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On the influence of jack-up footprints on the dynamic behaviour of offshore foundations

Influence de l'empreinte des jack-up sur le comportement dynamique des fondations offshore

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ABSTRACT: Jack-up vessels are frequently used to install offshore structures. These vessels are shipped to the construction site and then lifted out of the water using their legs to create a stable working platform. Shallow foundations, so-called spudcans, are attached to the legs and pressed into the ground until sufficient bearing capacity is achieved. When the construction work is finished, the spudcan is pulled out of the ground again and usually a footprint remains representing a hole in the seabed. As the installation of offshore structures usually consists of several construction phases, several jack-up vessels are placed around the structure at different times and each vessel leaves several footprints. The influence of footprints on the dynamic behaviour of offshore structures is exemplified by the foundation of offshore wind turbines. The investigations were carried out with numerical simulations using the FEM. The influence of the footprint location as well as its distance to the structure is investigated. General recommendations are given and how this influence can be addressed in the design of the structure.

RÉSUMÉ: Les navires de type "jack-up" sont fréquemment utilisés pour l'installation de structures offshore. Ces navires sont transportés jusqu'au site de construction, puis soulevés hors de l'eau à l'aide de leurs pieds afin de créer une plate-forme de travail stable. Des fondations peu profondes, appelées "spudcans", sont fixées aux jambes et enfoncées dans le sol jusqu'à ce que la capacité portante soit suffisante. Lorsque les travaux de construction sont terminés, le spudcan est à nouveau retiré du sol et il ne reste généralement qu'une empreinte représentant un trou dans le fond marin. Étant donné que l'installation de structures offshore se compose généralement de plusieurs phases de construction, plusieurs navires autoélévateurs sont placés autour de la structure à différents moments et chaque navire laisse plusieurs empreintes. L'influence des empreintes sur le comportement dynamique des structures offshore est illustrée par les fondations des éoliennes offshore. Les recherches ont été menées à l'aide de simulations numériques utilisant la méthode des éléments finis. L'influence de l'emplacement de l'empreinte et de sa distance par rapport à la structure est étudiée. Des recommandations générales sont données sur la manière dont cette influence peut être prise en compte dans la conception de la structure.

Keywords: Offshore; jack-up; spudcan; FEM.

1 INTRODUCTION

Jack-up vessels are extensively used oil and gas exploration and in the offshore wind sector for the installation of wind turbines. These vessels are transported to their designated deployment sites, where they lower their legs to elevate the platform above the seawater level. This operational method ensures a higher degree of safety compared with conventional floating vessels, as the impact of sea conditions and water levels on jack-up vessels is less pronounced.

In oil and gas applications, jack-up legs can reach lengths of up to 170 m, with spudcan diameters reaching 20 m (refer to Figure 1). However, in the offshore wind industry, where water depths are shallower and the focus is solely on tower and turbine installation, the dimensions of jack-up vessels are significantly smaller. This fast-paced industry demands layout flexibility when positioning turbines offshore, considering various constraints such as seabed features such as cables and crane length limits. Consequently, it is imperative to assess the stability of jack-up vessels and load-bearing capacity of their spudcans across different soil types and layers.

On certain occasions, jack-up vessel spudcans may penetrate several meters of soft soil, significantly disturbing the soil and creating footprints with crater-like depressions. In scenarios where vessels revisit the same location for repeated jack-up activities, the necessity of reusing the same footprint for spudcan re-installation arises. This aspect has been investigated by researchers such as Stewart and Finnie (2001), Cassidy et al. (2009), Qiu et al. (2013), and Jun et al. (2018).

All of these studies involve centrifuge testing and numerical modeling utilizing the Coupled Eulerian-Lagrangian method. They collectively conclude that spudcan resistance, both vertically and horizontally, decreases after reinstallation within a footprint area.

Additionally, researchers, including Leung et al. (2012), Liang et al. (2020) and Molina Mesa et al. (2023) have extensively evaluated the induced load on existing foundations resulting from adjacent spudcan penetrations and the impact of footprints on the vertical bearing capacity of nearby piles. Notably, this study delves into a comprehensive examination of horizontal capacity, particularly for relatively short foundations such as suction caissons.

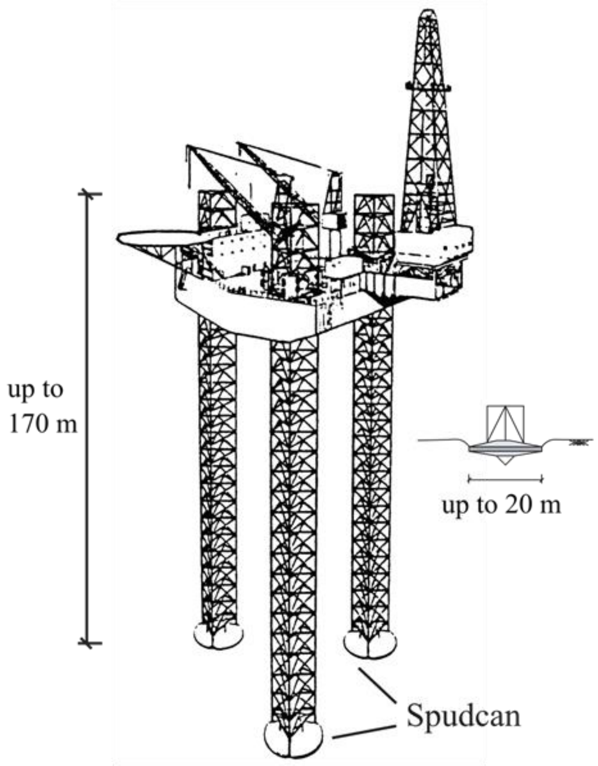

Figure 1. Illustration of a jack-up platform with three legs and spudcans including a detailed spudcan with central tip (modified after Reardon, 1986).

2 NUMERICAL MODEL

Numerical analyses are performed using the finite element software package Plaxis 3D Version 2023.2.0.1059. To save computational time, as the geometry is symmetrical, only half of the monopile and footprint is modelled.

2.1 Soil

A homogenous soil profile consisting of a single sand layer is selected for this study. The material parameters for the sand are listed in Table 1. The Hardening Soil Small Strain Model is used as material model for the sand to account for the stress dependency of the stiffness, loading history and small strain effects.

Table 1. Material parameter for the Hardening Soil Small Strain Model.

Parameter	Value
γ / γ'	19.6 / 9.6 kN/m^3
E_{50}^{ref}	30000 kN/m^2
E_{Oed}^{ref}	30000 kN/m^2
E_{ur}^{ref}	100000 kN/m^2
ν_{ur}	0,20
m	0,50
φ'	40°
c'	0.001 kN/m^2
ψ	0.0
G_0^{ref}	120000 kN/m^2
$\gamma_{0.7}$	0.00045
p_{ref}	100 kN/m^2

2.2 Monopile

The monopile has a penetration depth of 30 m and a free length above the seabed level of 50 m. The free length is chosen to consider a realistic combination of lateral and moment loading magnitudes at the seabed level. The outer pile diameter is 8 m. The pile is modelled using plate elements and the wall thickness is assumed to be 70 mm.

To evaluate the lateral stiffness of the monopile, the head of the monopile is moved horizontally while the reaction force is calculated. The lateral displacements at the seabed level are evaluated and compared with calculations with and without the footprint of a spudcan.

The load level of the monopile is taken as 1.5 MN in the fatigue limit state (FLS) and 10.0 MN in the ultimate limit state (ULS).

2.3 Soil pile interaction

The soil pile interaction is modelled using interface elements. The material for the interface elements is taken from the surrounding soil considering a wall friction angle of 2/3φ'.

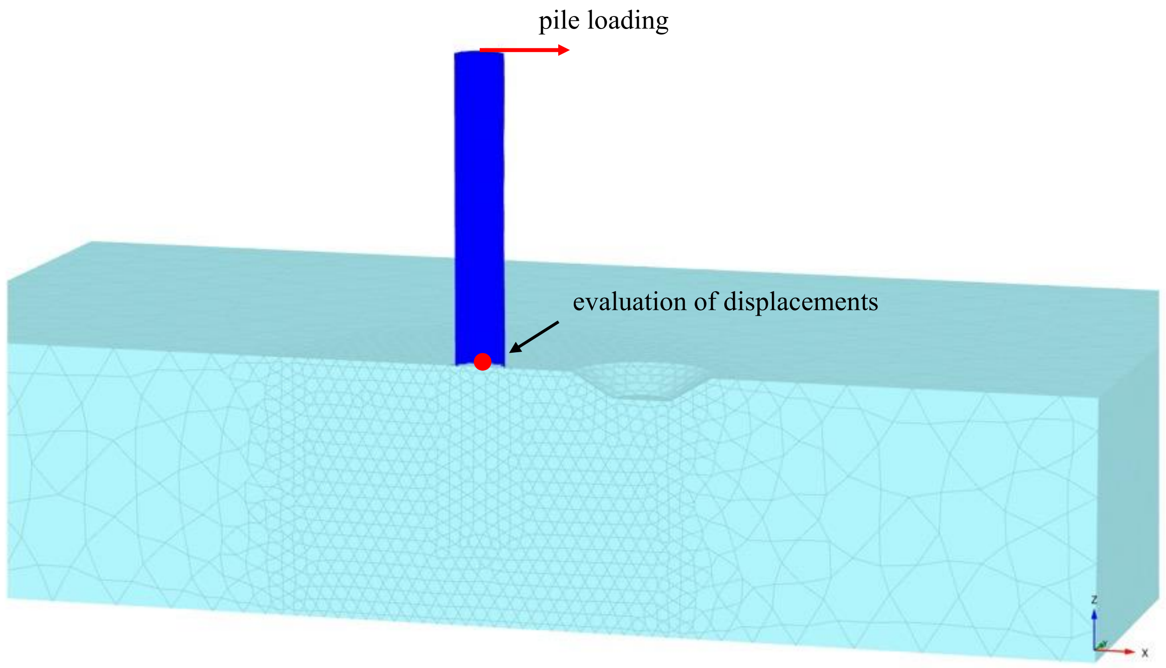

Figure 2. Numerical model of soil and pile including a footprint in 15 m distance.

2.4 Footprint

The geometry of the footprint is chosen based on offshore measurements of real footprint geometries. The geometry of the footprint is simplified as a truncated cone. The depth of the footprint is assumed to be 4 m while the diameter at the bottom of the footprint is 9.5 m and the diameter at the seabed level is 23.0 m. The distance between the footprint and monopile is varied in this study between 5.0 and 20.0 m.

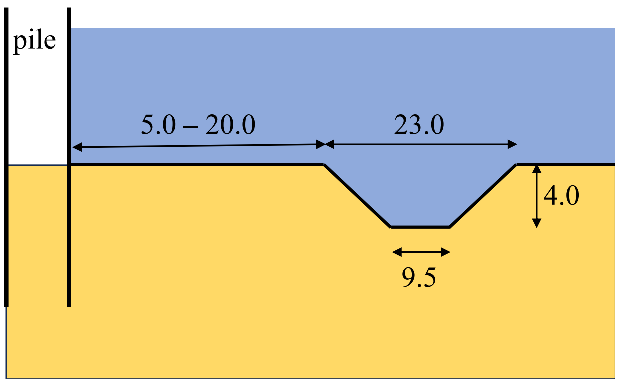

Figure 3. Geometry of the footprint and distance to monopile.

3 RESULTS

The load deflection curves for the ULS load are shown in Figure 4. As expected, decreasing the distance between the footpad and monopile increased the pile deflection at the seabed level. Hence, the horizontal stiffness of the pile soil interaction decreases resulting in a softer load response of the monopile.

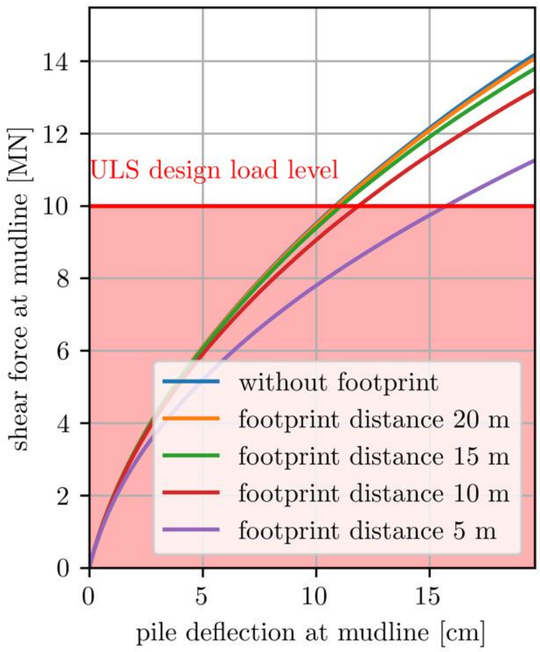

Figure 4. Load deflection curve for ULS load level considering multiple distances between monopile and footpad.

A detailed illustration of the effect of the footprint on the initial stiffness at lower load levels, such as the FLS load level, is shown in Figure 5. The influence on the initial stiffness of the pile soil interaction is much smaller than that on the stiffness at the ULS load level for distances larger than 10 m.

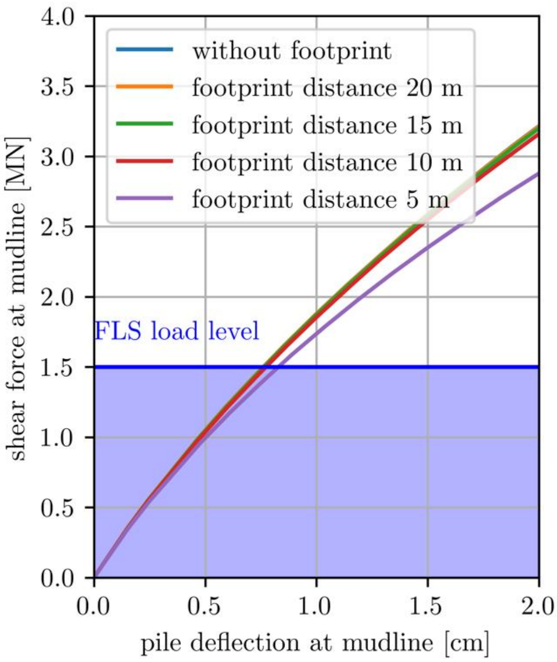

Figure 5. Load deflection curve for FLS load level considering multiple distances between monopile and footpad.

The relative change in lateral stiffness depending on the distance between the monopile and the footprint is shown in Figure 6.

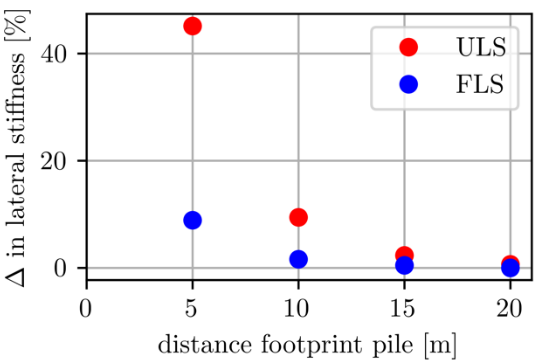

Figure 6. Change in lateral stiffness at the seabed level for multiple distances between monopile and footprint.

4 CONCLUSIONS

The present study presents an approach for estimating the influence of a spudcan footprint on the lateral stiffness response of a monopile foundation. It could be demonstrated, that for the investigated sand profile, the influence on the initial stiffness at FLS level seems to be subordiante for larger distances while the influence at the ULS level is more obvious. Nevertheless, the influence of the change in stiffness should be proven for the actual design by taking it into account for load simulations, fatigue calculations etc. In addition, it must be considered that there are several jack-up operations until the turbine is fully installed. Each operation leaves footprints that interact with a monopile foundation. Therefore, the superposition of footprints needs to be considered as well.

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