14th EAWE PhD Seminar on Wind Energy
18-20 September 2018
Vrije Universiteit Brussel, Belgium

Lifetime tilting prediction of offshore wind turbine foundations due to soil strain accumulation

G Zorzi[a], F. Kirsch[a], T. Richter[a]

M.U. Østergaard[b], S.P.H. Sørensen[b]

[a] GuD Geotechnik und Dynamik Consult GmbH, Berlin, Germany
[b] COWI A/S, Aalborg, Denmark

E-mail: zorzi@gudconsult.de

Abstract. Cyclic loading can lead to progressive degradation of soil in terms of plastic strain accumulation, pore pressure build-up, and changes in soil strength, soil stiffness and stress redistribution, which may significantly influence the behaviour of offshore wind turbine foundation structures throughout their lifetime. The prediction of these effects is of vital importance for the design of offshore wind turbine foundations, yet there is a lack of a generally accepted method to account for cyclic loading conditions. The present paper introduces the application of an innovative explicit method to predict the accumulated foundation displacement under cyclic loading for different foundation types. The explicit method integrates cyclic contour diagrams derived from cyclic laboratory tests into the finite element software PLAXIS by means of a remote scripting interface. The effect of cyclic degradation is taken into account by reducing the elastic shear modulus of the soil in a cluster-wise division in the finite element mesh. The interface automates the model creation in terms of meshing, cluster division, load parcel application and soil parameter degradation, which is optimal as it minimizes the amount of manual work and the risk related hereto. Application examples of the method for different offshore wind turbine foundations (such as gravity based foundations, monopiles and suction buckets) under a design storm condition are presented. This paper demonstrates the advantages of the developed method in terms of automatized design while taking into account the 3D behaviour of soil surrounding the foundations.

Keywords: Offshore foundations, Cyclic loading, Accumulation of displacements, Numerical modelling.

1 Introduction

During the detailed design phase of offshore wind turbine (OWT) foundations, the structures have to be evaluated for fatigue to ensure that they will withstand the variable and cyclic environmental loads maintaining the operational and safety level throughout their intended design life (typically 25 years) [1]. The prediction of the fatigue life of the foundation embedded in the soil is generally not easily included. This needs to be based on an accurate modelling of the soil-structure interaction under cyclic loading conditions.

Occasionally, soil fatigue models [2] are used in geotechnical engineering projects. These types of models explicitly predict the behaviour of cyclic loaded soil by using empirical formulations based on the number of cycles and calibrated against constant stress amplitude tests. One of them is the Fatigue (or Cyclic) Contour Diagram Model [3]. The concept of the contour diagrams is to provide a relation for the chosen response of the material (fatigue variable) subjected to N number of cycles and certain stress conditions (mean and amplitude stress). This fatigue model is interpolated from laboratory test campaigns. Different "fatigue" variables (i.e. different sets of contour diagrams) can be derived such as average and cyclic pore pressure, average and cyclic shear strain, damping and stiffness. These diagrams can be used independently for predicting the soil-structure interaction under cyclic loading (i.e. earthquakes or storm events): accumulation of deformation (serviceability problems), liquefaction evaluation (stability problems), and change in damping and stiffness (useful for dynamic analysis).

One of the operational restrictions for wind turbine manufacturers is to ensure that the maximum tilting of the structure during its lifetime is less than e.g. 0.25°. In order to make use of the previous soil fatigue models, assumptions need to be made about the loading conditions. Offshore wind turbines experience more than 10^8 cycles during their lifetime. The nature of these cyclic loadings is random over time and regarding the direction. Therefore, it is common practice for wind turbine manufacturers to provide the irregular variation of extreme loads of an *n*-year return period storm events, which is assumed to have the most significant impact on the foundation during its lifetime. The irregular load series of the selected storm event is then broken down to a series of ascending parcels with constant mean and amplitude loads and number of cycles.

The cyclic explicit method explained in [4,5] is considered in the present paper for different case studies. The methodology is defined to evaluate the tilting of a foundation due to the application of an ascending series of regular load packages. The fatigue variable used is the average shear strain. The effects of cyclic degradation in terms of plastic strain accumulation are considered by the modification of a fictional elastic shear modulus of the soil in a cluster-wise division in the finite element domain. The reduction of the soil modulus is based on the Fatigue (or Cyclic) Contour Diagram framework, which is embedded in the Finite Element domain. This is achieved through the use of a Python interface, which allows for a fast communication between the finite element model and the cyclic contour diagram (figure 1). The method is implemented in the commercial code PLAXIS 3D, which consent to develop automatic model by means of a remote scripting interface based on Python language [6].

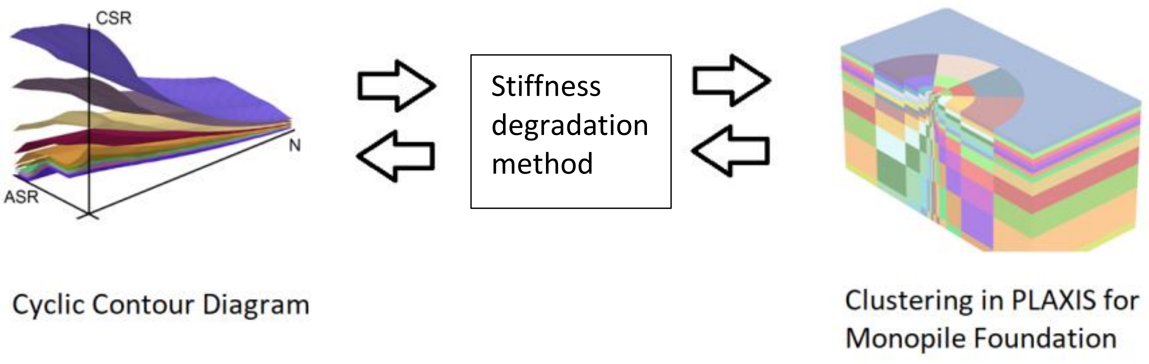

Figure 1 Framework of the method

The paper will briefly shows the cyclic contour diagrams, typically for North Sea sand, which will be used for the case studies. Then the explanation of the methodology, from the load application to the reduction of the shear modulus, and the final application for different wind turbines foundations, will be presented.

2 Fatigue Contour Diagram Model

In the present method a basic ingredient for the prediction of the behavior of the foundations under the design storm event is the development of fatigue contour diagrams representative of the soil condition, stress distribution and stress path under the considered foundation. In [3], an exhaustive explanation of the basic concepts is given.

The soil considered in the following case studies is typical for North Sea sand with a relative density of 90%. The contour diagrams have been extrapolated from stress-control two-way cyclic simple shear tests performed at the Soil Mechanics laboratories of the Technical University of Berlin. The tests were carried out undrained (constant volume) with different mean and amplitude stresses. The Average Stress Ratio (ASR), which is defined as the ratio between the average shear stress and the vertical effective stress in the tests, ranges from 0.00 to 0.26, while the Cyclic Stress Ratio (CSR), which is the ratio between the cyclic shear stress and vertical effective stress in the tests, ranges from 0.02 to 0.26. The present methodology is focused on the prediction of the strain accumulation. Therefore, the fatigue variable extracted from the tests was the average plastic shear strain γ_p at the end of each cycle. Figure 2 shows two contour plot slices (log(N)-CRS, where N is the number of cycles) of the 3D data at different ASR. The different surfaces represent the average plastic shear strain γ_p.

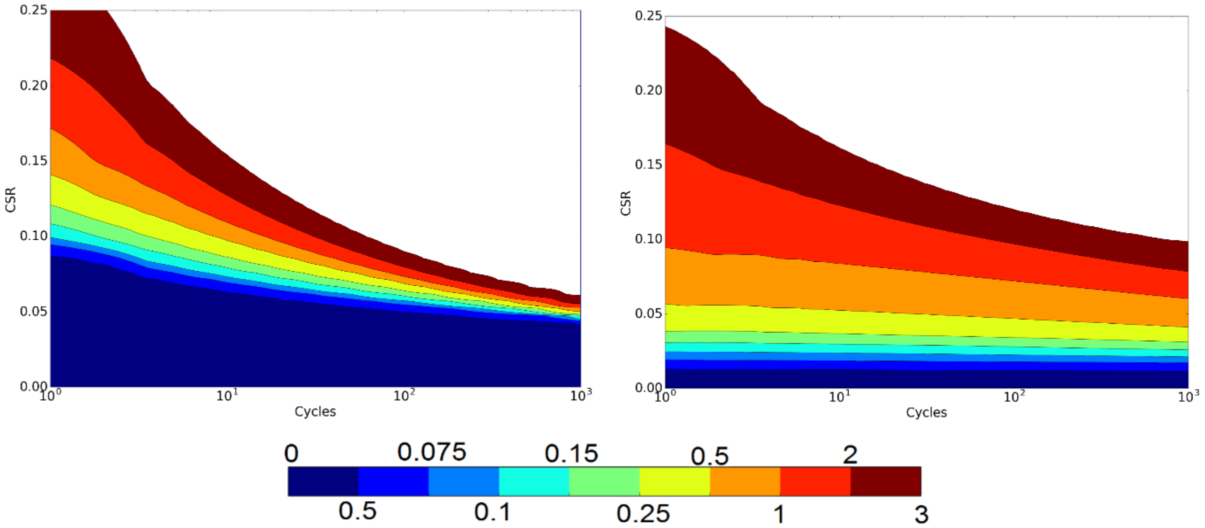

Figure 1 Cyclic contour diagrams of average plastic shear strain, γ_p, shown in percentage. Left figure – ASR equals 0.02. Right figure – ASR equals 0.20.

3 Method explanation:

Of the methods explained in [4], "*method 2*" is the preferable one in which the equivalent number of cycles is used to take into account the strain history between the parcels (damage accumulation). Figure 3 [4] shows the procedure in which three independent parcels are applied and in each parcel an equivalent number of cycles is used to take into account the previous accumulation of strain (dashed blue lines).

The present method requires an extensive exchange of information between the cyclic contour diagram framework and the Finite Element Method. Table 1 describes the steps taken in the python script. The [i] denotes input steps in PLAXIS Input, while [o] denotes the steps after the phase calculation in which PLAXIS Output is open in order to retrieve the stress and strain values from the stress points. The explicit method is presented thoroughly in [4].

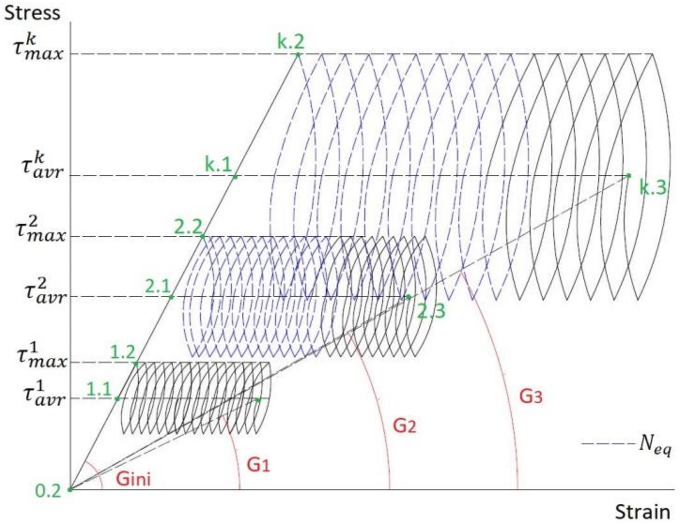

Figure 2 Accumulation procedure [4]

Table 1 Steps in the Finite Element Method

Phases	**Description**
0.1	[i] Cluster division of the soil domain a. A function has been developed in order to automatize the cluster division. [i] Assign a material set with the initial shear modulus G_{ini} to each cluster a. A very fine cluster division required the creation of a high amount of Material Set, hence increasing the computational time [i] K0 procedure
0.2	[i] Installation of the foundation (wished into place) [o] Extraction of cartesian strain and stress tensors for each Stress point Average of the stress tensors for each Cluster: $\boldsymbol{\epsilon}^{ini}, \boldsymbol{\sigma}^{ini}$
1.1	[i] Application of Average Loads [o] Extraction of cartesian strain and stress tensors for each Stress point Average of the stress tensors for each Cluster: $\boldsymbol{\epsilon}^{avr}, \boldsymbol{\sigma}^{avr}$ Calculation of the Average Stress Ratio ASR and the initial shear strain γ_{ini}
1.2	[i] Application of Maximum Loads [o] Extraction of cartesian stress tensors for each Stress point Average of the stress tensors for each Cluster: $\boldsymbol{\sigma}^{cly}$ Calculation of the Cyclic Stress Ratio CSR Extrapolation of $\gamma_n(ASR, CSR, \gamma_{ini}, N, N_{eq})$ from the 3D Cyclic contour diagram for each cluster Calculation of G_n for each cluster (Eq. 1)
1.3	[i] Assign new material properties G_n for each cluster Application of Average Loads

The present scripts based on few inputs (foundation dimension, cluster division and load conditions) can give a fast evaluation of the predicted tilting of the foundation for the considered design storm event. Moreover, the use the automatic design procedure allows to run more simulations in order to take into account the uncertainty on the cyclic contour diagram on the final tilting of the foundation.

4 Case studies

In order to illustrate the applicability of the presented explicit method, three different types of offshore wind turbine foundations are modelled. Hence, the applied loading, the soil profile and the foundation dimensions are fictious. A uniform soil profile of dense sand typical of the North Sea is employed in all analyses (chapter 2). The soil parameters for the Mohr-Coulomb constitutive model are shown in Table 2. The 3D matrix of the cyclic contour diagrams is attached to the scripts. Table 3 shows load values at the mudline for a design storm event. To simplify, the same load series are applied for all the case studies. The load series consist of four load parcels each with an average and maximum horizontal force and overturning moment and a number of load cycles. Regarding the cluster division, a large stress variation is expected to occur in the vicinity of the foundations and therefore smaller clusters are used. The soil is then divided in larger clusters further away from the structure in order to reduce the computational time. A mean water level of 30 m is assumed in all the case studies.

Table 2 Soil model parameters

Soil Parameters	Values
E [MN/m^2]	76
ν [-]	0.2
φ [°]	36
ψ [°]	0
γ_{sat}[kN/m^3]	18
γ_{Unsat}[kN/m^3]	9

Table 3 Load Parcels

Load Parcel	H_{avr} $[kN]$	H_{max} $[kN]$	M_{avr} $[kNm]$	M_{max} $[kNm]$	Number of Cycle
1	1000	1500	30000	50000	700
2	2000	3000	50000	85000	500
3	3000	5000	70000	115000	100
4	4000	7000	80000	150000	20

4.1 Gravity Based Foundations (GBF)

The dimensions of the gravity based foundation and the cluster dimension of the soil domain are presented in figure 4. To each cluster a soil material is assigned, hence the clusters are represented with different colours (figure 4). The substructure consists of a base plate, a conical and a cylindrical section. A constant vertical force of 15 MN is applied to account for the weight of the superstructure. The interface element is used for the reduced shear strength at the GBF surface. The reference point for the load application is the mudline. The "fictious degradation phase", i.e. the reduction of the stiffness modulus, from the last parcel is shown in figure 5. The figure is a slice of the soil domain along the loading direction and shows the variation of the Young's modulus in each cluster. The accumulation of deformations are extending up to 21 m below the foundation base.

4.2 Monopile

The pile dimension are shown in figure 6. The pile is modelled as a hollow rigid body cylinder and interface elements are used for the reduced shear strength at the pile surface. The monopile is modelled until 2 meters above the mudline. The reference point for the load application is the mudline. The clusters division has been chosen as in figure 7. Finer clusters are chosen close to the pile. A vertical load of 20 MN is applied to account for the entire load of the structure. Figure 7 shows the stiffness degradation of the Young’s modulus for each clusters due to the application of the last parcel. The soil is accumulating deformations up to 55 meters below the mudline.

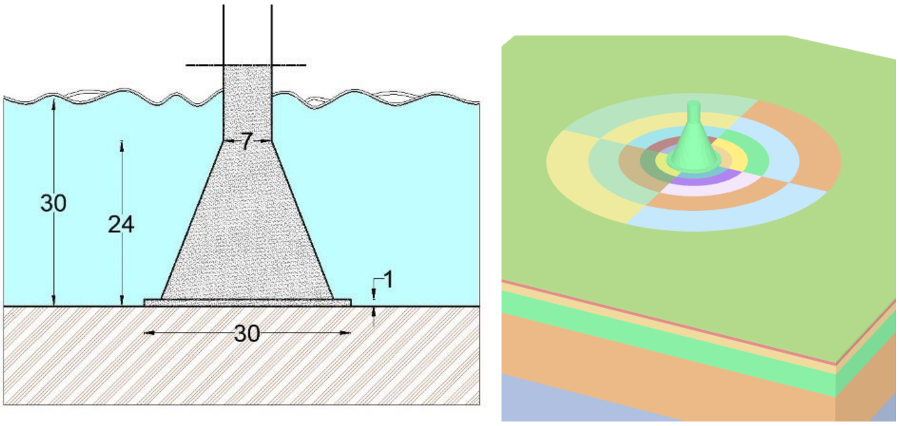

Figure 3 GBF dimension and cluster division of the soil domain

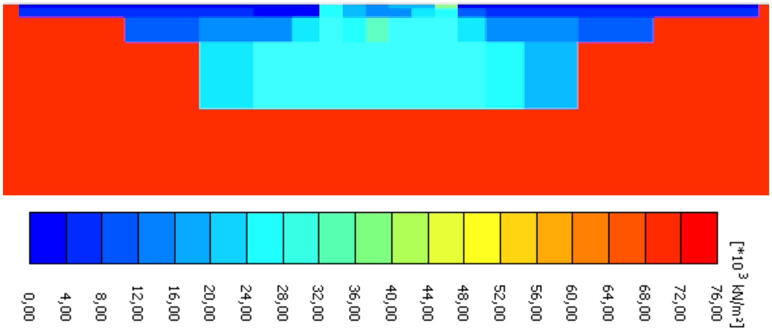

Figure 4 Young's modulus degradation at the last loading parcel over the clusters for the GBF

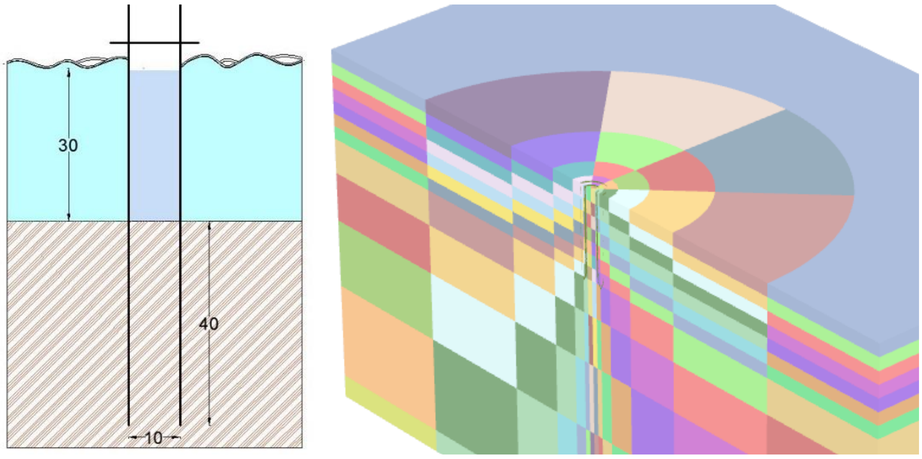

Figure 5 Monopile dimension and cluster division of the soil domain

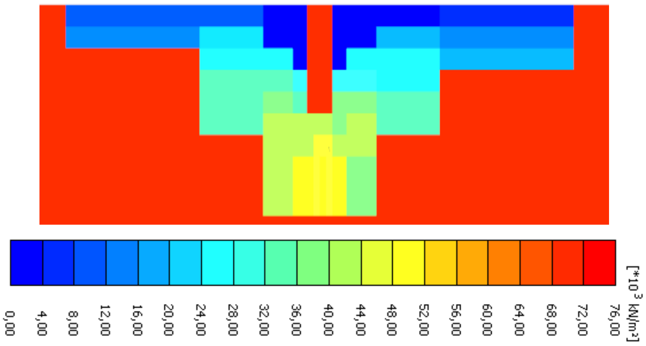

Figure 6 Young's modulus degradation at the last loading parcel over the clusters for the monopile

4.3 Suction bucket foundation

The dimension of the suction bucket is shown is figure 8. The bucket is modelled as a hollow rigid body cylinder with a rigid cap and interface elements are used to account for the reduced shear strength at the pile surface. The cluster division of the soil domain is chosen as in figure 8. Finer clusters are present close to the foundation. The soil deformation are developing until a depth of minus 40 m from the mudline (figure 9).

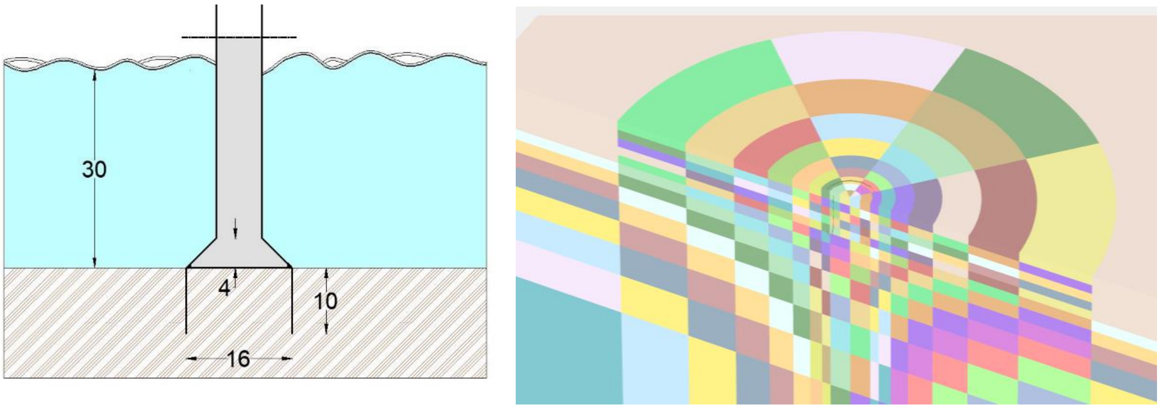

Figure 7 Suction bucket dimension and cluster division of the soil domain

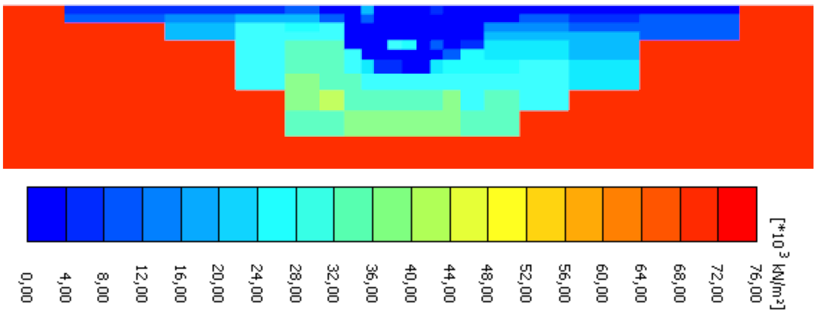

Figure 8 Young's modulus degradation at the last loading parcel over the clusters for the suction bucket

5 Output of the method and future development

The output of the presented analysis is the accumulated foundation tilting during the storm event. Figure 10 shows the comparison of the relative inclination along the loading direction of the three foundations subjected to the same design storm. For each foundation, the rotations are normalized with the initial rotation (parcel 1). The automatic modeling of the tilting makes it suitable for a design optimization of the foundation against the maximum allowed tilting.

The link between the cyclic contour diagrams and the stiffness degradation method seems promising. The python script developed for the above case studies can easily be adapted with different structural geometries and different soil layers by changing few inputs. Even though the calculation and creation of the model have been automatized with the python interface, some effort to create the cyclic contour diagrams is required.

Different improvements and method validations are under way:

1. Validation of the fictious stiffness phase against laboratory tests and validation against full scale tests.

2. The possibility of integrating a convergence criteria between the expected strain from the contour diagrams and the strain developed by the FEM model after the "fictious degradation phase".
3. The sensitivity of different cluster divisions of the soil domain to the final foundation tilting will be analysed
4. Effect of uncertainty of the cyclic contour diagram on the predictions of accumulated tilt.

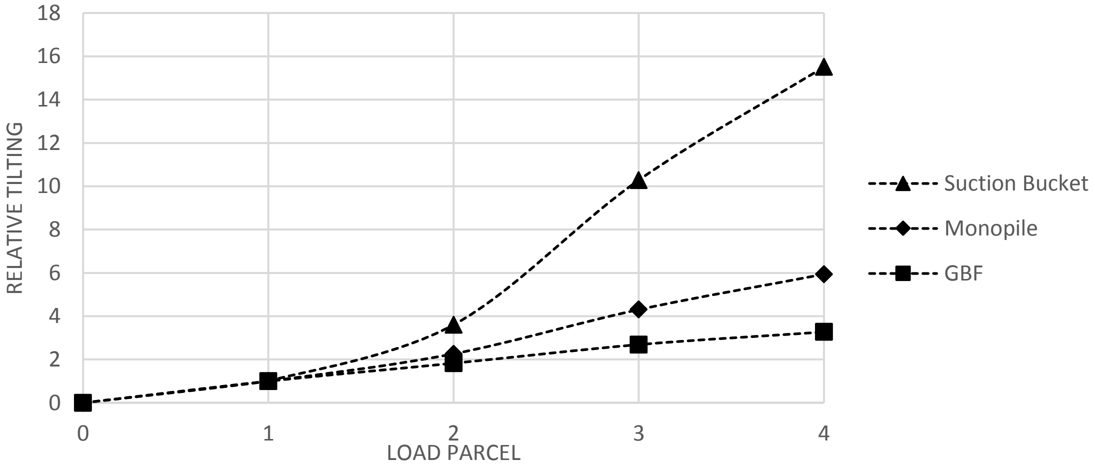

Figure 9 Relative accumulated tilting

Acknowledgements

This research is part of the Innovation and Networking for Fatigue and Reliability Analysis of Structures - Training for Assessment of Risk (INFRASTAR) project. This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No. 676139.
The laboratory tests are provided by the Chair of Soil Mechanics and Geotechnical Engineering of the Technical University of Berlin. We are grateful for the kind permission to use those test results.

Bibliography

[1] Velarde, J., Kramhøft, C., & Sørensen, J. D. (2018). Uncertainty Modeling and Fatigue Reliability Assessment of Concrete Gravity Based Foundation for Offshore Wind Turbines. International Society of Offshore and Polar Engineers.
[2] Allotey, N. and El Naggar, M.H. (2005). "Cyclic soil degradation/hardening models: a critique". Proc. of 16th International Conference of Soil Mechanics and Geotechnical Engineering. MillPress Science Publishers, Rotterdam, 785-790.
[3] Andersen, K.H. (2015), "Cyclic soil parameters for offshore foundation design". The 3rd McClelland Lecture. Frontiers in Offshore Geotechnics III, ISFOG'2015, 1, 5-82.
[4] Zorzi, G., Richter, T., Kirsch, F., Augustesen, A. H., Østergaard, M. U., & Sørensen, S. P. H. (2018). "Explicit Method to Account for Cyclic Degradation of Offshore Wind Turbine Foundations Using Cyclic Interaction Diagrams". International Society of Offshore and Polar Engineers.
[5] Kirsch, F., Richter, T., Schädlich, B., Wiesener, S. (2016)."Ansatz zur Erfassung der Porenwasserdruckakkumulation bei Offshore-Monopilegründungen", Der Bauingenieur, 91(1), 26-33
[6] PLAXIS (2017). "Plaxis 3D, Reference Manual", Edited by Brinkgreve, R.B.J., Kumarswamy, S., Swolfs, W.M., and Foria F.