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Soil conditions and bounds to suction during the installation of caisson foundations in sand

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ABSTRACT

Suction installation of caisson foundations is widely adopted in the oil offshore industry. When such foundations are installed in sand, seepage conditions are known to play a pivotal role in the installation process. Pressure gradients generated by the imposed suction inside the caisson cavity cause an overall reduction in the lateral soil pressure acting on the caisson wall as well as in the tip resistance. This transient loosening of soil around the caisson wall facilitates caisson penetration into the seabed. However, these effects must be controlled to avoid soil failure due to critical conditions such as piping or loss of soil shear strength, which may cause the installation procedure to fail due to instability of the soil plug trapped inside the caisson cavity. In this paper, we endeavour to study these effects based on the analysis of the normalised seepage problem, assuming the installation process to take place in homogeneous sand. We first investigate the effects of seepage conditions on soil resistance to caisson penetration with a particular focus on how frictional resistance and tip resistance are differently affected. We then consider modes of failure due to soil piping inside the caisson cavity and sliding of soil mass in a failure mechanism where the soil plug inside the caisson cavity is pushed upward. Based on this study, some insight is gained into the critical conditions for piping. These conditions evolve during the installation process as the penetration depth increases under an increasing suction. Upper and lower bounds are also estimated for the critical suction based on an assumed mode of failure using a simple mechanism of rigid blocks. By comparing these modes of failure we conclude that piping is not always the most critical condition. The critical mode of failure for a given soil may change during the installation process and this is highlighted by comparing the critical suction for piping to the suction upper and lower bounds related to shear failure.

1. Introduction

Suction caisson foundations have been very popular in the oil industry and the current trend is to extend their use to the developing industry of wind farms (Byrne et al., 2002; Byrne and Houlsby, 2003). A suction caisson is an upturned 'bucket' of cylindrical shape made from steel. The thin caisson wall facilitates installation when a pressure differential is induced by suction on the caisson lid, which pushes the caisson to penetrate into the seabed. This is achieved by pumping out the water trapped in the caisson cavity after initial penetration under self-weight. When such procedure is used for caisson installation in sand, suction must be controlled during the whole installation process so that its magnitude does not exceed the critical limit that causes soil failure. It is recognised that within the safety limits against soil piping, porewater seepage induced by suction is beneficial to caisson installation as it reduces the overall force that resists caisson penetration (Senper and Auvergne, 1982; Tjelta et al., 1986; Erbrich and Tjelta, 1999; Tran et al., 2004; Tran et al., 2005). CPT tests conducted inside the caisson before and after installation, revealed significant loosening of sand (Senders and Randolph, 2009).

The role of porewater seepage has been considered in the development of design procedures for the installation of suction caissons in sand (Tjelta, 1994, 1995; Bye et al., 1995; Erbrich and Tjelta, 1999; Houlsby and Byrne, 2005). Tran and Randolph (2008) conducted a series of model tests in a geotechnical centrifuge to investigate the variation of suction during the installation of caisson foundations in dense sand. They also performed finite element simulations to study the critical hydraulic conditions that develop during caisson installation. Finite element simulations of seepage induced by suction around caisson foundations have also been performed by Zhang et al. (2004). Finite element models with remeshing capabilities have been used to model caisson penetration into clay (Vasquez and Tassoulas, 2000; Maniar and Tassoulas, (2002)). Similar simulations have been performed for sand, where soil behaviour has been described with a

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Drucker–Prager model with cap (Zeinoddini et al., 2011). Ibsen and Thilsted, (2011), used FLAC3D and performed finite difference simulations to study piping limits to suction, which were applied to field installations of suction caissons in sand.

Experimental investigations in dense sand have revealed that soil heave, which is likely to occur during suction assisted installation, sets an additional limit to suction for the required installation depth to be achieved safely (Allersma et al., 1999; Bang et al., 1999; Allersma, 2003; Tran et al., 2004).

Specific soil conditions such as the existence of low permeability silt layers that may affect seepage at some stage of the installation process have been considered by Tran et al., (2007). More recently, Harireche et al. (2013) have considered the effects of suction induced seepage during the installation of caisson foundation in sand with permeability varying with depth.

In the aforementioned literature, the hydraulic gradient on both sides of the caisson wall has been described in terms of an overall value based on the pressure difference between the mudline and the caisson tip. However, due to the importance of the variation of pressure gradient over the caisson penetration depth, it is important to investigate the gradient distribution over the penetration depth throughout the installation process.

In this paper, we consider the excess porewater pressure gradient in terms of the magnitude of its vertical component at each location within the soil mass. This is motivated by the fact that such component defines the seepage force that acts against gravity and directly affects effective stresses.

In the first part of this study we address the effects of excess pore pressure gradients on soil resistance to caisson penetration. A simple finite element procedure is first performed to solve the normalised seepage problem. The variation in effective stresses on both sides of the caisson wall is calculated as a function of the penetration depth and integrated numerically to provide an estimation of the reduction in magnitude of the penetration resisting forces caused by seepage. Problem dimensions are normalised so that the results obtained are independent of caisson prototype and apply to any caisson size. Based on the analysis of the normalised seepage problem, we derive analytical expressions for the magnitudes by which penetration resisting forces are reduced for a given suction and caisson dimensions. The second part of this study is devoted to the investigation of critical soil conditions during caisson installation. In addition to critical conditions for piping, a second mode of failure has been investigated, which is based on a shear failure mechanism. This failure mode has been motivated by the observed deformation process which consists in soil moving into the caisson cavity. For dense sand, such large deformation process results into volume expansion or heave of the soil plug. It is worth examining whether such a deformation process may lead to soil failure that might become more critical compared to the piping condition. Based on the finite element model of the normalised seepage problem, critical conditions for piping and the assumed failure mechanism can be tracked during the whole installation process. Upper and lower bounds to suction have been obtained assuming a simple failure mechanism that consists of two rigid blocks and one single stress discontinuity. Comparison of these bounds to the critical suction for piping revealed that the critical mode of failure may switch from the piping condition to shear failure at some stage of the installation process depending on soil shear strength.

2. Formulation of the normalised seepage problem

We consider the model problem of a suction caisson of radius R, height L and we denote h the depth of caisson penetration into the seabed. The soil consists of homogeneous sand with permeability k and saturated unit weight γ_{sat}. Fig. 1 shows a vertical section through the vertical plane of the system caisson-soil where only half of the caisson is represented due to axisymmetric geometry. A cylindrical system with coordinates r^* and z^* in the meridian plane is adopted for the normalised problem geometry where all dimensions are scaled with respect to the caisson radius.

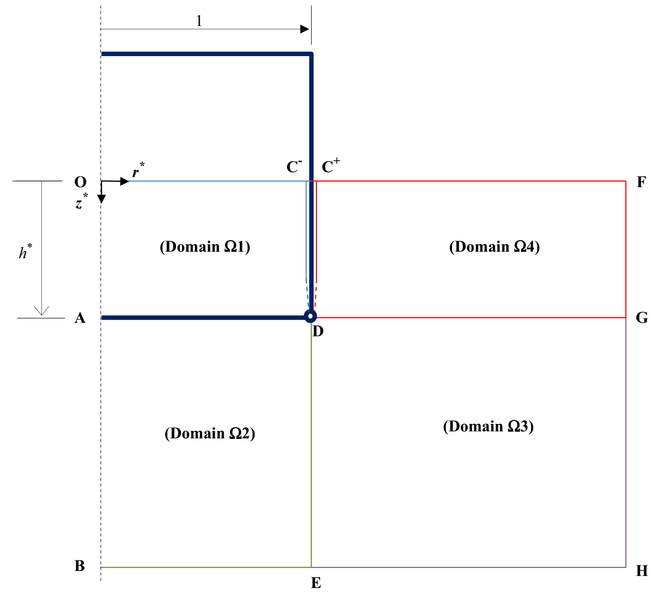

Fig. 1. Normalised geometry.

Before caisson installation, water pressure is in hydrostatic condition with an ambient absolute magnitude at depth z, $p_0 = p_{at} + \gamma_w h_w + \gamma_w z$, where p_{at} is the atmospheric pressure, γ_w the unit weight of water and h_w the water height above the mudline. A deviation of the porewater pressure from the hydrostatic value at any location within the soil is referred to as excess porewater pressure and is denoted as p. This terminology will be used even in cases where p is negative.

At a certain stage during the caisson installation process, a penetration depth h is reached under the effect of a suction of magnitude $\bar{s}$, assumed constant over the radial distance OC^- (Fig. 1). It is important to note that suction has a negative value; however the magnitude $\bar{s}$ is a positive number. On the mudline boundary C^+F outside the caisson, and on the boundaries FH and BH sufficiently far from the zone of significant suction disturbance, the excess porewater pressure p remains zero.

The porewater seepage is assumed to obey Darcy's law: $\boldsymbol{u} = -k\nabla p$ where $\boldsymbol{u}$ is the porewater velocity field, k the permeability and ∇p denotes the excess porewater pressure gradient. Assuming volume incompressibility of the porewater flow, the constraint $div\boldsymbol{u} = 0$ $(div \equiv (1/r)\partial/\partial r + (1/r)\partial/\partial\theta + \partial/\partial z)$, must be superimposed onto Darcy's law which, for a homogeneous soil in axisymmetric conditions, results into the well-known Laplace equation:

$$\nabla^2 p \equiv \partial^2 p/\partial r^2 + (1/r)\partial p/\partial r + \partial^2 p/\partial z^2 = 0.$$

As the caisson penetrates into the seabed, radial porewater flow across the caisson wall is prevented, which is described by the boundary condition on CD: $\partial p/\partial r = 0$ and due to symmetry, this condition must be satisfied on the z-axis. In order to obtain the distribution of excess porewater pressure, we divide the soil domain into four regions. Region (Ω_1) represents soil inside the caisson, (Ω_2) is the region occupied by soil which passes inside the caisson after further penetration and regions (Ω_3) and (Ω_4) are the complementary soil regions outside the caisson.

In order to draw conclusions that are not affected by the prototype dimensions, we adopt the following normalisation