International Journal of Offshore and Polar Engineering (ISSN 1053-5381)

Vol. 31, No. 2, June 2021, pp. 243–253; https://doi.org/10.17736/ijope.2021.cl18

http://www.isope.org/publications

Evaluating the Penetration Resistance of Spudcan Foundations in Clay Overlying Sand

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The response of spudcan foundations during penetration through a soft clay layer toward a sand layer is investigated through large deformation finite element analyses. Relationships for the penetration resistance taking account of the evolving soil failure mechanisms are explored. The findings show that the substantial increase in the penetration resistance is associated with the squeezing mechanism, as the softer soil that is trapped beneath the spudcan base and the stronger sand layer is squeezed horizontally. A simplified expression is proposed to predict the spudcan penetration resistance between the depth at which the squeezing prevails and the clay-sand interface, with its performance compared with centrifuge test results and conventional design approaches.

INTRODUCTION

Mobile jack-up rigs are widely used for offshore drilling in shallow to moderate water depths up to 150 m. A typical oil and gas jack-up rig consists of a buoyant triangular platform and three independent retractable legs, with each leg resting on a large 10–20 m diameter spudcan (Menzies and Roper, 2008). Jack-ups have more recently been used, with modified designs, as heavy lift vessels for the installation of offshore wind turbines. When used as installation vessels, jack-ups usually have a more rectangular hull design and smaller size spudcan foundations, possibly equipped with more than three legs. Jack-ups can be self-installed once on-site. During the installation stage, the spudcan foundations are first pushed into the seabed through self-weight before being preloaded by pumping sea water into ballast tanks in the hull. This proof load is 50%–100% higher than that expected during operations, which ensures the footings can withstand extreme environmental loads in any extreme storm design event (International Organization for Standardization (ISO), 2016).

The accurate prediction of the bearing capacity for spudcans is a major concern in a site-specific assessment that is conducted prior to any installation and preloading (ISO, 2016). Difficulties can arise as a result of soil layering, where a significant soil strength difference is presented between layers. In the case of a spudcan that penetrates vertically through a soft clay layer toward a sand layer, a substantial increase in the ultimate bearing capacity occurs when the footing starts to "sense" the stronger layer underneath. This is because the softer soil that is trapped beneath the spudcan base starts to be squeezed horizontally by the stronger underlying sand layer. Precise predictions of the load-penetration curves are also critical in defining the size of the ultimate capacity surface in combined vertical, horizontal, and moment load space (Wang et al., 2018)—the second stage of any site assessment that determines the preloading level required for safe operations under storm loading.

The theoretical solution of the bearing capacity of a foundation resting on the surface of a thin clay layer with a rigid base has conventionally been used to predict the spudcan penetration resistance in soft over strong layers. In contrast to the wished-in-place surface foundations, during the spudcan penetration into the soft clay layer overlying a sand layer, large deformation of the soils adjacent to the foundation is involved. In addition, recent centrifuge experimental studies of spudcan penetration in three-layered clay-sand-clay deposits suggest that the squeezing starts in the top clay layer at a larger distance from the clay-sand interface than that predicted by the design guidelines (Hossain, 2014; Ullah et al., 2017b). Within the depth range that the squeezing prevails prior to penetration into the sand layer, the design approach recommended by ISO (2016) was not adequately accurate in predicting the sharp increase in the penetration resistance recorded in the centrifuge (Ullah et al., 2017a).

In this paper, three-dimensional large deformation finite element analyses performed to investigate the continuous spudcan penetration in a soft clay layer overlying a sand layer are discussed. The penetration resistance profiles and evolving soil failure mechanisms are examined as the spudcan foundations penetrate toward the stronger sand layer. The effects of strain softening and strain rate of the clay layer are considered. A simplified expression is proposed to predict the spudcan penetration resistance between the depth at which the squeezing prevails and the clay-sand interface. The conventional design approaches are compared against the new prediction method for the numerical results obtained and centrifuge test results.

BACKGROUND

Previous studies have mostly focused on strip or circular footings resting on the surface of thin clay layers with a rigid base representing the sand. For instance, Meyerhof and Chaplin (1953) proposed theoretical equations for estimating the bearing capacity

Received November 22, 2019; updated and further revised manuscript received by the editors April 17, 2020. The original version (prior to the final updated and revised manuscript) was presented at the Twenty-ninth International Ocean and Polar Engineering Conference (ISOPE-2019), Honolulu, Hawaii, June 16–21, 2019.

KEY WORDS: Spudcan, bearing capacity, clay overlying sand, squeezing, large deformation FE analyses, CEL.