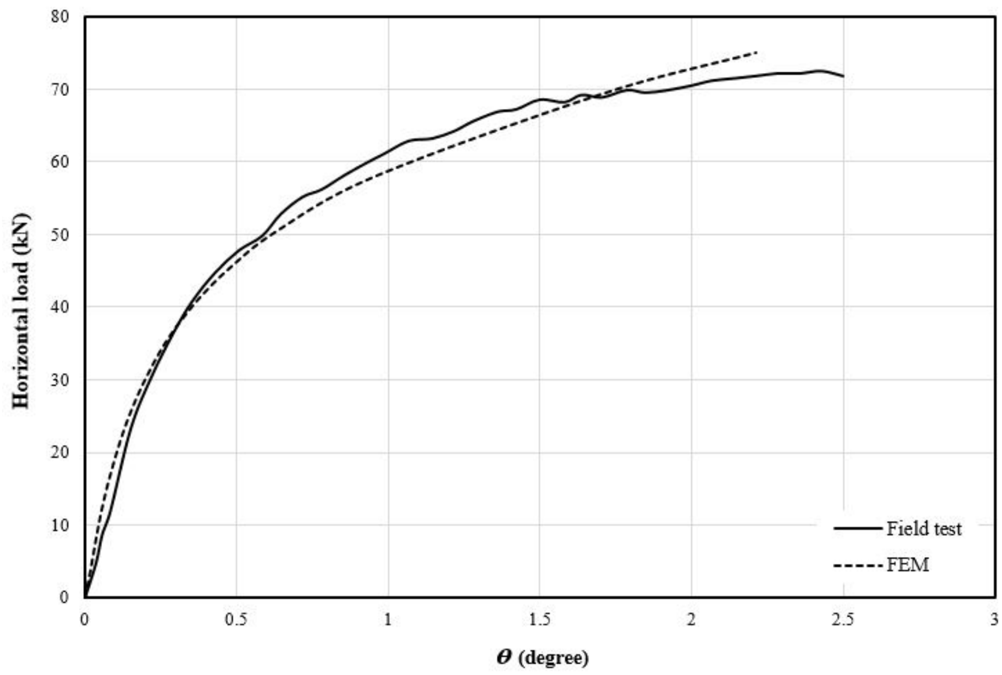
The suction caisson at the Sandy Haven site had a diameter of 4 m and a skirt length of 2.5 m, and it was installed in medium to dense sand. The foundation was subjected to a constant vertical load of 100 kN. The horizontal load test was then conducted at a loading point height of 14.5 m above the ground surface. The suction caisson tested at the Frederikshavn site, which had a diameter of 2 m and a skirt length of 2 m, was installed in dense sand. The foundation was subjected to horizontal loading at a height of 17.4 m above the ground surface under a constant vertical load of 37.3 kN. Figures 17a, and 17b show that load-displacement curves obtained from the FE analysis agreed well with those measured in the field tests and the centrifuge test. In the numerical simulations presented here the friction coefficient was calculated using $\tan(\delta)$, where δ is interface friction angle and assumed with the well-known assumption of δ=2/3ϕ [47]. The elastic modulus of the sands (E) is estimated based on the shear modulus G proposed by Seed and Idriss [41]. An average penetration depth was considered for estimation of equivalent modulus of elasticity. The modulus of elasticity(E), 210GPa and Poisson'sratio (ν), 0.3 were used as the steel properties [48].

TABLE 3. Detailed reference studies for validation of FEM modelling

Case study	Diameter (D)	Length (L)	Load eccentricity (e)	Aspect ratio (L/D)	Effective unit weight (γ')	Internal friction angle ($\emptyset$)
Frederikshavn [46]	2m	2m	17.4m	1	9	37-38
Sandy Haven [4]	4m	2.5m	14.5m	0.625	8.5	34



(a)



(b)

Fig. 17. Comparison of the numerical modelling and the field test results a) Frederikshavn, b) Sandy haven

5.4.2 FE modelling of large-scale hybrid tripod foundation

The validated FE model was subsequently used to predict the overturning capacity of a hypothetical full-size tripod foundation ($L/D = 1$), with three caissons of diameter 2 m, circular mats of diameter 1.9 times larger than the bucket diameter (D'=3.8 m) and spacing $S = 6.3$ m under a constant vertical load of 37.3 kN. The soil parameters and loading condition were adopted from Houlsby et al. [49]. Conventional and hybrid tripod foundations were modelled and the improvement in overturning moment under forward and backward loading conditions were recorded. Assume the maximum allowable tilting angle of the foundation must be smaller than 0.25 degree [50, 51]. Accordingly, for the given foundations the results are presented in terms of maximum allowable tile at foundation head (Fig. 18).

Based on the results from numerical analysis, the allowable overturning bearing capacity for the foundation with mat diameter ratios ($\frac{D'}{D}$) equal to 1.9, increased by approximately 27%, and 30% under a forward and backward loading systems, respectively (see Fig. 18).

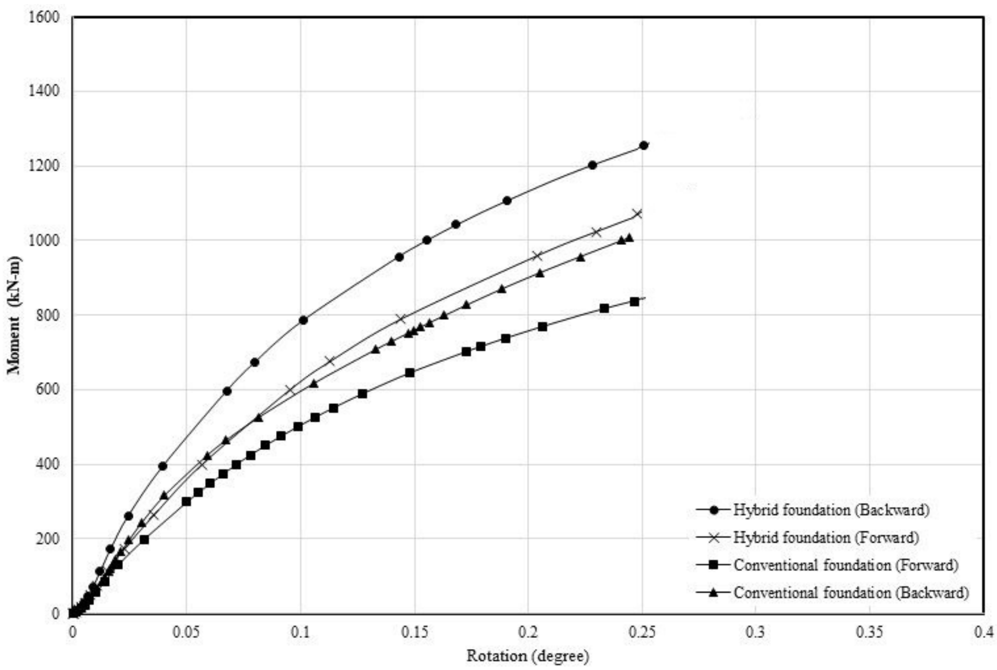


Fig. 18. Comparison of the moment-rotation plots for the conventional and hybrid foundations with a bucket spacing of 6.3 m and circular mat size of 3.8 m, due to a forward and backward loading direction (FEM)

It is clear from the experiments and the FEM studies that there are benefits of using circular mats in combination with buckets to enhance the overall capacity of tripod suction bucket foundations. Making an effort to reduce the high costs associated with manufacturing and installing of a conventional tripod foundation (with large diameter) at large spacing, the hybrid foundation can provide cost effective operation for offshore wind turbines.

Since the main goal of this paper was to evaluate the bearing capacity improvement of the proposed foundation, the structural aspects were beyond the scope of this study and were not evaluated; however, the analysis must account for the structural behaviour of the proposed foundation in the future design.

In the present study, drained conditions have been assumed for the experiments, however the models should also be examined under partially drained or undrained conditions. Tripod bucket foundations may be installed in a variety of soils, therefore the effectiveness of mats for tripod bucket foundations installed in different soil types, with different sand density, should also be investigated. Further studies are also necessary in order to investigate the behaviour of the hybrid tripod bucket foundations under combined loads.

6. Conclusions

In this study a novel hybrid tripod bucket foundation has been proposed with the intention of improving the overturning capacity of bucket foundations typically designed for offshore wind turbines. The behaviour of conventional and hybrid tripod bucket foundations subjected to an overturning moment with different bucket spacings and circular mat sizes has been investigated using 1g experimental studies and three-dimensional nonlinear FEM analyses in loose dry sand (drained condition).

The results obtained from the experimental and numerical studies were compared to validate the FEM and to assess the suitability and possible benefits of using hybrid tripod bucket foundations. Based on the results, the following key conclusions can be drawn:

- Tripod foundations combined with three circular mats provides considerably higher overturning capacity compare with a conventional tripod foundation (between 25–100% depending on the diameter of the circular mats and the spacing of the buckets).
- The overturning capacity of the conventional and the hybrid tripod bucket foundations is influenced by the loading direction, where higher capacity is usually achieved under backward loading, i.e. where the loading direction is towards a single bucket of a tripod foundation and the other two buckets are being rotated out of the seabed.
- The overturning capacity of the conventional and the hybrid tripod bucket foundations depends greatly on the centre-to-centre distance between the buckets and the direction of the load. In general, the overturning capacity increases as the bucket spacing increases.

Reference:

1. Randolph, M., et al. *Challenges of offshore geotechnical engineering*. in *Proceedings of the international conference on soil mechanics and geotechnical engineering*. 2005. AA Balkema Publishers.
2. Byrne, B., et al., *Suction caisson foundations for offshore wind turbines.* Wind Engineering, 2002. **26**(3): p. 145-155.
3. Cox, J.A. and S.J.P.o.t.I.o.C.E.G.E. Bhattacharya, *Serviceability of suction caisson founded offshore structures.* 2016. **170**(3): p. 273-284.

4. Houlsby, G.T., L.B. Ibsen, and B.W. Byrne, *Suction caissons for wind turbines.* Frontiers in Offshore Geotechnics: ISFOG, Perth, WA, Australia, 2005: p. 75-93.
5. Cotter, O., *Installation of suction caisson foundations for offshore renewable energy structures*. 2010, Oxford University.
6. Veritas, D.N., *Design of Offshore Wind Turbine Structure.* Offshore Standard DNV-OS-J101, 2004.
7. Kim, S.-R. and M. Oh, *Group effect on bearing capacities of tripod bucket foundations in undrained clay.* Ocean Engineering, 2014. **79**: p. 1-9.
8. Villalobos, F.A., G.T. Houlsby, and B.W. Byrne. *Suction caisson foundations for offshore wind turbines*. in *Proc. 5th Chilean Conference of Geotechnics (Congreso Chileno de Geotecnia), Santiago*. 2004.
9. Sukumaran, B., et al., *Efficient finite element techniques for limit analysis of suction caissons under lateral loads.* Computers and Geotechnics, 1999. **24**(2): p. 89-107.
10. Bakmar, C.L., et al. *The Monopod Bucket Foundation: recent experiences and challenges ahead*. in *The European Offshore Wind Conference & Exhibition*. 2009. European Offshore Wind Conference 2009.
11. Welschen, Y., *Suction bucket buckling: Buckling behaviour of suction buckets during installation in layered soils.* 2015.
12. Bienen, B., et al., *Numerical modelling of a hybrid skirted foundation under combined loading.* Computers and Geotechnics, 2012. **45**: p. 127-139.
13. CIVILE, C.D.L.I.I., *Behaviour of Monopod Bucket Foundations Under Horizontal Load in Dense Sand.* 2011.
14. Harireche, O., M. Mehravar, and A.M. Alani, *Soil conditions and bounds to suction during the installation of caisson foundations in sand.* Ocean Engineering, 2014. **88**: p. 164-173.
15. Mehravar, M., O. Harireche, and A. Faramarzi, *Evaluation of undrained failure envelopes of caisson foundations under combined loading.* Applied Ocean Research, 2016. **59**: p. 129-137.
16. Faramarzi, A., et al., *MODELLING THE SEEPAGE FLOW DURING CAISSON INSTALLATION IN A NATURAL SEABED.* Proceedings of the 24th UK Conference of the Association for Computational Mechanics in Engineering, 2016(Cardiff University, Cardiff.): p. 150-153.
17. Houlsby, G. and B. Byrne, *Calculation procedures for installation of suction caissons.* Report No. OUEL2268/04, University of Oxford, 2004.
18. Achmus, M., C. Akdag, and K. Thieken, *Load-bearing behavior of suction bucket foundations in sand.* Applied Ocean Research, 2013. **43**: p. 157-165.
19. Kim, S.R., *Evaluation of vertical and horizontal bearing capacities of bucket foundations in clay.* Ocean Engineering, 2012. **52**: p. 75-82.
20. Zhu, B., et al., *Deflection-based bearing capacity of suction caisson foundations of offshore wind turbines.* Journal of Geotechnical and Geoenvironmental Engineering, 2014. **140**(5): p. 04014013.
21. Tran, N.X. and S.-R. Kim, *Evaluation of horizontal and moment bearing capacities of tripod bucket foundations in sand.* Ocean Engineering, 2017. **140**: p. 209-221.
22. Kim, S.-R., *Evaluation of combined horizontal-moment bearing capacities of tripod bucket foundations in undrained clay.* Ocean Engineering, 2014. **85**: p. 100-109.
23. Gourvenec, S. and K. Jensen, *Effect of embedment and spacing of cojoined skirted foundation systems on undrained limit states under general loading.* International Journal of Geomechanics, 2009. **9**(6): p. 267-279.

24. Stergiou, T., D. Terzis, and K. Georgiadis, *Undrained bearing capacity of tripod skirted foundations under eccentric loading.* geotechnik, 2015. **38**(1): p. 17-27.
25. Kim, D.-J., et al. *Numerical Analysis of Cluster and Monopod Suction Bucket Foundation*. in *ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering*. 2013. American Society of Mechanical Engineers.
26. Kim, J.H., et al., *Bearing capacity of hybrid suction foundation on sand with loading direction via centrifuge model test.* Japanese Geotechnical Society Special Publication, 2016. **2**(37): p. 1339-1342.
27. Gaudin, C., et al. *Centrifuge experiments of a hybrid foundation under combined loading*. in *The Twenty-first International Offshore and Polar Engineering Conference*. 2011. International Society of Offshore and Polar Engineers.
28. Fu, D., et al., *Undrained capacity of a hybrid subsea skirted mat with caissons under combined loading.* Canadian Geotechnical Journal, 2014. **51**(8): p. 934-949.
29. Wang, X., et al., *Lateral bearing capacity of hybrid monopile-friction wheel foundation for offshore wind turbines by centrifuge modelling.* Ocean Engineering, 2018. **148**: p. 182-192.
30. Arshi, H. and K. Stone. *Lateral Resistance of Hybrid Monopile-Footing Foundations In Cohesionless Soils For Offshore Wind Turbines*. in *Offshore Site Investigation and Geotechnics: Integrated Technologies-Present and Future*. 2012. Society of Underwater Technology.
31. Wang, X., et al., *A review on recent advancements of substructures for offshore wind turbines.* Energy Conversion and Management, 2018. **158**: p. 103-119.
32. Villalobos J, F., *Model testing of foundations for offshore wind turbines*. 2006, University of Oxford.
33. Kelly, R., et al. *Tensile loading of model caisson foundations for structures on sand*. in *The Fourteenth International Offshore and Polar Engineering Conference*. 2004. International Society of Offshore and Polar Engineers.
34. Villalobos, F.A., B.W. Byrne, and G.T. Houlsby. *Moment loading of caissons installed in saturated sand*. in *Proceedings of international symposium on frontiers in Geotechnics, ISFOG. University of Western*. 2005.
35. Villalobos Jara, F.A., *Model testing of foundations for offshore wind turbines*. 2006, University of Oxford.
36. Ciampi, V., *MA Crisfield, Non-linear Finite Element Analysis of Solids and Structures.* Meccanica, 1997. **32**(6): p. 586-587.
37. Jaky, I., *The coefficient of earth pressure at rest.* Journal Soc. of Hungarian Architects and Engineers, 1944: p. 355-358.
38. Abdel-Rahman, K. and M. Achmus. *Behavior of foundation piles for offshore wind energy plants under axial cyclic loading*. in *Proceedings of Simulia Customer Conference*. 2011.
39. Ahmed, S.S., B. Hawlader, and K. Roy. *Finite Element Modeling of Large Diameter Monopiles in Dense Sand for Offshore Wind Turbine Foundations*. in *ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering*. 2015. American Society of Mechanical Engineers.
40. Abdelkader, A.M.R., *Investigation of Hybrid Foundation System for Offshore Wind Turbine.* 2015.
41. Seed, H.B.a.I., I.M. , *Soil moduli and damping factors for dynamic response analysis.* Report No. UCB/EERC-70/10. University of California, Berkeley, 1970.

42. Byrne, B. and G. Houlsby, *Foundations for offshore wind turbines.* Philosophical Transactions: Mathematical, Physical and Engineering Sciences, 2003: p. 2909-2930.
43. Senders, M., *Suction caissons in sand as tripod foundations for offshore wind turbines*. 2009: University of Western Australia.
44. Kim, D.-J., et al., *Investigation of monotonic and cyclic behavior of tripod suction bucket foundations for offshore wind towers using centrifuge modeling.* Journal of Geotechnical and Geoenvironmental Engineering, 2014. **140**(5): p. 04014008.
45. Nabipour, M. and H. Matin Nikoo, *An Investigation into the Pull-out Failure Mechanisms of Suction Caissons.* International Journal of Maritime Technology, 2015. **4**: p. 21-35.
46. Houlsby, G.T. and B.W. Byrne, *Suction caisson foundations for offshore wind turbines and anemometer masts.* Wind engineering, 2000. **24**(4): p. 249-255.
47. Foglia, A., M. Kohlmeier, and M. Wefer, *Physical modeling and numerical analyses of vibro-driven piles with evaluation of their applicability for offshore wind turbine support structures.* Proc nord geotech meet, 2016.
48. Bagheri, P., S.W. Son, and J.M. Kim, *Investigation of the load-bearing capacity of suction caissons used for offshore wind turbines.* Applied Ocean Research, 2017. **67**: p. 148-161.
49. Houlsby, G.T. and B.W. Byrne, *Design procedures for installation of suction caissons in clay and other materials.* Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 2005. **158**(2): p. 75-82.
50. Bhattacharya, S., *Challenges in design of foundations for offshore wind turbines.* Engineering & Technology Reference, 2014. **1**(1): p. 1-9.
51. Wang, L., et al., *Comparison of monotonic and cyclic lateral response between monopod and tripod bucket foundations in medium dense sand.* Ocean Engineering, 2018. **155**: p. 88-105.