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Jack-up push-over analyses featuring a new force resultant model for spudcans in soft clay

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ABSTRACT

With the development of the offshore oil and gas industry, mobile jack-up drilling platforms are increasingly utilized in deeper waters and harsher environments. Excessive conservatism in jack-up site specific assessment may result in undue rejection of a unit. In soft clayey seabeds, the spudcan foundations of the jack-up platform penetrate deeply into the soil with partial or complete backflow. Although the deep penetration and associated backflow are widely perceived to increase horizontal and moment foundation bearing capacities in particular, the problem is not well understood. In this paper therefore, a plasticity foundation model is proposed that accounts for the effects of backflow. It has been developed through a combined numerical and experimental study. The model is suitable for performing integrated soil–structure analyses. Results of such analyses of a jack-up under quasi-static push-over load are discussed to highlight the impact of the model in the context of site specific assessment of jack-up rigs in soft clay.

1. Introduction

In the offshore industry, mobile jack-up platforms (Fig. 1a) are widely used for performing drilling activities. A modern jack-up platform is typically supported by three independent legs. Each leg is equipped with a circular saucer shaped foundation known as spudcan (Fig. 1b). A jack-up is installed by preloading the platform to typically one and a half to twice the platform's self-weight through ballasting the hull with sea water. The spudcan foundations penetrate into the soil under the preload. Once installation is completed, the ballast is dumped and the jack-up operates under its self-weight and working variable loads. In addition, a jack-up platform is subjected to significant environmental loading from wave, wind and current. This transfers combinations of vertical (V), horizontal (H) and moment (M) loading to the spudcan footings (see Fig. 1b for the sign conventions adopted for positive loads and conjugate displacements). A jack-up is deployed multiple times throughout its life and before every installation at a new location a site specific assessment must demonstrate its stability in large storms (SNAME, 2008; ISO, 2012). This requires understanding of the bearing capacity of spudcans under combined VHM loading, as well as their interaction with the jack-up structure, which is influenced by the boundary conditions provided by the seabed soil.

In Fig. 2, two idealized scenarios after spudcan installation in clay are schematically illustrated. Fig. 2a shows a situation that occurs in stiff clay where an open cavity is formed above the spudcan. Failure is governed by a general shear mechanism. Fig. 2b, on the other hand, illustrates complete soil backflow due to a continuous flow-around mechanism. The undrained shear strength of offshore soft clayey soil profiles often has a small non-zero value at the surface (less than 15 kPa) and increases linearly with depth at a strength gradient (k) of typically in the range of 0.6–3.0 kPa/m (Tani and Craig, 1995). In these soils, deep penetration of the spudcan footings is required to provide sufficient resistance, and soil backflow occurs after a critical depth of penetration (though backflow may not be complete, depending on the shear strength). A method to assess the critical cavity depth has been recommended by recent studies of Hossain et al. (2005) and Hossain and Randolph (2009a), which is incorporated into the new ISO guidelines (ISO, 2012).

For the site specific assessment of jack-ups in soft clay, the deep penetration of the spudcan foundations and the associated backflow are important. It is commonly perceived that the backflow will increase the foundation's bearing capacity, especially the horizontal

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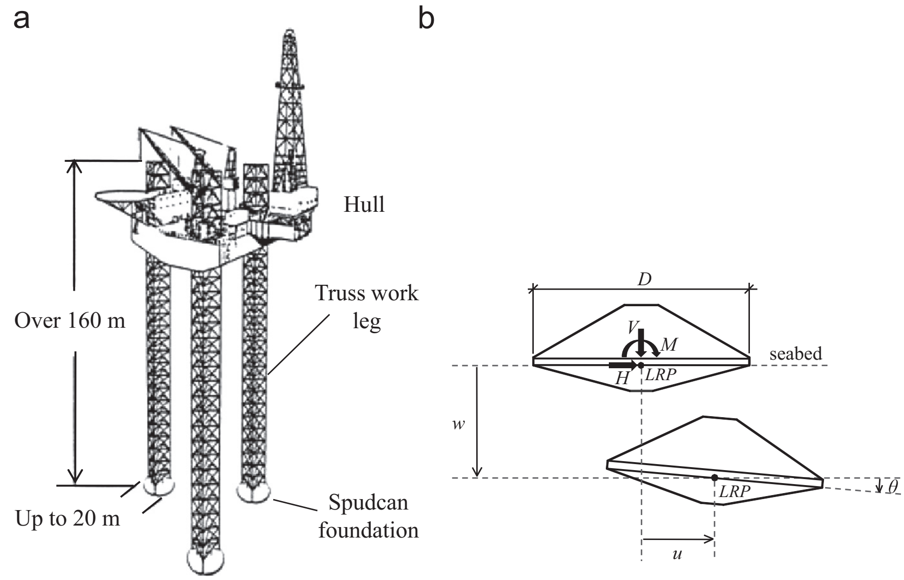

Fig. 1. A typical jack-up platform (after Reardon, 1986) and a spudcan under *VHM* loading.

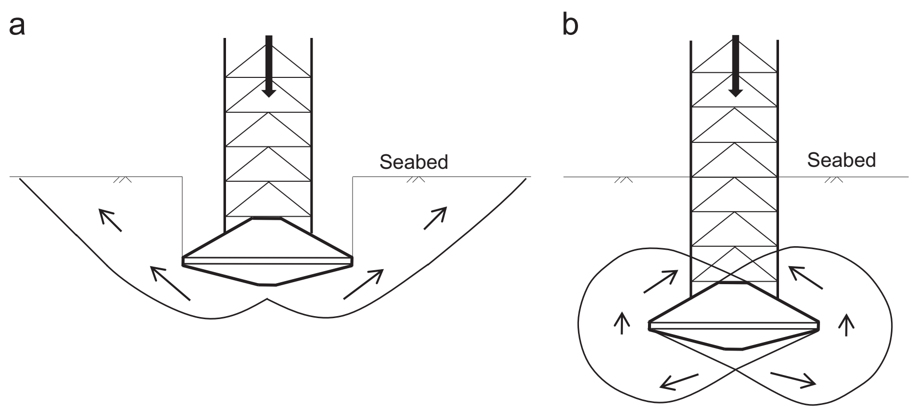

Fig. 2. Two idealized scenarios after spudcan penetration in clay.

and moment capacities. This is indeed indicated in the work by Templeton et al. (2005), Templeton (2009) and Zhang et al. (2011, 2012a), though the soil disturbance caused by spudcan installation was neglected in these numerical studies. The backflow also potentially acts as a "seal" on top of the spudcan, allowing suction to be developed, as observed in centrifuge experiments (Cassidy et al., 2004a; Purwana et al., 2005; Gaudin et al., 2011). Therefore, tensile loading of the jack-up leg is possible, though it is not currently considered in conventional site specific assessment. Furthermore, the backflow is likely to enhance the foundation stiffness, importantly in rotation. This is beneficial for reducing the stress level in critical parts of the jack-up structure, such as the leg-hull connection, as illustrated in Santa Maria (1988). Identifying and quantifying these perceived benefits will have significant economical implications for the jack-up industry while at the same time enhancing safety through improved understanding.

This paper proposes a model for describing the load–displacement behavior of the spudcan in soft clay that accounts for the effects of backflow. The framework of the model is based on displacement-hardening plasticity theory. Previous models in the same family include Schotman (1989), Nova and Montrasio (1991), Dean et al. (1997), Gottardi et al. (1999), Martin and Houlsby (2001), Cassidy et al. (2002a), Houlsby and Cassidy (2002), Bienen et al. (2006) and Knappett et al. (2012). Foundations described by force resultant models can be readily incorporated into a finite element structural analysis program as "macro elements" as they are written directly in terms of force resultants and displacements about the spudcan's load reference point (*LRP*, Fig. 1). This avoids any complex discretization of the soil. Such integrated soil–structure analyses can be found, amongst others, in Thompson (1996), Williams et al. (1998), Martin and Houlsby (1999), Houlsby and Cassidy (2002), Cassidy et al. (2001, 2002c), Bienen and Cassidy (2006, 2009) and Vlahos et al. (2011).

This paper will first set out the components of proposed force resultant model. A brief comparison of this model with a previous model for spudcans without backflow is then provided. To demonstrate the implications of the proposed model, integrated jack-up structure analyses under quasi-static monotonic push-over load are performed and results are discussed.

2. Proposed force resultant model

Based on plasticity theory, the force resultant model includes four components:

(i) a yield surface written directly in the *VHM* load space;
(ii) a hardening law that establishes the yield surface size as a function of the plastic vertical footing displacement (w_p);
(iii) an elastic matrix for describing any increment of load within the yield surface;