NUMERICAL INVESTIGATIONS ON THE BEARING CAPACITY OF BUCKET FOUNDATIONS UNDER COMBINED HORIZONTAL AND MOMENT LOADING

CALCULS NUMÉRIQUES SUR LA CAPACITÉ PORTANTE DE FONDATIONS "BUCKET" SOUMIS À L'ACTION COMBINÉE DE CHARGE HORIZONTALE ET DE MOMENT

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ABSTRACT – The behaviour and the bearing capacity of large bucket foundations for offshore wind energy converters under horizontal and moment loading is investigated by means of numerical modelling. For specific deformation states (rotation angles) and especially for the ultimate limit state of the foundation structure H-M-interaction diagrams for buckets in medium dense sand are presented.

RÉSUMÉ – Le comportement et la capacité portante de foundations larges "Bucket" utilisées pour les ouvrages éoliens en mer sous l'action d'une charge horizontale et d'un moment ont été étudiés à l'aide d'une modélisation numérique. Pour les états de deformation spécifiques (angle de rotation) et spécialement pour l'état limite ultime de la fondation les diagrammes d'interaction H-M pour des "Buckets" dans du sable semi-dense ont été présentés.

1. Introduction

Bucket foundations can be used as foundation structures for the planned offshore wind parks in the German part of North and Baltic Sea at large water depths varying from approximately 15 to 40 m. A suction bucket foundation consists of an upside down cylinder, which is pressed into the subsoil (Fig. 1). The bucket penetrates into the seabed partly by self-weight and partly by applied suction.

The large horizontal forces and moment loads applied to the bucket foundation resulting from wind and wave action must be economically and safely transferred to the sea ground. This paper investigates the behaviour of suction buckets in sand under different loading components using the finite element method to develop "interaction diagrams" based on load-deformation curves.

The interaction diagrams approach to bearing capacity estimation for shallow footings enables the engineer to take into account the interaction between different loading components acting on the footing.

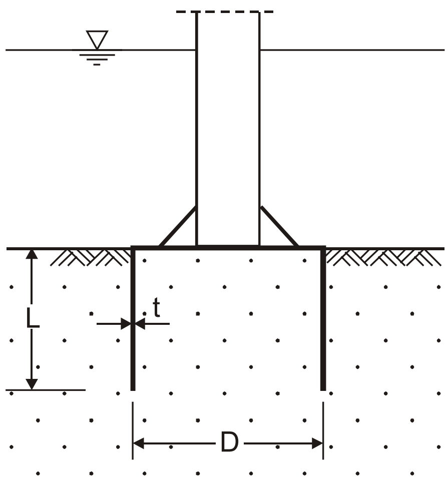

Figure 1. Schematic cross section of a suction bucket foundation.

An approach for the case of a strip footing was firstly published by Butterfield and Ticof (1979) and Butterfield (1981). Georgiadis et al (1988) suggested a procedure for the determination of the foundation displacement and rotation. This procedure is based on an interaction approach to determine the ultimate load capacity. Gottardi et al. (1993) analyzed the interaction diagrams to relate the different loading components for a strip footing at failure. Butterfield et al. (1996) predicted the failure load for shallow foundations on dense sand using a simplified transformation of 3-D failure envelopes.

2. Suction bucket foundation

The suction bucket was developed from the suction caisson foundation already used in the offshore technology (see e.g. Ibsen et al., 2004). In principle its behaviour can be considered as a combination of a gravity base and a pile foundation structure. For installation an under-pressure (suction) is applied in the cavity between the top plate and the seabed (Fig. 2).

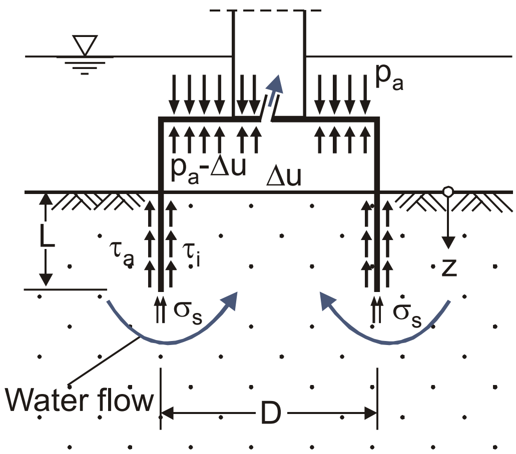

Figure 2. Suction bucket during installation.

The mobilized penetration force results from the actual under-pressure multiplied with the internal cross section area of the bucket plus the dead weight of the bucket foundation. The penetration resistance results from the skin friction mobilised along the outside and inside surface of the bucket as well as the base resistance at the bucket sleeves' toe.

For sandy soils the soil resistances can be calculated as for vertically loaded piles in accordance with API (2000). Feld (2001) suggests a set of correction factors to consider the effect of the water flow produced by the under-pressure during the penetration procedure of the bucket into the seabed.

According to the water flow from outside into the bucket it could come to large hydraulic gradients which cause a hydraulic shear failure of the soil in the bucket. This would lead to a loosening of the subsoil and to uncontrolled penetration of the bucket. Therefore a permissible under-pressure, which is dependent on the current penetration depth, may not be exceeded during installation.

According to computations of the authors given in Achmus and Abdel-Rahman (2005) it results that in homogeneous medium dense sandy soil for a bucket diameter of 15 m a penetration depth of about 10 to 13 m and for a bucket diameter of 20 m of 13 to 17 m can be realized (Fig. 3). Due to that, penetration depths of 8 m and 12 m were assumed for a bucket diameter of 15 m and of 10 m and 15 m for a bucket diameter of 20 m. For suction buckets with these dimensions in a sandy soil the load-deformation behaviour was calculated using finite element computations.

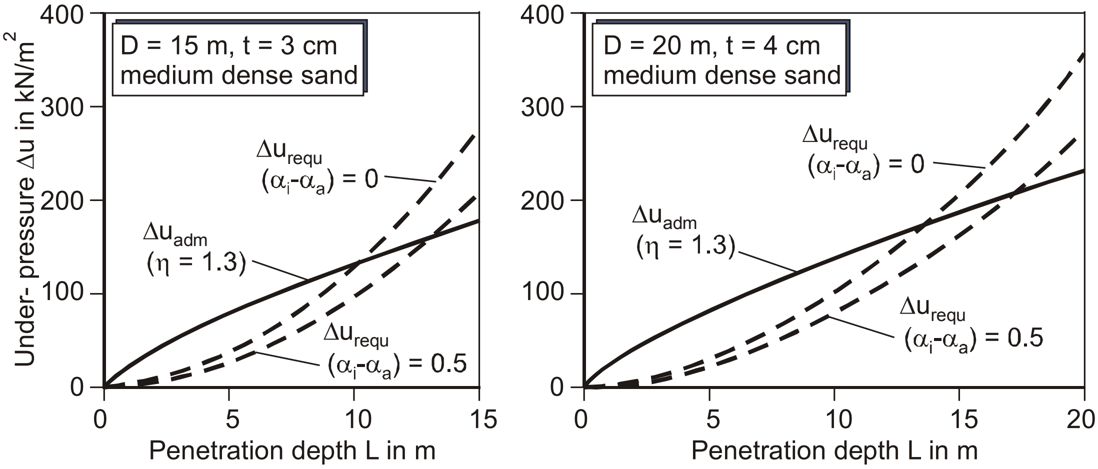

Figure 3. Relation between required and admissible suction pressure and the embedded length of the suction bucket.

3. Numerical modelling of suction bucket behaviour

For the investigation of the behaviour of suction buckets under combined loading conditions a three-dimensional (3-D) numerical model was developed. In the present study, the finite element program ABAQUS 2005 was used to determine the load-deformation curves for buckets under combined horizontal and moment loading. An advanced computer system with parallel processor technology was used to minimize the computation time.

The most important issue in geotechnical numerical modelling is the simulation of the soil's stress-strain-behaviour. The elasto-plastic material law with Mohr-Coulomb failure criterion provided in the ABAQUS program was used. This material law was extended in the elastic range by taking a stress-dependency of the oedometric modulus of elasticity into account. This stress-dependency is given by the following equation:

$$E_S = \kappa \, \sigma_{at} \left(\frac{\sigma_m}{\sigma_{at}} \right)^{\lambda} \tag{1}$$

Herein σ_{at} = 100 kN/m^2 is a reference stress and σ_m is the current mean principal stress in the regarded soil element. The parameter κ determines the soil stiffness at the reference stress state and the parameter λ rules the stress dependency of the soil stiffness (EAU 2004).

In Table I the material parameters used to describe the behaviour of medium dense sand are given. The material behaviour of the piles was assumed linear elastic with the parameters $E = 2.1 \cdot 10^5$ MN/m^2 (Young's modulus) and $\nu = 0.2$ (Poisson's ratio) for steel.

Due to the symmetric loading condition only a half-cylinder representing the sub-soil and the bucket could be considered. The discretized model area had a radius of at least three times the bucket diameter. The bottom boundary of the model was extended twice the bucket diameter below the toe of the bucket (Fig. 4). With these model dimensions the calculated behaviour of the bucket is not significantly influenced by the boundaries.

Table I. Material parameters used for medium dense sand.

Unit buoyant weight γ'	11.0 kN/m^3
Oedometric stiffness parameter κ	400
Oedometric stiffness parameter λ	0.60
Poisson's ratio ν	0.25
Internal friction angle φ'	35°
Dilation angle ψ	5°
Cohesion c'	0.1 kN/m^2

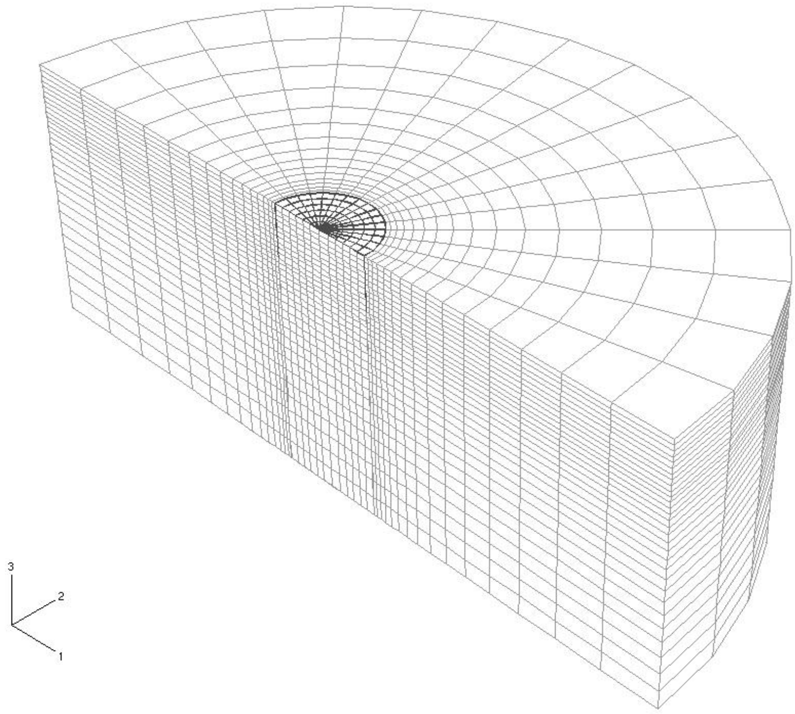

Figure 4. Finite element mesh for the suction bucket foundation.

For the sandy soil as well as for the bucket 8-node continuum elements were used. The frictional behaviour in the different boundary surfaces between the bucket and soil was modelled using contact elements based on slave-master concept, whereby the wall friction angle was set to $\delta = 0.67\ \varphi'$.

This study was carried out to investigate the influence of the load combinations (horizontal load / moment load) on the bucket behaviour, i. e. the horizontal displacement and the rotation of the bucket top plate for different cases. The bucket geometries considered for the analyses are summarised in Table II.

Table II. Bucket geometries.

Case	Diameter D	Wall thickness	Embedded Length L
	m	m	m
1	15.0	0.03	8.0
2	15.0	0.03	12.0
3	20.0	0.04	10.0
4	20.0	0.04	15.0

The finite element calculations were executed stepwise. At first, for the generation of the initial stress state the whole model area is discretized using soil elements only. Subsequently, the bucket is generated by replacing the soil elements located at the bucket position by steel elements and activating the contact conditions between both of them.

Then a vertical load of 10.0 MN representing the own weight of the tower and the turbine is applied on the bucket. Finally the combined loading resulting from wind and wave loads is applied and increased incrementally until failure.

4. Numerical modelling results

4.1 Suction Bucket with outer diameter D = 15 m (cases 1 & 2)

The deformations and in particular the rotation of the foundation construction and thus the base of the wind tower are of special importance for the design of wind power plants, since a trouble free operation is only secured under relatively small tower inclinations. Therefore the computation results are presented as the horizontal displacement (w) and the rotation of the bucket (ϕ) at the connection of the bucket with the main tower.

The upper bucket plate was modelled as rigid to take the stiffening plates connecting the bucket to the tower into account. Therefore the presented results are the displacement and the rotation of the bucket top plate.

In Figure 5 the calculated load-displacement and load-rotation curves for the cases 1 and 2, i. e. bucket diameters of 15 m, are given. Each curve is valid for a specific height of the loading point (h) above the bucket top plate and thus for a specific ratio of moment and horizontal load (h=M/H). To cover all relevant load combinations for OWECs this value was varied between h=0 m (pure horizontal loading) and h=100 m.

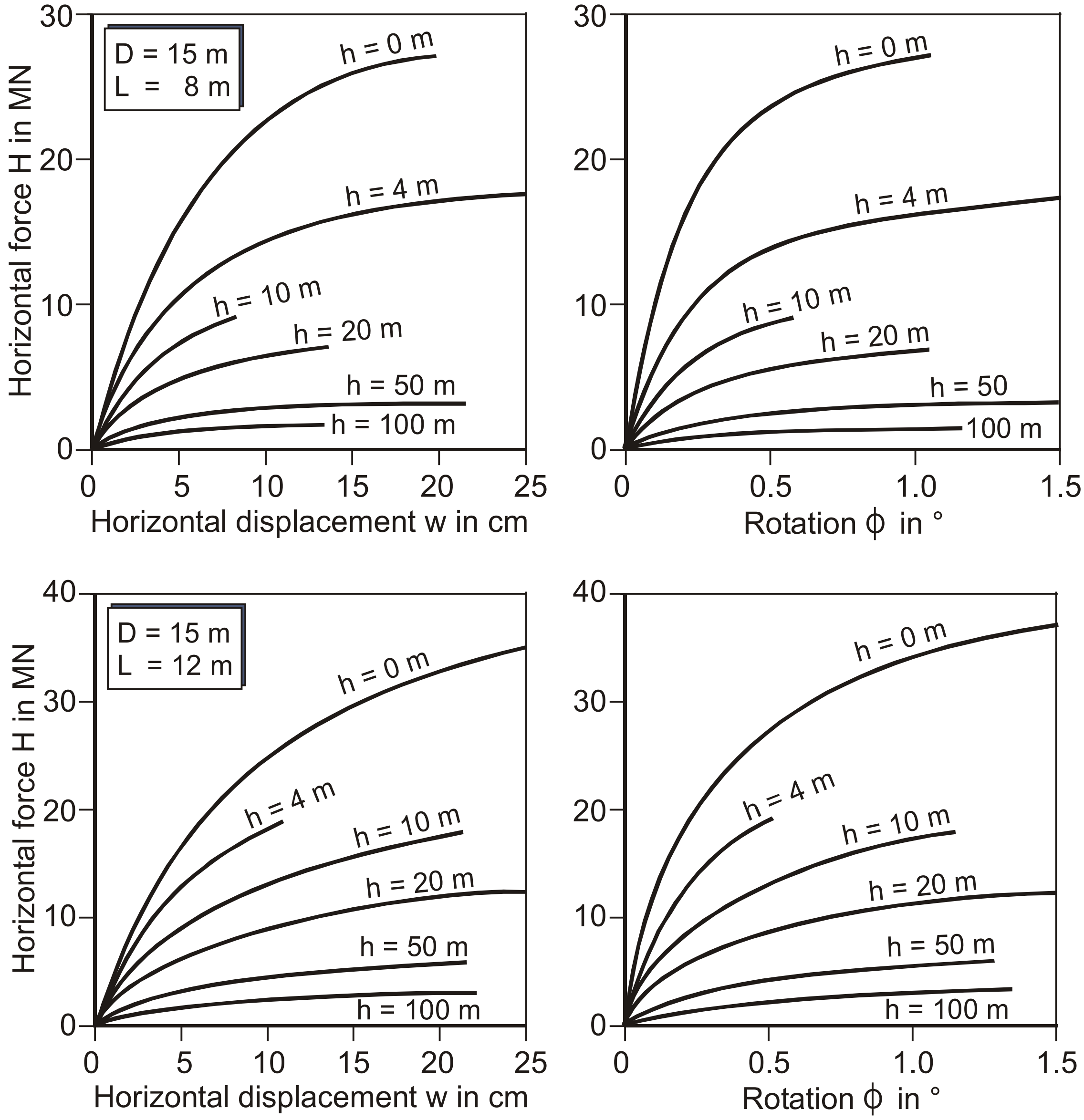

Figure 5. Load-deformation curves for suction bucket foundations in medium dense sand (top: D = 15 m, L = 8 m, bottom: D = 15 m, L = 12. m).

The typical load-deformation behaviour of foundation structures is obtained with a nearly linear dependence for loads significantly lower than the ultimate load and over-proportional increase of the deformations when approaching the ultimate load. As was to be expected, the height of the loading point and with that the moment load considerably affects the stiffness as well as the ultimate load. For pure horizontal loading the ultimate load is about 30 MN (L = 8 m) and 40 MN (L = 12 m), whereas for h = 20 m it decreases to about 7 MN and 12 MN, respectively. In a similar way the loads belonging to specific deformations are affected. For a rotation of 0.25°, which lies in the order of admissible rotations for OWECs, loads of about 18.5 MN (L = 8 m) and 20.5 MN (L = 12 m) are obtained for pure horizontal loading and of about 7 MN and 10 MN, respectively, for h = 20 m.

With the load-deformation curves obtained interaction diagrams for horizontal and moment loading were derived. These diagrams are presented in Figure 6. The calculated load values for specific rotations of 0.1° and 0.25° and for failure of the foundation structure are depicted. The latter were determined by extrapolation of the load-deformation curve, if a horizontal tangent of the curve was not reached. In a first approximation, the interaction of horizontal load and moment can be described by the nearly parallel straight lines given in the diagrams.

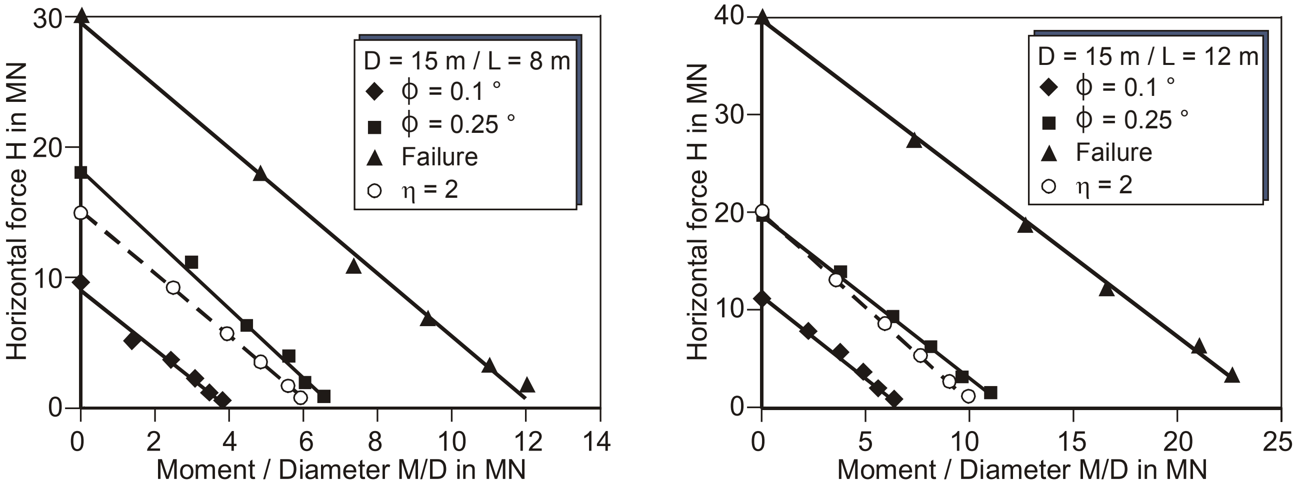

Figure 6. Interaction diagram for suction bucket foundations D = 15 m in medium dense sand (left: L = 8 m, right: L = 12 m).

In the interaction diagrams also a dashed line is included which implies a global safety factor of 2.0 versus failure derived from the load combinations for failure. So, whith such interaction diagrams ultimate limit as well as serviceability limit design can be carried out.

4.2 Suction Bucket with outer diameter D = 20 m (cases 3 & 4)

In Figure 7 the load-deformation curves for the buckets with a diameter of 20 m and embedded lengths of 10 m (case 3) and 15 m (case 4) are shown. The results correspond qualitatively to the results for the buckets with 15 m diameter. Due to the larger diameter, considerably smaller displacements and rotations for equal loads and of course larger ultimate loads are obtained.

In Figure 8 the interaction diagrams for horizontal and moment load are presented. Like for the cases 1 and 2, also for the bucket geometries considered here the interaction can be described by nearly parallel straight lines.

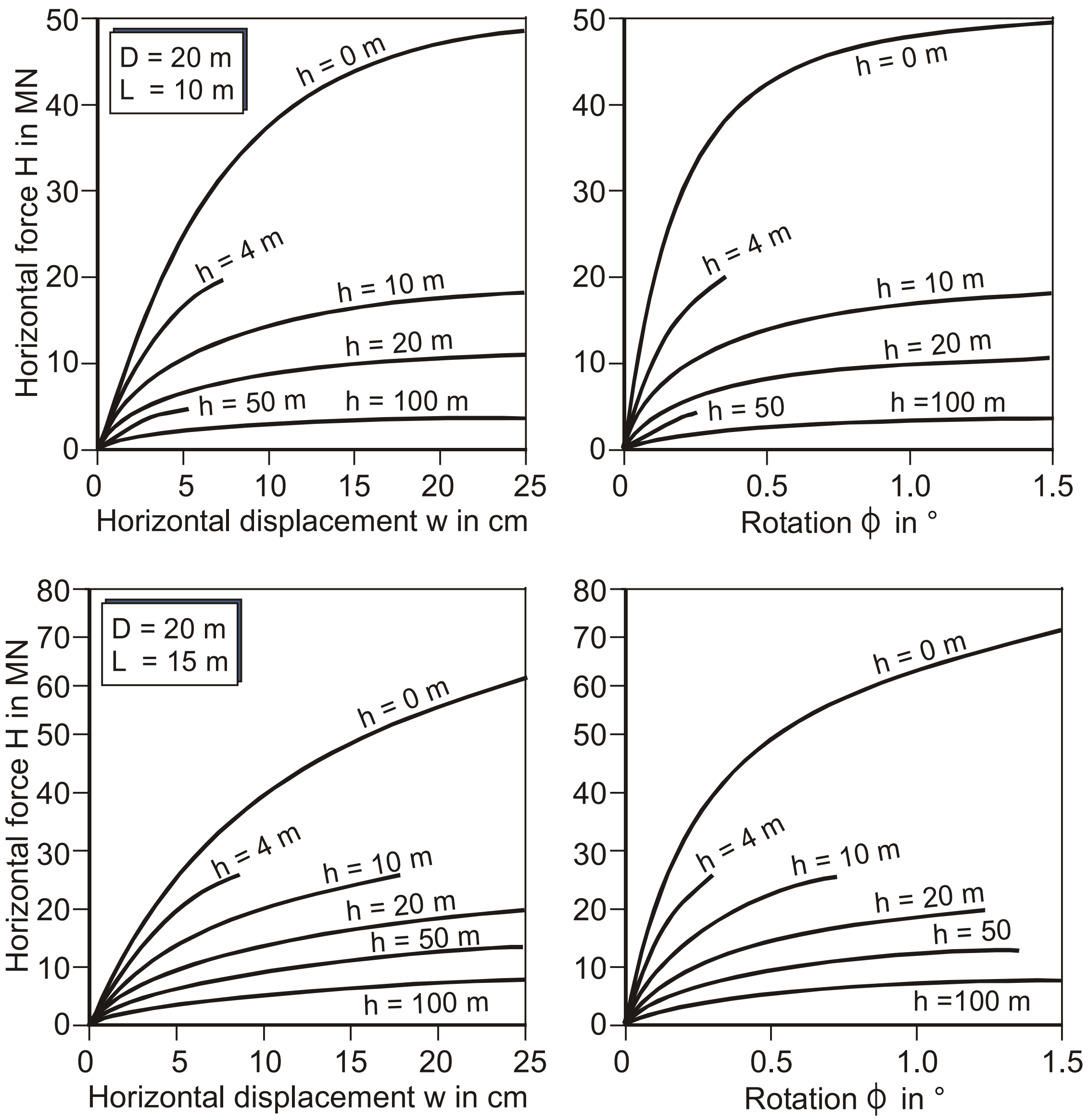

Figure 7. Load-deformation curves for suction bucket foundations in medium dense sand (top: D = 20 m, L = 10 m, bottom: D = 20 m, L = 15 m).

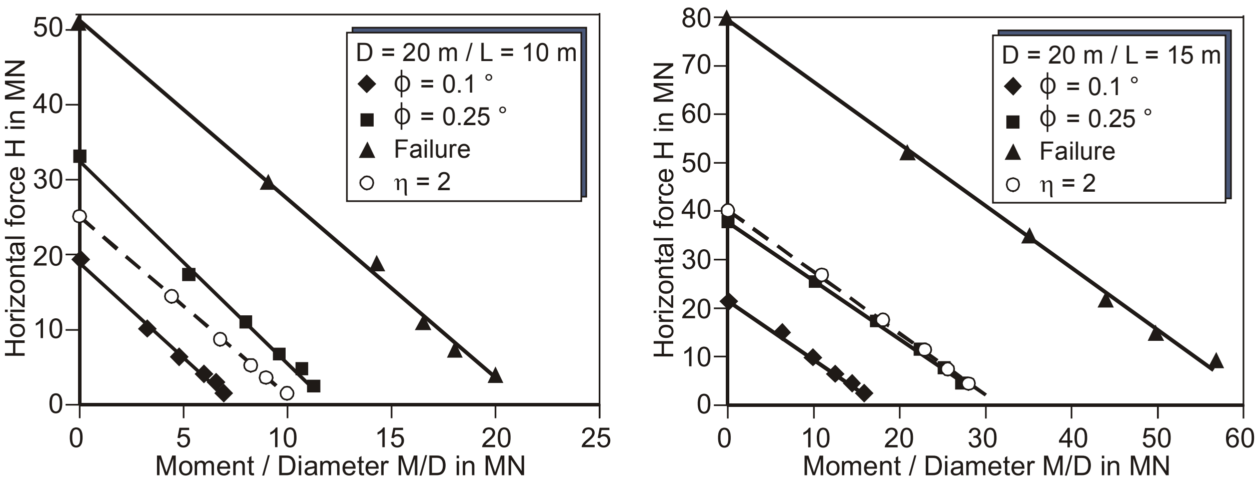

Figure 8. Interaction diagrams for suction bucket foundations D = 20 m in medium dense sand (left: L = 10 m, right: L = 15 m).

5. Conclusions

The design of bucket foundations for the ultimate limit state as well as for the serviceability limit state can be carried out by means of horizontal load-moment interaction diagrams. With such diagrams also the identification of relevant load cases is easily possible.

In this paper, load-deformation curves and interaction diagrams are presented for buckets with different geometries embedded in medium dense sand. It is obtained that the load-moment interaction for the ultimate state as well as for specific deformation states can be described by nearly parallel straight lines.

A possible design load for a Offshore Wind Energy Converter in the German Bight (North Sea) for a water depth of about 30 m is a horizontal load of H = 8 MN with a height of the loading point of h = 25 m (M = 200 MNm). For this loading, only a bucket with a diameter of 20 m applies. With an embedded length of 10 m a rotation of about 0.4° is to be expected, which might be admissible due to operational requirements. The factor of safety for that case is about 1.5. With an embedded length of 20 m the rotation would be only about 0.1° and the factor of safety is about 2.6.

6. References

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