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Numerical investigations on the behaviour of offshore suction bucket foundations under cyclic axial loading

Etude numérique du comportement des fondations de nacelles d'aspiration offshore en chargement axiale cyclique

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ABSTRACT: Cyclic loads, induced by wind and waves, play a special role in the design of suction bucket foundations for offshore wind turbines (OWTs). Understanding the cyclic behaviour is essential to assess the design requirements of bucket foundations in both ultimate and serviceability limit states. Due to lack of experience on cyclic response, the behaviour of a bucket embedded in saturated sandy soil subjected to cyclic axial compressive load is investigated by using a sophisticated finite element model. In order to take into account the accumulation of permanent soil deformations and excess pore water pressure in saturated sandy soil due to cyclic axial loading, a fully coupled two-phase model combined with a hypoplastic constitutive model with intergranular strain is used. The porosity-permeability dependence is taken into account by Kozeny-Carman relationship. The main focus is dedicated to cyclic axial load depended effect on the load-bearing behaviour of bucket. The changes in load transfer via bucket skirt and top plate are quantified. The investigations have provided important findings in which the effects of cyclic loading on the behaviour of suction buckets can be reliably determined.

Keywords: cyclic axial load, displacement accumulation, hypoplasticity, pore pressure accumulation, suction bucket foundation

1 INTRODUCTION

The offshore wind turbines have evolved considerably in recent years on par with the increased clean and renewable energy demand. Therefore, importance of safe and economic design of OWTs has significantly increased.

Suction bucket is an economic foundation for OWTs which can be described as a single, open ended, top closed large cylindrical steel structure, as shown in Figure 1.

Beside the successful applications in oil industry (Clausen and Tjelta, 1996), the suction buckets have already been used in offshore wind industry as foundation for met masts, substations and OWTs (Ibsen 2008; Zhang et al. 2007; Bakmar 2009; Kim et al. 2014; Oh et al. 2018). Experiences have shown that construction and material costs can be significantly reduced in addition to noise free, easy and reversible installation process.

Offshore structures are subjected to high cyclic loads due to harsh environmental conditions. Guidelines and standards for fixed offshore platforms such as API (2014) and DNVGL (2016) are used for suction buckets, where the cyclic effects are pointed out, but a design method is not suggested for this purpose.

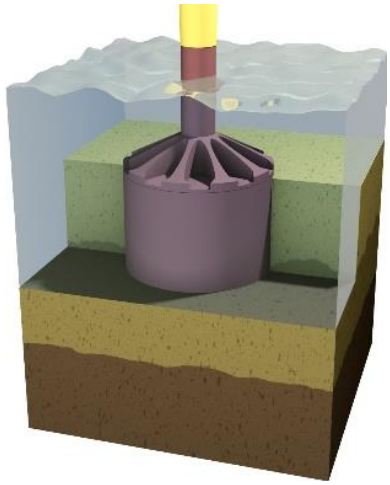

Figure 1. Suction bucket foundation

There are two foundation concepts with suction buckets. A single bucket (monopod) with large diameter is mainly subjected to lateral loads and bending moments. Secondly, combination of several buckets (multipods) with relatively smaller diameters form the foundation elements of lattice structures, which are predominately subjected to loads in axial direction.

In axial direction, tensile and compressive resistances show differences in the behaviour of bucket foundations. The tensile resistance results from self-weight, skin friction and suction pressures that resist formation of a gap between top plate and soil surface (Byrne and Houlsby 2002; Senders, 2008; Thieken et al. 2014; Ukritchon et al., 2018). Skin friction, base and top plate are of primary importance for the transfer of axial compressive loads into soil.

The behaviour under cyclic axial compression has been investigated mainly experimentally by Kelly et al. (2006), Kim et al. (2014) and also numerically by Cerfontaine et al. (2016), Liingaard (2006), Taşan 2017, which emphasizes the importance of the displacement and pore pressure accumulation effects on the bucket behaviour. There is still a substantial need for research regarding to changes in the load transfer via skirt and top plate due to the cyclic accumulation effects (Sturm, 2017).

In this study, a numerical investigation performed to quantify the response of suction buckets subjected to cyclic axial compressive loads in saturated sandy soils. Bucket response under cyclic axial compressive loading and related changes in load transfer via top plate, outer, inner and the base of bucket skirt are determined, which plays a special role for the safe and economic design of bucket foundations.

2 TWO-PHASE MODEL

Two-phase models in which the soil consists of a solid skeleton and a pore fluid, are used for geotechnical problems where the pore fluid significantly affects the mechanical behaviour of soil.

In the model shown in Figure 2, the two-phase mixture is assumed to consist of a solid phase (the skeleton) and a fluid phase which fully occupies the pores in the skeleton.

The problem is formulated in terms of the absolute displacements of soils skeleton (u_x, u_y, u_z) and the pore water pressure p. The theory of u-p model for soil is described in more detail in Zienkiewicz and Shiomi (1984), Potts and Zdravkovic (1999) and Taşan (2011).

A stable 3D continuum element u20p8 is implemented by Taşan (2011) (Figure 2). Triquadratic interpolation functions are used to approximate 20-node displacement field where trilinear approximation is used for 8-node fluid phase. Using higher order of displacement than pressure field is required for stability of elements.

Taşan (2011) assumes that the solid and fluid constituents can be modelled as incompressible. In this study, the u20p8 element was refined for modelling the saturated soil in which the compressibility properties of constituents were considered.

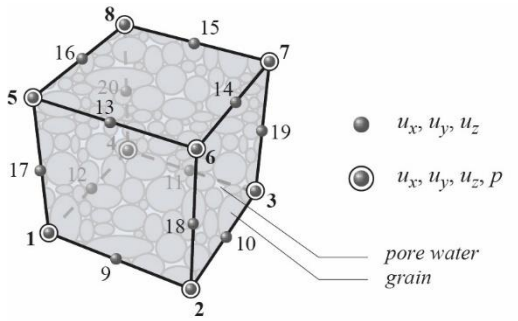

Figure 2. u20p8 element (Taşan, 2011)

3 CONSTITUTIVE MODEL

Kolymbas (1985) presents a non-linear hypoplasticity theory to relate stress increments to strain rate by a single tensorial equation. Unlike elasto-plastic theories, a yield surface or flow rule does not exist. In order to characterize the soil state, the granular effective stress and void ratio is used. An improved version of hypoplastic constitutive equation that is capable of modeling pyknotropy and barotropy is proposed by von Wolffersdorff (1996). The experimental determination of the model parameters listed in Table 1 are presented in Herle and Gudehus (1999).

Hypoplastic constitutive equation in cyclic loading or small deformation problems may result in overprediction of deformations (Niemunis and Herle 1997, Bauer and Wu 1993). Niemunis and Herle (1997) presents an improved hypoplastic constitutive equation that account for both small strain and cyclic behaviour of sandy soils. In this study, the hypoplastic constitutive model according to Niemunis and Herle (1997) was used which requires additional 5 parameters listed in Table 1.

The suitability of hypoplastic constitutive model with intergranular strain (IGS) proposed by Niemunis and Herle (1997) by using the u20p8 element is confirmed by Taşan (2011).

Table 1. Material Properties for Hypoplastic Constitutive Law with Intergranular Strain

Model Parameters according to von Wolffersdorff (1996)	
Critical Friction Angle	Φ_c
Granulate Hardness	h_s
Exponent controlling void ratio	n
Minimum void ratio	e_{d0}
Maximum void ratio	e_{c0}
Critical Void Ratio	e_{i0}
Exponent	α
Exponent	β
Additional Parameters according to Niemunis and Herle (1997)	
Parameter controlling initial shear modulus upon 180	m_R
Parameter controlling the shear modulus upon 90 strain path reversal	m_T
Parameter controlling the size of the elastic range	R_{max}
Parameter controlling the intergranular strain evolution rate	β_R
Parameter controlling the tangent stiffness degradation	χ

4 KOZENY-CARMAN RELATIONSHIP

In order to consider the variation of the permeability due to loosening or densification of soil during cyclic loading, the Kozeny–Carman approach was used in this study.

A semi-empirical, semi-theoretical formula is developed by dealing the soil as an assembly of capillary tubes of equal length by Kozeny (1927) to account for the porosity-permeability relation, in which the specific surface concept per unit mass of solid is introduced to express the permeability. Carman (1956) removes the assumption that fluid moves in a straight channel by introducing Carman coefficient C (Chapuis and Aubertin, 2003). Hence the permeability according to Kozeny–Carman can be formulated as;

$$k = C\frac{e^3}{1+e} \quad (1)$$

where e is void ratio and the coefficient C is dependent on density and dynamic viscosity of water as well as specific surface.

In this study, the hydraulic conductivity of soil was updated at each step with respect to load dependent void ratio of the two-phase model.

5 FINITE ELEMENT MODEL

A finite element (FE) model of a bucket of a multipod was developed to investigate the behaviour under cyclic axial compressive loads. Considering the future studies (such as cyclic horizontal loading), a half cylinder medium was modelled with three dimensional elements by utilizing the FE program system ANSYS (2016).

The model consists of soil elements, a steel bucket and contact elements. Two-phase u20p8 element was used to represent saturated soil medium. The bucket was modelled with 3D 20-node solid elements and bucket-soil interface was simulated with contact pairs considering isotropic Coulomb friction.

Translational boundary conditions were schematically described in Figure 3. Drainage was only allowed on the surface of the model and a hydrostatic pore pressure profile that is equal to the initial pressure was applied to the edges. Impermeable bedding was assumed at the bottom.

Boundary and mesh of FE model were optimized based on preliminary calculations in order to avoid boundary effects. The dimensions of the model were sufficient for the bucket questioned, so that its behaviour was not affected by the boundaries.

At the initial stage, only the soil elements were modelled and initial stress state was calculated under gravity with at rest earth pressure coefficient. Later, the bucket was activated and the soil elements coinciding with the bucket were deactivated. Static dead load was applied in the next stage and thereafter the bucket was subjected to cyclic axial compressive load.

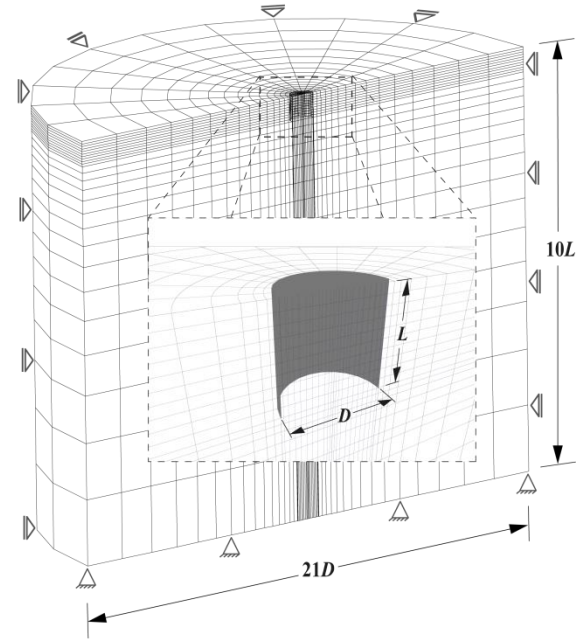

Figure 3. FE model of suction bucket

6 VERIFICATION OF FE MODEL

The numerical implementation of the two-phase element u20p8 in combination with hypoplastic model is already verified for various soil-pile-interaction problems in Taşan (2011) and for soil liquefaction analyses in Bayraktaroglu et al. (2018).

Prototype field tests with buckets embedded in saturated sandy soils subjected to cyclic axial loads are not currently available. Therefore, for the verification of FE model, the results of geotechnical centrifuge tests of a single bucket performed at 50g by Wang et al. (2018) under both static and cyclic lateral loading were used, which, however were performed in dry sand.

In the framework of the simulation of tests, the coupled u20p8 elements were used for the modelling the sand. Thereby, a coefficient C according to Eq. 1 is assumed that is high enough to prevent any possible pore pressure develop-

ment in the soil. The hypoplastic model parameters of Fujian Sand were used according to Wang et al. (2018) which are given in Table 3. The soil relative density was $I_D = 0.60$.

In the tests, a bucket with an outer diameter $D = 15$ m, embedded length $L = 15$ m and a wall thickness $t = 0.40$ m was subjected to lateral loads at a height $h = 31.5$ m (Figure 4).

The bucket was modelled with 3D solid elements. Linear elastic material model with Young's modulus $E = 72$ GPa and Poisson's ratio $\nu = 0.30$ were assumed for the material behaviour of bucket.

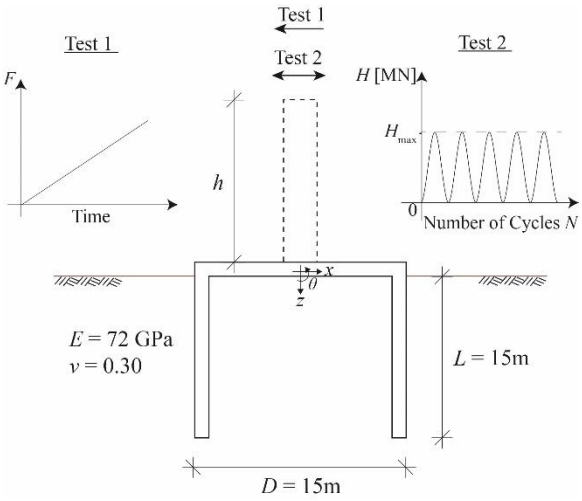

Figure 4. Simulated tests according to Wang et al. (2018)

The frictional behaviour in the interface between bucket and soil was modelled by contact elements with Coulomb friction law. Therefore a wall friction angle of $\delta = 21.66°$ is adopted.

Table 2. Hypoplastic material parameters for Fujian Sand (Wang et al., 2018)

Φ_c	32.50°	m_R	8.0
h_s	2.00 GPa	m_T	4.0
n	0.34	R_{max}	1E-04
e_{d0}	0.61	β_R	0.40
e_{c0}	0.95	X	0.80
e_{i0}	1.14		
α	0.08		
β	1.80		

In the first analysis, monotonic load test was simulated to verify the modelling for bucket foundation. Comparison of the moment-rotation response is given in Figure 5. Furthermore, cyclic loading tests with a maximum value $H_{max} = 1270$ kN were simulated (Figure 4). Only first few cycles of test were focused to avoid numerical error accumulation.

The numerical results presented in Figure 6 showed a good agreement with the observed bucket behaviour in centrifuge tests according to Wang et al. (2018).

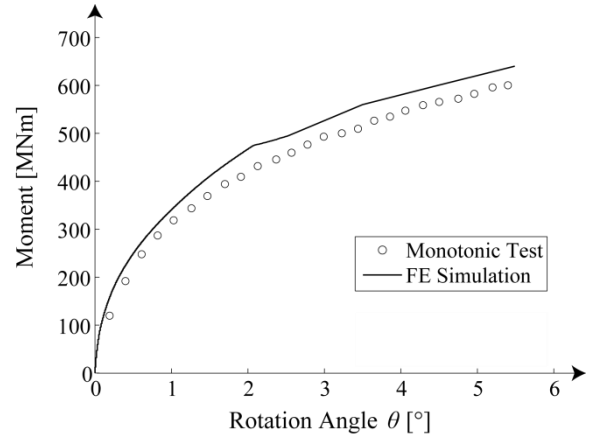

Figure 5. Simulation of monotonic centrifuge test

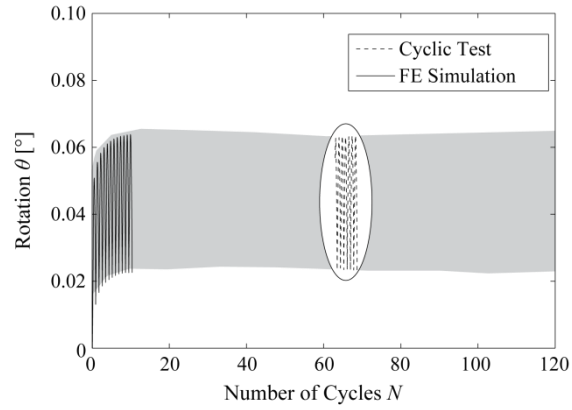

Figure 6. Simulation of cyclic centrifuge test

7 BUCKET BEHAVIOR UNDER CYCLIC AXIAL COMPRESSIVE LOADING

In order to study the bucket response under cyclic axial compressive loading and related changes in load transfer via top plate, outer, inner and the base of bucket skirt in the sandy soil, FE simulations with using the model described in Chapter 5 were performed. For this purpose, a poorly graded, medium to coarse sand with a characteristic grain size d_{50} = 0.55 mm and a coefficient of uniformity U = 3.3 was considered. The hypoplastic material parameters of the sand used is given in Table 3. A Kozeny-Carman coefficient C = 0.00159 was calculated according to Carrier (2003).

Table 3. Hypoplastic model parameters, adopted from Le (2015)

Φ_c	31.50°	m_R	4.4
h_s	2.30 GPa	m_T	2.2
n	0.3	R_{max}	1E-04
e_{d0}	0.39	β_R	0.20
e_{c0}	0.69	χ	6.00
e_{i0}	0.79		
α	0.13		
β	1.00		

Linear elastic material behaviour with Young's modulus E = 200 GPa and Poisson's ratio v = 0.20 was assumed for the modelling of the steel bucket with a diameter D = 10 m, embedded length L = 10 m and wall thickness t = 0.05 m. A numerically rigid top plate was considered regarding the stiffeners.

Static dead load and cyclic axial compressive load with a sinusoidal pattern were applied according to Figure 7 which idealises the dead, wind, wave and current load that act one bucket of a 4-pod system for an OWT with a rated power of 8 MW. The minimum value of cyclic loading F_{min} was 5 MN and the loading frequency was f = 0.10 Hz. The number of loading cycle was limited with 12 to avoid accumulation of numerical errors.

Before the cyclic tests, the ultimate axial load capacity F_{ult} which is defined as the load by an axial displacement $u_{z,ult} = 0.1D$ was determined as F_{ult} = 101.60 MN for the considered soil-bucket-system with a monotonic loading test.

The findings have shown that the bucket response is highly dependent on the cyclic load level. The displacement ratio $u_z/u_{z,ult}$ which is defined as the ratio of accumulated axial displacement u_z to static ultimate displacement $u_{z,ult}$ is shown for the bucket with aspect ratio L/D of 1.0 and a sand with initial void ratio e_i of 0.45 in Figure 8. According to this, the bucket response can be classified in shakedown and attenuation as well as incremental collapse depending on the cyclic loading levels as described in Cuellar (2011).

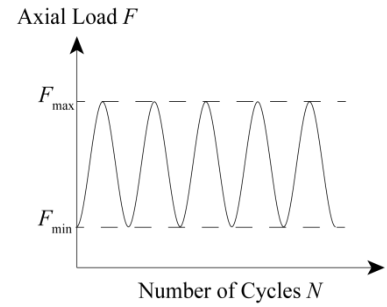

Figure 7. Cyclic loading pattern

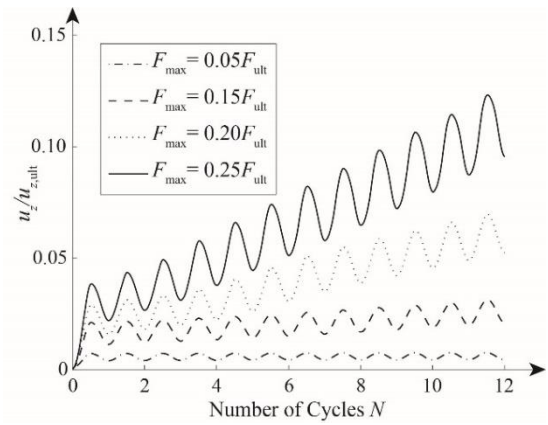

Figure 8. Bucket response under cyclic loading

In all load levels, the highest increase of plastic deformations was calculated at the

beginning of the cyclic loading. For cyclic loads up to a maximum amplitude of $F_{max} = 0.05F_{ult}$ the deformations remained nearly unchanged during the rest of loading cycles and the case of shakedown was calculated. For $F_{max} > 0.05F_{ult}$ and $< 0.25F_{ult}$ the increase of deformations decreased with loading cycles but it never reached zero. This case is called as attenuation. For $F_{max} \geq 0.25F_{ult}$, the deformations were increased progressively and the system failed to stabilize, which is called as progressive failure.

The transfer of the loads into soil via top plate, skirt and base during cyclic loading were studied corresponding to the classified bucket responses. The load transfer was affected by changes in the effective stresses at soil-bucket-interfaces which were highly dependent on drainage conditions, in other words, excess pore pressure accumulation. The cyclic loading amplitude was a governing factor for the different bucket responses since it mainly affects the pore pressure accumulation in soil.

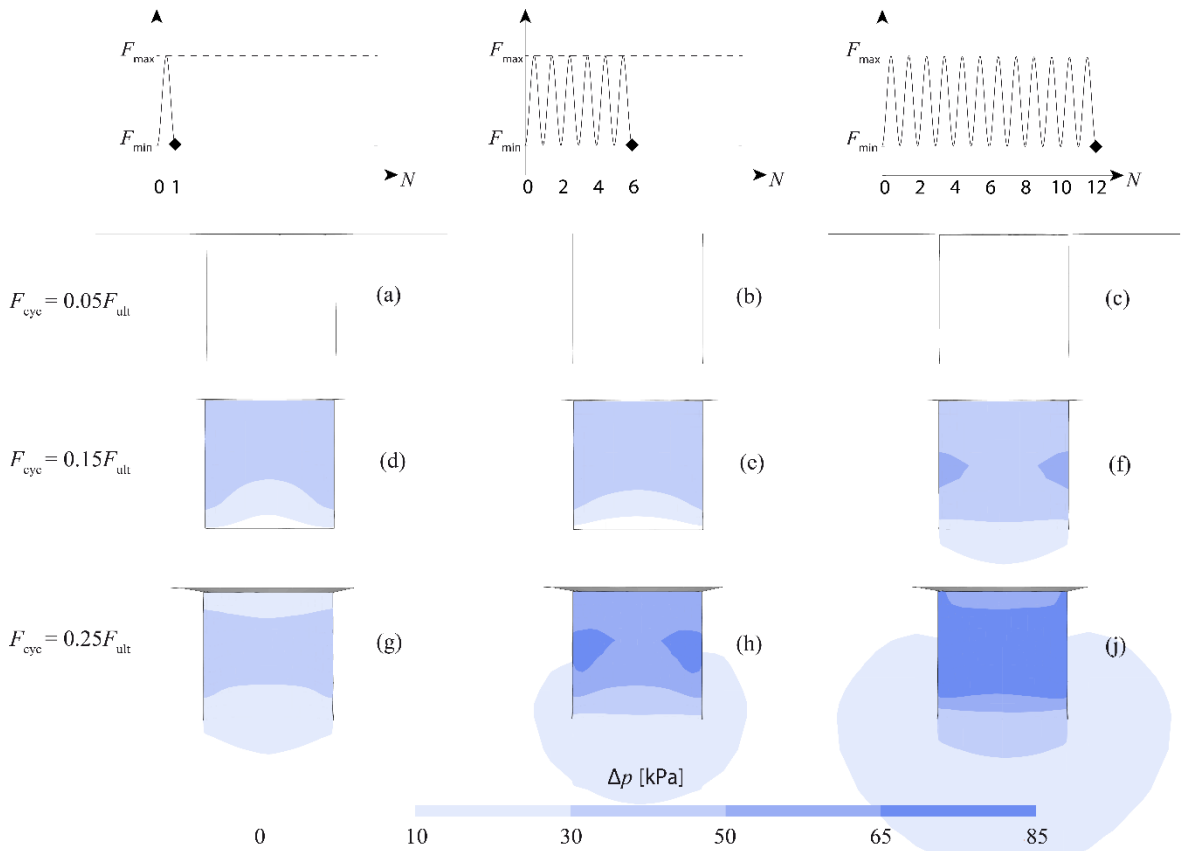

Figure 9. Excess pore pressure development in soil after loading cycle number N = 1, 6 and 12 for different cyclic loading levels

The excess pore water pressure development after cyclic loading number $N = 1$, 6 and 12 for the cases of shakedown, attenuation and progressive failure are shown in Figure 9. In the shakedown case, no significant excess pore pressure was calculated depending on the cyclic loading. However, an excess pore pressure accumulation in soil took place for the attenuation and progressive failure cases (Figure 9), which led to the decrease of effective stresses especially at lower half of the skirt. This also led to changes in the shares of the axial loads trans-

ferred into the sandy soil via components of the bucket depending on loading cycle.

The percentage shares of the axial loads transferred into the sandy soil via the bucket members are depicted as a function of the number of load cycles corresponding to $F_{max} = 0.05F_{ult}$, $0.15F_{ult}$ and $0.25F_{ult}$ in Figure 10. The data points represent the load share of bucket members at the end of each cycle for F_{min}. In the shakedown case, no significant changes were determined in load transfer. However, in the attenuation case, due to the decrease of effective stresses inside the bucket, the proportions of the axial loads transferred by the top plate and base increased with ascending load cycles. In the case of progressive failure, in addition to inner friction, outside friction forces were also substantially reduced due to the inefficiency of the soil to dissipate the excess pore water pressure completely between consecutive cycles.

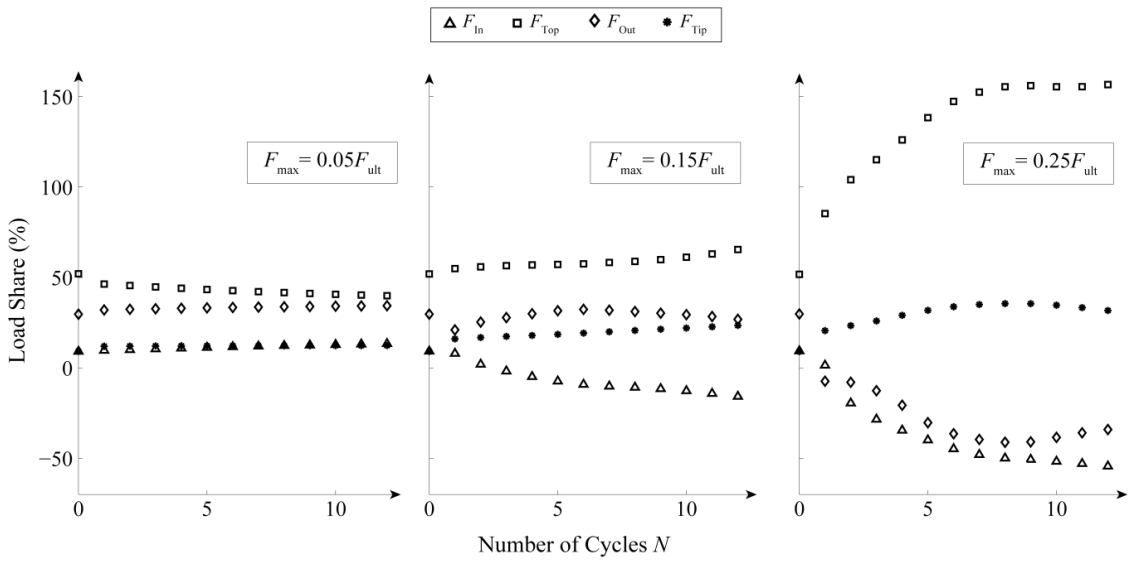

Figure 10. Percentage shares of the axial loads via the top plate, the outer and inner skirt, as well as bucket base for different cyclic loading levels at the end of each loading cycle

For the case attenuation ($F_{max} = 0.15F_{ult}$), if the share of loading at the end of each cycle is analysed closer, it can be seen that the percentage shares for inner skirt have negative values. The accumulated excess pore pressure (Figure 9) caused a reduction of soil effective stresses and due to the unloading, additional decrease in soil effective stresses led to a greater soil movement compared to the bucket. The resulting negative friction forces additionally acted to the inner skirt. When viewing the case progressive failure ($F_{max} = 0.25F_{ult}$), during unloading, a greater upward soil movement relative to the bucket was calculated also at the soil outside of bucket which can be traced back to excessive pore pressure accumulation as shown in Figure 9. The pore pressure accumulation was the substantial factor that led to system instability.

8 CONCLUSION

The behaviour of a bucket in saturated sandy soil was investigated focusing on the load transfer of top plate, skirt and base in respect to the cyclic axial compressive loading. Numerical studies led to the following results:

- The bucket response can be classified depending on the cyclic loading level as; shakedown, attenuation and incremental collapse
- The cyclic loads were transferred into the soil predominantly via top plate and the outer skirt for the case of shakedown.
- In the case of attenuation and incremental collapse, a greater soil movement relative to bucket was determined due to the excess pore pressure accumulation in soil, which caused additional loads on the bucket.

At present, there are no verified practical design methods for the buckets subjected to cyclic loading. Therefore, the aim of the further investigations will be to formulate a practical design model, which might enable the determination of expected bucket displacements over the service life time taking into account the cyclic accumulation effects. The proposed model must also be verified by further experimental tests.

9 ACKNOWLEDGEMENTS

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