A Semi-Analytical Framework for Suction Caisson Installation in Sand

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Abstract

Controlling the installation procedure for a caisson foundation requires a preliminary design phase. For suction assisted installation of caisson foundations in sand, such a design phase is important to predict the force required to overcome soil resistance as caisson is pushed into the seabed, and to identify the limits to a safe installation process such as the occurrence of seepage induced piping. The present paper provides a framework where analytical expressions are obtained for the required suction magnitude to overcome soil resistance to caisson penetration, these analytical expressions are derived for a normalized caisson geometry, based on compiled results obtained from finite element analysis of seepage around a caisson wall. The proposed suction predictions for the whole process of caisson installation in sand are validated against field trials reported in the literature.

Key-words: Suction caisson, normalized seepage problem, polynomial regressions, suction profile.

1. INTRODUCTION:

Over the past few decades, suction caisson gained popularity with the rapid development that took place within the oil and gas industry. Economic advantage and easiness of installation and decommissioning added substantial value to this type of foundation, which appears to become a competitive solution for future use as a foundation for offshore wind turbines (Byrne and Houlsby, 2003, Byrne et al., 2002).

Design procedures of caisson installation depend on the type of soil that makes the seabed formation (Houlsby and Byrne, 2005b, Houlsby and Byrne, 2005a). In sand, the driving force pressure differential results into an overall downward force. Such a force acts in conjunction with the seepage taking place around the caisson wall, which reduces frictional resistance. The present paper aims at proposing a standard formulation of the design procedure for the installation of suction caissons in sand. The present formulation uses a standard mathematical description of the installation problem that integrates the solution of the seepage counterpart. In order to achieve this, we propose a normalized framework for the installation process, using a normalization procedure similar to the one adopted in (Harireche et al., 2014, Harireche et al., 2013). Polynomial regressions are used to obtain standard forms of the normalized pore pressure. The proposed mathematical model will be obliged in accessing the critical condition in suction caissons installation design procedures.

2. NORMALIZED SEEPAGE PROBLEM:

We a suction caisson of radius *R*, height *L*. The depth of caisson penetration into the seabed is denoted as *h*. The seabed profile consists of homogeneous sand. Figure 1 shows a vertical section where only half of the caisson is represented. A cylindrical system with coordinates *r** and *z** is used for the normalized geometry with respect to caisson radius, *R*. A Suction of magnitude $\bar{s}$ is applied, which causes an excess pore pressure, $p^* = p/\bar{s}$.

Seepage equations is: $\nabla^{*2} p^* \equiv \dfrac{\partial^2 p^*}{\partial r^{*2}} + \dfrac{1}{r^*}\dfrac{\partial p^*}{\partial r^*} + \dfrac{\partial^2 p^*}{\partial z^{*2}} = 0$.

Due to impervious caisson wall: $\partial p^* / \partial r^* = 0$ on AD and on z^*-axis due to symmetry.

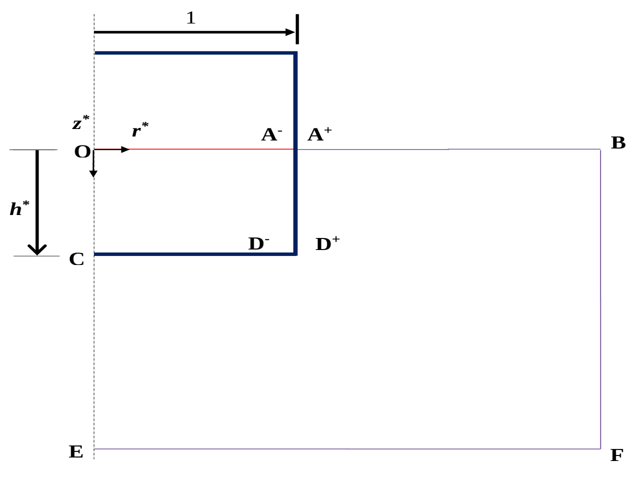

Figure 1: Normalized caisson geometry and surrounding soil

The normalized pressure satisfies the conditions: $p^* = -1$ on OA$^-$, $p^* = 0$ on A$^+$B, BF, and EF. The normalized pressure gradient is denoted by g^*. The normalized seepage problem is solved with finite elements. Preliminary numerical tests have been performed to ensure that boundaries are far enough from the zone affected by seepage so that no disturbance is caused to the predicted results. The mesh, which consists of six-node Lagrange triangular elements in axisymmetric geometry, has been refined around the caisson wall to the extent that ensures convergence. Figures 2 and 3 show the contours of normalized pressure and normalized pressure gradient. Note that in terms of magnitude, pressure gradient is higher on the inner side. This is consistent with the large scale experiments performed by Chen et al. (Chen et al., 2016). A significant drop of inner soil pressure was observed in these experiments and this was induced by seepage. Normalized excess pore pressure, p^* can be represented with the following polynomial regressions:

$$p_o^*(z^*) = \sum_{k=0}^{6} a_k(h^*) \times \left(z^*\right)^k \quad , \quad p_i^*(z^*) = \sum_{k=0}^{6} b_k(h^*) \times \left(z^*\right)^k$$

(1)

Where indices '*o*' and '*i*' are used to denote pressure values on the outer and inner sides of the caisson wall, respectively. A degree six of the polynomial interpolation ensures a coefficient of determination (R-squared value) larger than 0.999. The coefficients a_k and b_k depend on the normalized penetration depth, h^* and have the expressions:

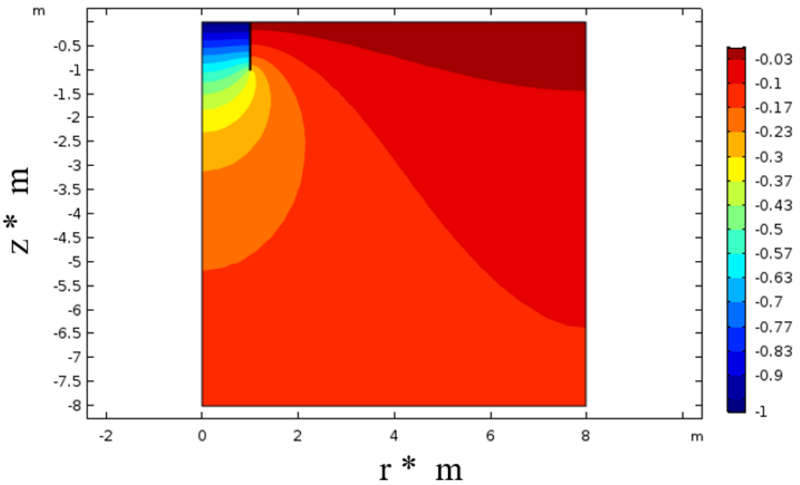

Figure 2: Contours of normalized excess pore pressure

$$a_0(h^*) = \alpha_0 h^* + \beta_0, \quad a_k(h^*) = \alpha_k \left(h^*\right)^{\beta_k}, \quad k = 1, \ldots, 6$$

(2)

$$b_0(h^*) = \gamma_0 h^* + \eta_0 \ , \quad b_k(h^*) = \gamma_k \left(h^*\right)^{\eta_k}, \quad k = 1, \ldots, 6$$

(3)

The constants α_k, β_k, γ_k and η_k, $k = 0, \ldots, 6$ are provided in the appendix.

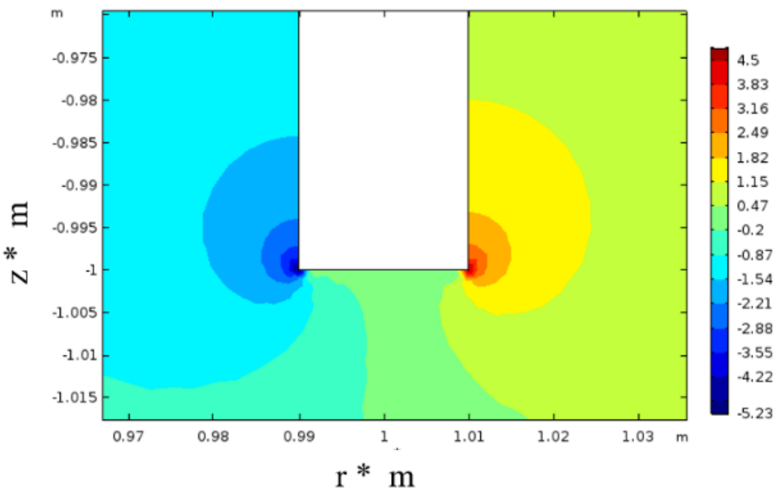

Figure 3: contours of normalized pressure gradient

3. SOIL RESISTANCE TO CAISSON PENETRATION AND SUCTION PROFILE:

At a soil depth *z* below the mudline, the vertical effective stress is given by

$$\sigma'_{vi}(z) = \gamma' z - \int_0^z g_i(\zeta)\, d\zeta = \gamma' z - \left(p_i(z) + \bar{s}\right)$$

(4)

$$\sigma'_{vo}(z) = \gamma' z - \int_0^z g_o(\zeta) d\zeta = \gamma' z - p_o(z)$$

(5)

Where γ' is the submerged unit weight of soil and g_o, g_i denote the z-components of pressure gradients on each side of the caisson wall, respectively. Lateral soil pressure is expressed as:

$$\sigma_{ho}(z) = K\sigma'_{vo}(z) = K\left(\gamma' z - p_o(z)\right)$$

(6)

$$\sigma_{hi}(z) = K\sigma'_{vi}(z) = K\left(\gamma' z - \left(p_i(z) + \bar{s}\right)\right)$$

(7)

Where *K* is a soil lateral pressure coefficient. In terms of normalized depth, z^*

$$\sigma_h(z^*) = K\left[2\gamma' R z^* - \bar{s}\left(p^*_o(z^*) + p^*_i(z^*) + 1\right)\right]$$

(8)

Note that the term $p^*_o(z^*) + p^*_i(z^*) + 1$ is positive as the sum of normalized pressures on each side of the caisson wall is negative, with a total magnitude less than unity. This shows that the lateral pressure, and hence, the mobilized friction, on the caisson wall, is reduced because of seepage. The lateral frictional force is obtained as the resultant of frictional shear stress acting on both sides of the caisson wall and has the expression

$$F_s = \int_0^h 2\pi R \sigma_h \tan \delta dz$$

(9)

Where δ is the angle of friction at the interface caisson-soil. Tip resistance is given by

$$F_t = 2\pi R N_q \int_{R_i}^{R_o} \sigma_t^{'} dr + 2\pi R t \left(\frac{1}{2} \gamma^{'} t N_\gamma \right)$$

Where N_q and N_γ are bearing capacity factors, [3] and $\sigma_t^{'}$ denotes the vertical effective stress at the caisson tip, defined as:

$$\sigma_t^{'} = \frac{1}{2}\left(\sigma_{vi}^{'}(h) + \sigma_{vo}^{'}(h) \right) = \gamma^{'} h - \frac{1}{2}\left(p_{ih} + p_{oh} \right)$$

(10)

Where p_{ih} and p_{oh} are pressure values at caisson tip on the inner and outer sides of the caisson wall, respectively.

Required suction magnitude is given by the ratio of total resisting force over unit caisson cross sectional area and is expressed as:

$$\bar{s} = \frac{F_s + F_t}{\pi R^2}$$

(11)

4. RESULTS AND ANALYSIS:

The analytical approach presented in previous sections is validated against field data obtained from trial experiments and reported by (Chen et al., 2016).These field trials took place at Tenby on the south coast of Wales. The seabed formation consists of dense sand with a saturated unit weight of 18.3 kN/m^3, an angle of shearing resistance of 40° and a factor *K× tan (δ)* estimated at 0.48. The caisson prototype used has a diameter of 2 m, a height of 2 m and a wall thickness of 8 mm. Figures 4 shows the theoretical predictions of installation suction and the results obtained from the field trial. It can be seen from this figure that theoretical predictions are in range. The field test were suspended at 1.4 m depth and hence reflect sudden drop in pressure.

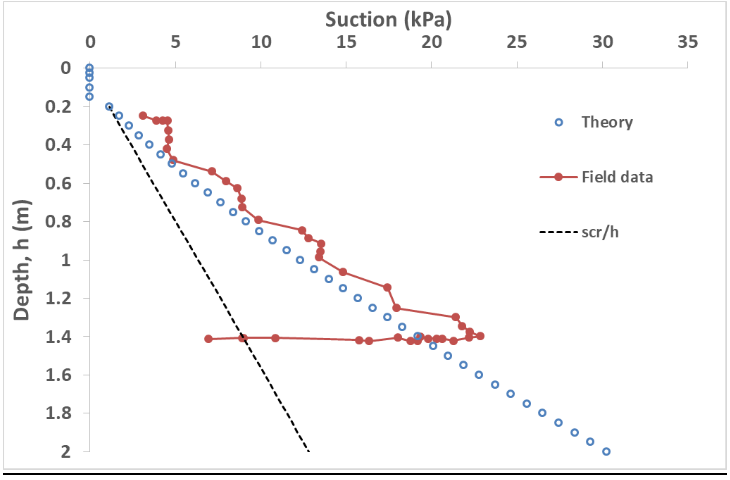

Figure 4: Installation suction. Theoretical prediction and experimental results for field test

The regression model can be applied to layered soil with modifications. However, it cannot be directly applied to bedrock.

5. CONCLUSION:

The proposed unified procedure where seepage was first solved for a normalized caisson geometry, then normalized excess pore pressure was expressed in terms of polynomial regressions. This resulted into an analytical representation of the required suction as a function of normalized penetration depth. The analytical results obtained were compared with the field trails and found to be in agreement. The model can accurately predict the pressure variation against caisson depth and hence the critical conditions for piping.

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APPENDIX:

Coefficients α_k , β_k γ_k **and** η_k **in the expressions** $a_k(h^*)$ **and** $b_k(h^*)$, $k = 0,...,6$.

$\alpha_0 = -0.0001$,	$\beta_0 = 0.0017$,	$\gamma_0 = 0.0001$,	$\eta_0 = 0.9983$
$\alpha_1 = 0.1214$,	$\beta_1 = -1.4920$,	$\gamma_1 = 0.4003$,	$\eta_1 = -0.6507$
$\alpha_2 = 0.8737$,	$\beta_2 = -2.0812$,	$\gamma_2 = 0.9029$,	$\eta_2 = -2.0802$
$\alpha_3 = 3.9790$,	$\beta_3 = -3.070$,	$\gamma_3 = 4.1311$,	$\eta_3 = -3.0714$
$\alpha_4 = 8.6348$,	$\beta_4 = -4.0763$,	$\gamma_4 = 8.9302$,	$\eta_4 = -4.0753$
$\alpha_5 = 8.6737$,	$\beta_5 = -5.0760$,	$\gamma_5 = 8.9749$,	$\eta_5 = -5.0763$
$\alpha_6 = 3.3330$,	$\beta_6 = -6.0760$,	$\gamma_6 = 3.4473$,	,