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Cavity Stability and Bearing Capacity of Spudcan Foundations on Clay

M.S. Hossain and M.F. Randolph, U. of Western Australia; Y. Hu, Curtin U. of Technology; and D.J. White, U. of Cambridge

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Abstract

The paper describes centrifuge modelling and finite element (FE) analysis of the penetration of spudcan foundations in clay, identifying soil flow mechanisms around the spudcan, the extent of any cavity above the spudcan and the evolving penetration resistance. Particle image velocimetry allowed accurate resolution of the flow pattern around a 'half-spudcan' penetrated adjacent to a transparent window. Separate tests on full spudcans quantified the penetration resistance relative to strengths obtained from T-bar penetrometer tests. All results were validated using conventional FE analysis of spudcans pre-embedded at various depths, and large deformation FE analysis where the spudcan was penetrated from the seabed surface. The study has shown that the present SNAME guidelines for predicting the point of 'back-flow' of soil above spudcans are incorrect, based on the wrong mechanism. Back-flow occurs not because of instability of the open cavity, but because of a preferential flow mechanism of soil from below the spudcan to above it. The paper provides new guidelines from which the penetration resistance and cavity depth can be computed accurately, based on the new penetration mechanisms presented.

Introduction

Mobile jack-up rigs are used widely in the offshore oil and gas industry for installing new platforms, maintenance work and drilling and even for production for fields of limited life. There has been continual development of rig operations into new regions and greater water depths, with larger jack-ups now capable of operation in depths of up to 120 m. A typical modern jack-up unit comprises a buoyant triangular platform supported by three independent *K*-lattice legs, each resting on a large inverted conical footing known as a spudcan (Young *et al.*, 1984). Spudcans are typically circular or polygonal in plan, with a shallow conical underside and a central spigot to provide improved sliding resistance, as illustrated schematically in Figure 1. With the move towards heavier rigs and deeper waters, assessment of the performance and safety of jack-up rigs has become increasingly important. A critical aspect of this is the penetration resistance, and the extent to which a cavity will remain above the spudcan as it penetrates, and the depth at which soil will flow back over the spudcan.

Before the commencement of the jack-up operations, the spudcans are preloaded by pumping seawater into compartments within the hull. The preload causes the spudcans to penetrate into the seabed until the load on the spudcan is equilibrated by the resistance of the underlying soil. In soft soil, a spudcan may penetrate up to 2 or 3 diameters to reach equilibrium (Endley *et al.*, 1981). The purpose of preloading is to penetrate the foundation sufficiently so that its resulting bearing capacity exceeds that required during extreme storm loading by an acceptable margin of safety. The ballast is then emptied and the hull is raised further to provide an adequate air-gap for subsequent operation.

In many areas of the world where offshore hydrocarbon development projects are taking place, such as in the Gulf of Mexico or off the West African coast, the seabed sediments comprise soft normally-consolidated (NC) or lightly over-consolidated (OC) clay (Gemeinhardt & Focht, 1970; Endley *et al.*, 1981). For these soils the undrained shear strength, s_u, increases more or less linearly with depth, and can be expressed as

$$s_u = s_{um} + kz \tag{1}$$

where s_{um} is the soil strength at the seabed (mudline) and k is the rate of increase in s_u with depth z (Figure 1). The short-term, or undrained, bearing capacity of a shallow foundation at a specific depth, d, under the action of purely vertical loading, can be determined as

$$q_u = N_c s_u + \gamma' d \tag{2}$$

where N_c is a dimensionless bearing capacity factor and γ' is the effective unit weight of the soil. The form of Equation 2 is consistent with q_u being the limiting average bearing pressure at the spudcan level. However, from a practical point of view it is more convenient to calculate q_u as the limiting load applied by the spudcan leg, divided by the projected horizontal area, A, of the spudcan. The two definitions for q_u are identical in the case where an open cavity exists above the spudcan, but for the more general case where back-flow occurs, a more general form of the equation is (SNAME, 1997)