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A Theoretical Study of the Vertical Uplift Capacity of Suction Caissons

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ABSTRACT

An extensive theoretical investigation has been carried out regarding suction caissons subjected to vertical uplift loading for cases where the behaviour of the seabed soil is undrained, partially drained or fully drained. Theoretical solutions for the uplift capacity are derived, based on the results of a finite element study, and then validated by previous field experiments and model test results. The expressions developed in this paper for the uplift capacity take into account the influence of the aspect ratio of the caisson, the shear strength parameters of the soil, the soil permeability and the loading rate.

INTRODUCTION

Compliant offshore structures, such as tension leg platforms (TLP), are usually subjected to considerable uplift forces. These structures require foundations that can anchor them to competent strata. It has been common in the past to use piles to provide such a foundation. However, there are difficulties associated with the installation of the long piles that are usually necessary, particularly in deep waters. Largely because of these difficulties a new type of foundation, the suction caisson, has been developed and used to provide uplift resistance for a variety of in situ soil conditions.

A suction caisson, open at the bottom and closed at the top, is designed to penetrate to the sea floor by its own weight and also by creating an internal underpressure relative to the external water pressure. The latter is known as the active suction installation method. As soon as there is any indication of pullout movement, the suction caisson mobilises significant pullout capacity through the development of negative changes of pore water pressure inside the soil plug and at the bottom of the caisson, depending on soil conditions. This is known as the passive suction condition. The length of time that these suction changes can be maintained is largely a function of the drainage properties of the seabed soil. The main advantages of suction caissons over tension piles are the ease of their installation with the active suction arrangement, the mobilisation of significant passive suction forces at the bottom of the caisson during uplift, and the possibility of placing additional ballast on the large-diameter sealed top, thus providing the ability to increase the pullout capacity. To date, suction caissons have been employed on mooring systems (Senpere et al., 1982), gravity-based structures (Tjelta et al., 1990), jacket and jack-up structures (Baerheim et al., 1995), TLP systems (Clukey and Morrison, 1993) and subsea production systems (Hefer, 1998). They have been deployed in both clays and sands.

Detailed study of the pullout behaviour of suction caissons commenced about 3 decades ago, and there have been several published experimental investigations of the pullout behaviour of suction caissons in clayey soil and quartz sands. Finn and Byrne (1972) carried out laboratory model studies to understand the factors governing the pullout capacity of suction caissons and reported that it depends mainly on the suction developed beneath the caisson. They suggested that an upper limit could be fixed by assuming a failure mechanism similar to a classical bearing-capacity approach based on limit equilibrium considerations, which they suggested was a reverse bearing-capacity problem. Similar studies were carried out by Wang et al. (1977, 1978). Andersen et al. (1993) carried out 4 field tests (1 static and 3 cyclic) to study the pullout behaviour of suction caissons in soft clay and concluded that the ultimate capacity may be calculated by assuming a reverse bearing-capacity failure. Fuglsang and Steensen-Bach (1991) and Steensen-Bach (1992) performed a parametric study on model suction caissons with aspect ratios (embedment depth divided by caisson diameter), $L/d = 1.67, 2.0$ and 3.33, in 2 types of soils, and studied the nature of pullout load-displacement behaviour. They reported that the pullout load increases with displacement until it reaches a maximum, then decreasing gradually as the displacement increases. However, they did not state explicitly the influence of pullout rate, aspect ratio and other parameters on the pullout behaviour of the suction caissons. Erbrich (1994) used the commercial finite element code ABAQUS (Hibbitt et al., 1997) to investigate the tensile capacity of a suction foundation on a dense silica sand profile with clay layers. In his analysis, a nondilational soil plasticity model was used. He found that faster load rates give greater tensile capacity, but did not quantify in detail the influence of load rate on the tensile capacity.

Although previous investigators have suggested the reverse bearing-capacity mechanism for undrained conditions, a literature review reveals that the failure mechanisms developed under different consolidation conditions and different loading rates are not well understood. The influence of the aspect ratio of the caisson has also not been adequately studied. Further, the bottom resistance has not been properly understood and quantified.

The study reported in this paper deals specifically with the typical cases illustrated in Fig. 1. The suction caisson is assumed to be cylindrical with an overall diameter d and an embedded length L. The uplift load (corresponding to an average traction, p_u) is applied vertically at the top of the caisson. The subsoil may be drained, partially drained or undrained. The present study is an

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