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MODELLING THE SEEPAGE FLOW DURING CAISSON INSTALLATION IN A NATURAL SEABED

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ABSTRACT

Seepage plays a crucial role in the installation of suction caisson foundations and this has been considered by several researchers via experimental, numerical and analytical studies. In most of the available numerical and analytical studies, the actual seabed profile has been modelled using a number of assumptions and considering a limited number of idealised conditions to simplify the problem. However, it is well established that the behaviour of seabed, and soil in general, is a complex and nonhomogeneous one and that these assumptions can affect the reliability of the results. This paper examines the installation of suction caisson foundation into a realistic and natural seabed profile. It identifies the changes in seepage flow at different stages of installation and the role of crucial parameters such as permeability on the installation process is discussed. The results show that a significant increase in resistance to penetration occurs at the interface layers.

Keywords: *suction caisson; installation; natural seabed soil; permeability*

1. Introduction

Suction caissons are relatively new types of foundations which have applications in offshore oil and gas industry as well as offshore wind farms. They are upturned buckets of cylindrical shape made from steel. Installation of these foundations in seabed soil is achieved by pumping out water trapped in the caisson hollow space which enables their penetration into the seabed after initial penetration under self-weight. Seepage occurs in permeable soils during suction caisson installation, as discussed by Hogervorst [3], leading to a reduction in the soil effective stress and hence its resistance to penetration [8]. However, in soils with low permeability, installation is mainly achieved by the difference between pressure inside and outside the caisson, caused by pumping out the trapped water in the caisson cavity, and the effect of seepage is limited [8, 1]. Installation in multi-layered soil profiles, e.g. very low permeable soil overlaid by sand, is expected to be more challenging since the reduction in resistance to the caisson tip penetration is restrained by restrictions of flow in the lower less permeable layer. It is unclear to what extent the lower less permeable layer impacts the seepage flow and thus the resistance to the suction caisson tip penetration. Installation aspects of suction caissons in homogeneous clay [2] or granular materials [4] are extensively studied by many researchers. However, limited documentation, references or guidelines are available for installation in stratified soils [5, 6]. In the present paper, a finite element (FE) model is developed to study the effect of a multi-layered seabed on the installation process of suction caisson foundations. The results are compared with those obtained from installation in a single layer soil and the differences are highlighted.

2. Formulation of the Normalised Seepage Problem

In order to draw conclusions regardless of specific dimensions, an FE model of a suction caisson normalised with respect to the caisson radius (R) is developed. The caisson height and penetration depth into seabed are denoted as L, and h respectively. The first case represents caisson installation in homogeneous soil with permeability k and saturated unit weight γ_{sat}. For the second case of a two-layer soil profile, the depths of the upper and lower layers are taken as 2m and 4m respectively. The permeability of the upper layer is taken as 10 times higher than that of the second layer. Figure 1, shows a vertical section through the meridian plane of the caisson-soil system where a cylindrical system of coordinates $z^* = z/R$, and $r^* = r/R$ is used. For the caisson penetration depth, the dimensionless parameter $h^* = h/R$, is adopted [7].

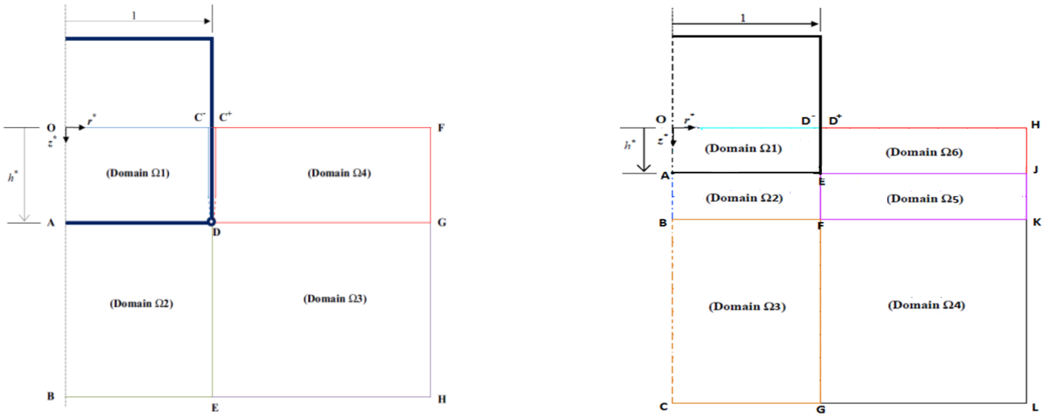

Figure1: Normalised Geometry and Finite Element Model; Homogeneous (left) and Layered (right)

To study the effect of porewater seepage on soil resistance to caisson penetration, lateral pressures on inside and outside caisson wall caused by seepage is investigated. Under seepage conditions produced by an applied suction, the lateral effective pressure (σ'_h) acting on the caisson wall at depth z, inside and outside the caisson is respectively given by:

$$\sigma'_{hi}(R,z) = K(\gamma' z - \int_0^z g_i(R,\zeta)d\zeta + \tilde{\sigma}_i(R,z)) \tag{1}$$

$$\sigma'_{ho}(R,z) = K(\gamma' z - \int_0^z g_o(R,\zeta)d\zeta + \tilde{\sigma}_o(R,z)) \tag{2}$$

where K is the coefficient of lateral earth pressure, γ' is the effective unit weight of the soil, $\tilde{\sigma}$ is the enhanced effective stress caused by the effect of shear resistance that develops on the soil-caisson interface and $g_i(R,\zeta)$,and $g_o(R,\zeta)$ denote the vertical component of the pressure gradient on the inner and the outer sides of the caisson wall respectively. Seepage causes the frictional resisting force acting on the caisson wall to decrease by a magnitude ΔF_s given as a function of the normalised penetration depth $h*$ by the expression:

$$\frac{\Delta F_s}{2\pi R^2 K\bar{s}\tan\delta} = \int_0^{h*} \left| L_i^*(Z*) + L_o^*(Z*) \right| dz* \tag{3}$$

$$\Delta F^*_s = \frac{\Delta F_s}{(2\pi R^2 K\bar{s}\tan\delta)} \tag{4}$$

Where:

$$L_i^*(Z*) = \int_0^{z*} g_i^*(1,\zeta*)d\zeta* \tag{5}$$

$$L_o^*(Z*) = \int_0^{z*} g_o^*(1,\zeta*)d\zeta* \tag{6}$$

and δ denotes the angle of friction at the interface soil-caisson. Suction magnitude at mudline level inside the caisson cavity are denoted by $\bar{s}$. In the next section, the normalised decrease of frictional resistance (ΔF_s^*) is calculated using the results of the FE models and the above relationships.

3. Results and Discussion

Figures 2a and 2b, show the distribution of normalised excess pore water pressure $P*$ around the caisson for the normalised penetration depth $h*$ =1 and 3 in a homogeneous seabed.

Water seepage cause by suction produces a hydraulic gradient which on both faces of the caisson wall varies with depth. Figures 2c, and 2d show the distribution of $P*$ for the seabed with layered soil profile at the same depths. From these figures it can be seen that the contours of excess pore water pressure have been affected due to the presence of a less permeable layer. This will accordingly have an impact on the penetration resistance as it can be seen in the next section. Figure 3a, and b depicts the contours of vertical component of the scaled pressure gradient $g* = \partial p* / \partial z*$ for normalised penetration depth $h*$ = 1, and 3, corresponds to a homogeneous seabed. It can be observed that the highest gradient magnitudes are concentrated around the caisson tip. At shallow penetration depths, high gradients around the caisson wall affect the whole penetration depth. As the penetration depth increases, these gradients tend to localise around the caisson tip. For comparison, Figure 3c, and 3d shows similar contours for a seabed layered profile. From these figures, it can be seen that discontinuity in the permeability profile at the interface between the two layers is reflected in the profile of the pore pressure gradient. This in turn affects the magnitude of frictional soil resistance as a function of normalised depth as will be shown later.

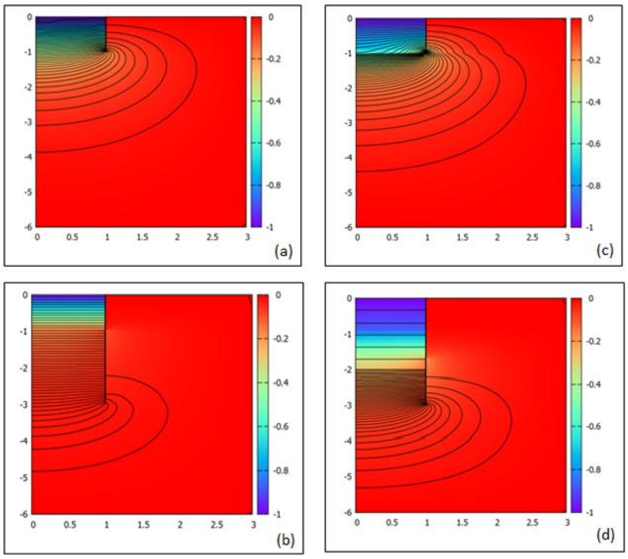

Figure 2: Excess pore water pressure for h*=1, 3; (a, b): homogeneous; (c, d): layered soil.

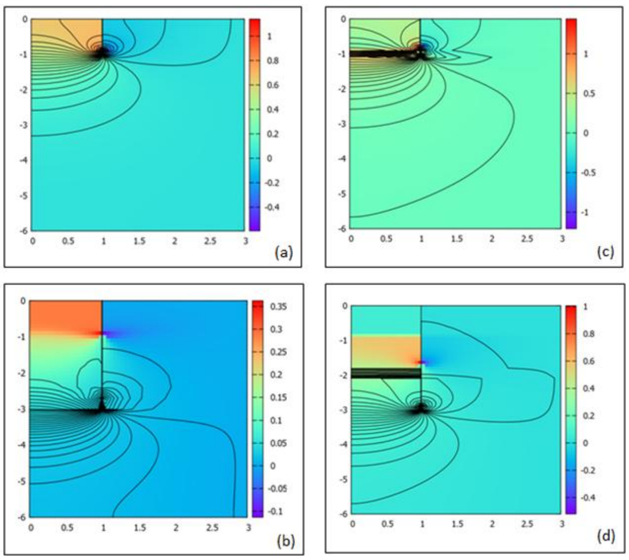

Figure 3: Normalised pressure gradient for $h*$=1, 3; (a, b): homogeneous; (c, d): layered soil.

Figure 4 shows clearly that the reduction in the magnitude of lateral friction resistance (ΔF_s^*) increases as the caisson passes through the layer with higher permeability. An increase (i.e. 50%) in resistance to penetration occurs at the interface between the soil layers. This result shows clearly that the suction pressure required could be affected by sudden changes in permeability in layered soils.

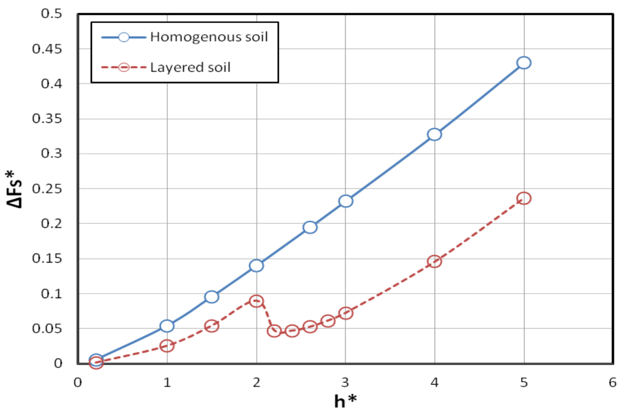

Figure 4: Effect of Suction-Induced Seepage on Soil Resistance at Caisson Wall

4. Conclusions

This study considered the effect of soil profile permeability on the prediction of soil resistance to caisson penetration. Two soil profiles were considered, namely homogeneous soil with constant permeability and a layered soil profile where low permeable soil is overlaid by a 2-meter thick layer of high permeable soil. The effect of suction-induced seepage on soil resistance to caisson penetration was investigated using the normalised solution of seepage around the caisson wall. It has been observed that taking into account the actual variation of permeability in layered soils may lead to a more accurate estimation of the critical suction.

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