PO.ID 013

Non-linear foundation modelling in multi-footing suction bucket design

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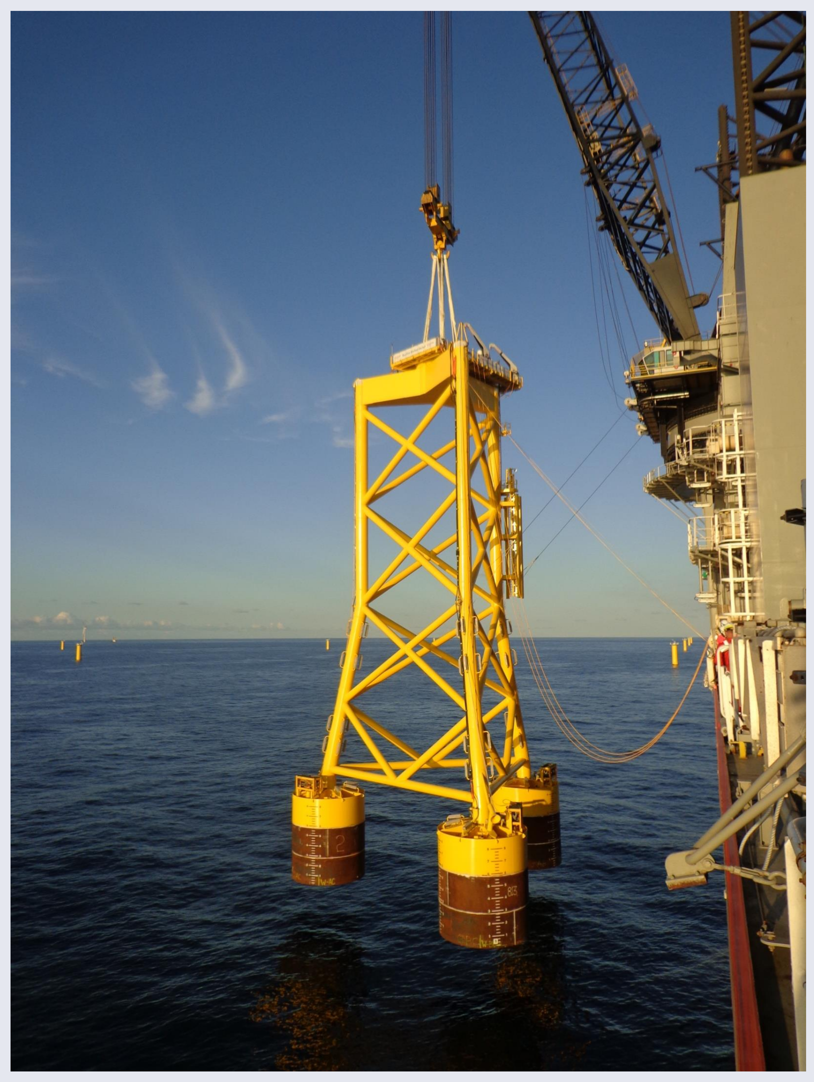
Abstract

Suction buckets are a type of offshore foundation that allow for fast and practically noise-free installation and decommissioning of offshore structures. They have been used for more than 30 years in the oil and gas industry and are also becoming more common in the offshore wind sector. SPT Offshore is the leading contractor for design and installation of suction buckets and has installed suction buckets for offshore substations (e.g. Global Tech I) as well as turbine foundations (Borkum Riffgrund I).

For an efficient design of foundations with multiple suction buckets the interaction between substructure and foundation has to be taken into account, as it determines how loads on the structure are transferred to each of the buckets. Suction buckets are currently implemented as linear elements in a structural model of the substructure. New foundation elements have been created to include non-linear soil behaviour.

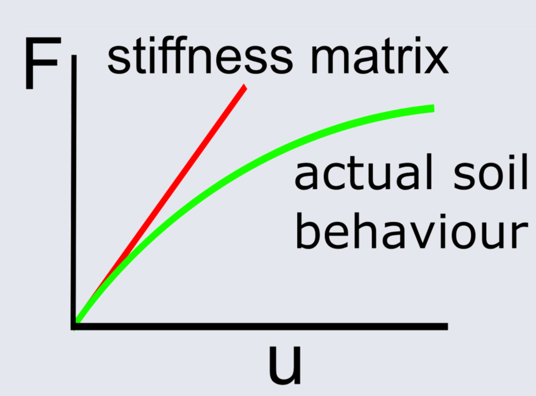


1. Installation by SPT Offshore of a jacket with 3 suction buckets for a wind turbine foundation in the Borkum Riffgrund wind farm for DONG Energy.

Objectives

Foundation elements have to describe the relation between loads acting on the suction bucket foundation and the resulting foundation displacements. This is currently done by means of a stiffness matrix. A stiffness matrix contains a set of spring constants that can be determined from literature, see e.g. Reference [1-5], or Finite Element (FE) or Boundary Element (BE) analysis. As such it represents a linear-elastic soil behaviour. An example stiffness matrix [6] is given below:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} K_h & 0 & 0 & 0 & -K_{hr} & 0 \\ 0 & K_h & 0 & K_{hr} & 0 & 0 \\ 0 & 0 & K_v & 0 & 0 & 0 \\ 0 & K_{hr} & 0 & K_r & 0 & 0 \\ -K_{hr} & 0 & 0 & 0 & K_r & 0 \\ 0 & 0 & 0 & 0 & 0 & K_t \end{bmatrix} \cdot \begin{bmatrix} u_x \\ u_y \\ u_z \\ \theta_x \\ \theta_y \\ \theta_z \end{bmatrix}$$

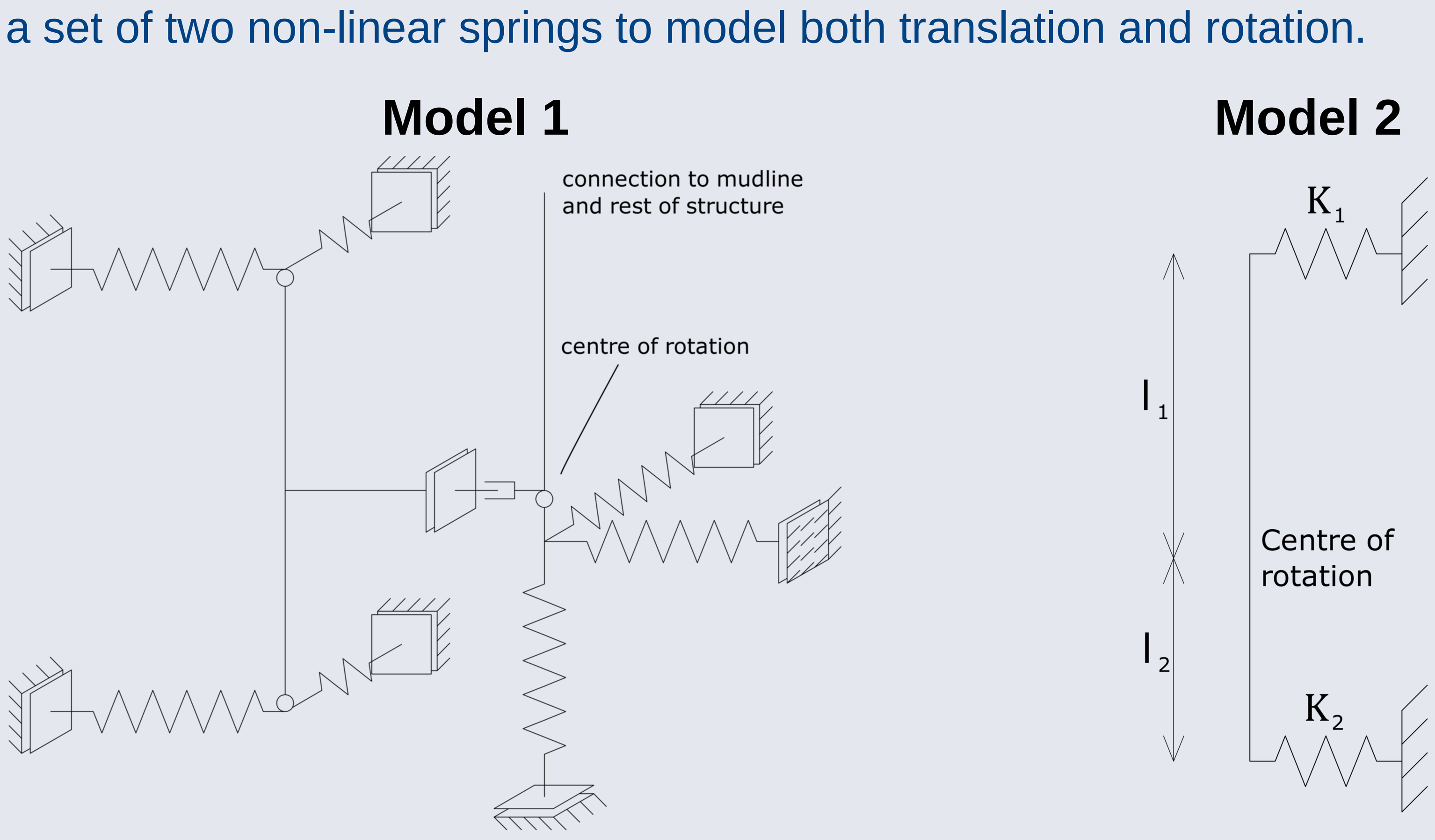


2. Load-displacement behaviour for a suction bucket foundation

In reality soil behaviour is non-linear, and an increase of the load on the suction bucket will lead to a decreasing soil stiffness. Using a linear stiffness matrix as a foundation element thus leads to incorrect and conservative foundation loads. The goal is to define foundation elements for suction bucket foundations that describe a non-linear load-displacement behaviour and lead to a more efficient design.

Methods

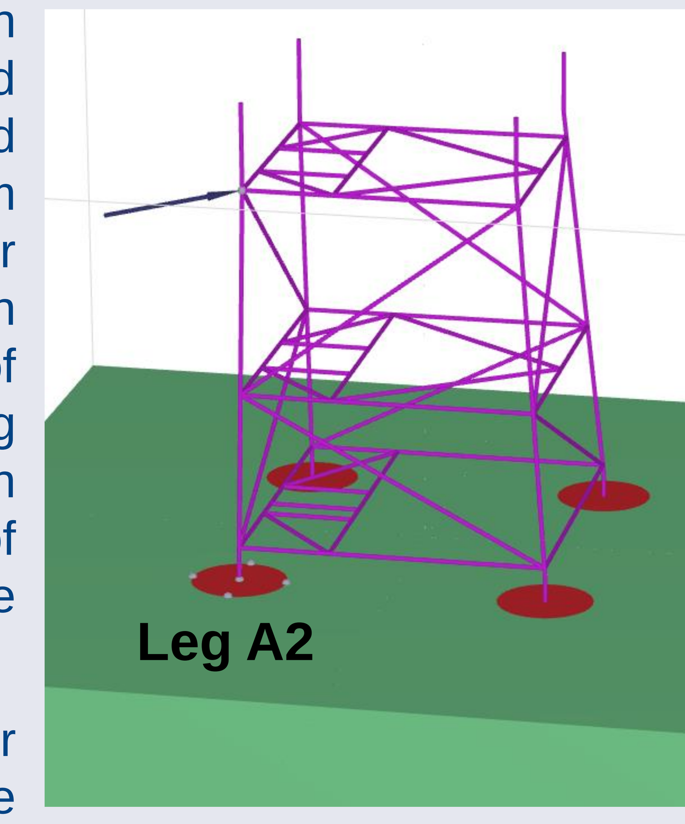
Two non-linear foundation elements for use in the structural software SACS have been developed, that will be compared to a Plaxis 3D model of the foundation and a linear system with stiffness matrices. The foundation elements are sets of non-linear springs that describe the load-displacement behaviour of the complete suction bucket. The behaviour of the springs is determined in a FE model of a single suction bucket. Since it is not possible to use stiffness matrices with coupling between the degrees of freedom by means of off-diagonal terms in a non-linear system, the coupling between lateral translation and rotation needs to be accounted for in a different way. In the first model this is done by attaching the springs to the centre of rotation of the suction bucket, located in a point inside the soil, where all degrees of freedom are uncoupled. The second foundation model uses a set of two non-linear springs to model both translation and rotation.



3. Diagrams of the two models for suction bucket foundations with non-linear springs

Results

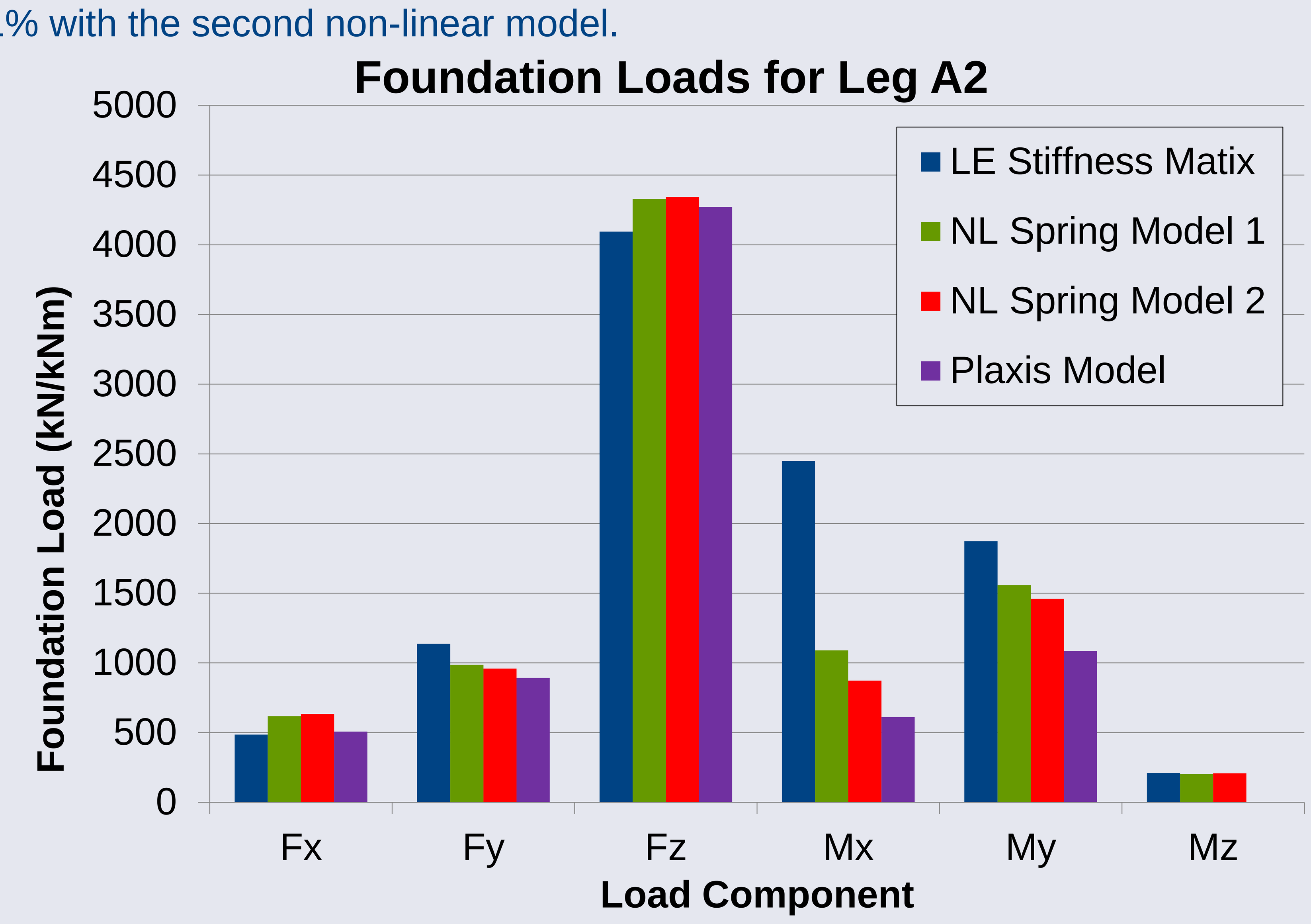
The two non-linear foundation models have been compared with the linear foundation model and the non-linear Plaxis model for a jacket founded on four suction buckets of 7 m diameter and 7 m length. Since the FE model does not allow for direct input of wave loading the foundation models have been compared for a point load of 4.2 MN acting on the top frame of the jacket along the jacket diagonal. The applied load is shown in the Figure 4 on the right. The soil consists of dense sand which is modelled using the Hardening Soil model.



4. FE model of the suction bucket foundation and substructure with the load applied for comparison

Foundation reaction loads for each of the four suction buckets have been determined at the connection between the jacket and suction bucket at sea bed level. The foundation loads for the bucket loaded in tension found using the different foundation models are given in the Figure below. It can be seen that the non-linear spring models give foundation loads close to the foundations loads found in the Plaxis model, whereas the linear foundation model gives deviating loads, especially for the rocking moments. On average the difference between the reaction loads found on the four buckets using the linear-elastic foundation model and the Plaxis model is 52%, while the difference of the Plaxis model with the first non-linear foundation model is 18% and with the second non-linear model 13%.

The comparison of foundation displacements and rotations, not shown here, gives similar results as for the loads. On average the displacements found in the Plaxis model differ 67% with the linear model, 24% with the first non-linear model and 11% with the second non-linear model.



5. Comparison of foundation loads found for the suction bucket with maximum vertical reaction load using various foundation models

Conclusions

Two non-linear foundation models based on non-linear springs have been developed and compared with a linear stiffness matrix and a non-linear Plaxis model for a simple load case. The comparison shows that using stiffness matrices to model the foundation gives results that differ significantly from the results for the non-linear models and seem inaccurate.

The non-linear spring models on the other hand give results that show good agreement with the Plaxis model results. Since the non-linear springs are implemented in a structural model they have several benefits over the use of a Plaxis model, including a shorter calculation time which allows for the evaluation of multiple load cases, the possibility to use environmental data directly as load input and the possibility to determine torsional moments acting on the foundation.

Compared to a stiffness matrix the non-linear foundation elements give more accurate results and show a more equal distribution of the load over the buckets, which allows for a more efficient bucket design and thus helps reduce the LCOE.

References

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