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Undrained pullout capacity of cylindrical suction caissons by finite element limit analysis

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ABSTRACT

Finite element limit analysis with axisymmetric condition is employed to determine plasticity solutions of undrained pullout capacity of cylindrical suction caissons in clay with linear increase of strength with depth and zero strength at the seabed. A closed-form approximation of numerical solutions of a suction caisson is proposed from nonlinear regression analysis. The proposed equation is used to check the accuracy and validity of the total pullout force and reverse end bearing force by conventional methods. The three-dimensional effect of suction caissons between axisymmetric and plane strain conditions is also deduced to evaluate the validity of conventionally assumed shape factor.

1. Introduction

Floating platforms of oil and gas exploration in deep water are usually maintained in position by a mooring system. A suction caisson is one of the most widely used types of embedded anchors for mooring systems of floating platforms in deep water. Generally, a suction caisson appears in a cylindrical shell with an opening at the bottom and a closed top cap. Its ratio of length to diameter ranges from 3 to 8, which is considerably low as compared to typical piles with slenderness ratios up to 60. During an installation, the initial penetration of each caisson into the seabed is achieved by its self-weight, while the remaining penetration is caused by suction in which water is pumped out from the inside of the caisson top cap, thus generating a net driving force to drive the caisson into the seabed. Once installed, the caisson top cap is sealed to maintain suction that provides a pullout capacity during operational loading conditions. Randolph and Gourvenec [1] provide an extensive overview of suction caissons and other types of mooring systems in deep water.

A hand calculation using the static vertical force equilibrium together with an assumption of the reverse end bearing failure is a widely used approach for estimating the undrained pullout capacity of suction caissons in clay. By assuming a completely sealed cap of suction caissons, the undrained pullout capacity of a suction caisson in a cohesive soil is conventionally estimated as the sum of the external friction force around its cylindrical area and the reverse end bearing force acting over its full basal area. The latter is calculated from the standard bearing capacity equation of a surface footing under a compressive (downward) loading together with correction factors accounting for effects of embedment depth and caisson shape. Thus, computed pullout capacity of this conventional method may be subjected to some uncertainties arising from these correction factors and the standard bearing capacity of a surface footing.

In the past, various studies on the pullout capacity of suction caissons have been conducted in field experiments (e.g., [2,3]), centrifuge model tests (e.g., [4,5]), 1 g physical model in a laboratory (e.g., [6]), finite element analysis (e.g., [7,8]) and limit analysis (e.g., [9–14]). Even though a cylindrical shell is a typical geometry of suction caissons, their vertical and lateral capacities in plane strain condition have been studied using numerical limit analysis (e.g., [15,16]). Very recently, Keawsawasvong and Ukritchon [17] solved the pullout capacity of planar caissons in clay using finite element limit analysis. A closed-form approximation of numerical solutions was proposed, and a conventional method was found to give a conservative estimate of pullout capacity of planar caissons. However, their numerical solutions are still limited to the case of planar caissons. Correction shape factors are introduced to modify the solution of planar caissons so that it can be used for cylindrical caissons in practice. Up until now, even though solutions of pullout capacity of suction caissons are available in the literature, upper and lower bound solutions of the undrained pullout capacity of suction caissons in axisymmetric condition are desirable for an accurate and reliable calculation of this problem in practice.

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The objectives of this paper are: (1) to determine plasticity solutions for the undrained pullout capacity of suction caissons in axisymmetric condition using finite element limit analysis (FELA) software, OptumG2 [18]; (2) to propose closed-form approximation of numerical solutions based on the computed data for predicting the pullout capacity of suction caissons in practice; (3) to assess accuracy and validity of a conventional solution and (4) to examine conventionally assumed shape factor on a reverse end bearing factor between axisymmetric and plane strain conditions.

2. Problem statement

Fig. 1(a) shows a general layout of the undrained vertical pullout capacity of suction caissons in clay. A suction caisson is a cylindrical shell with an embedded length, L, and a diameter, D. A vertical pullout load, P, is applied at the center of cylindrical caisson. The scope of this study is limited to suction caissons in a non-homogeneous clay profile with a linear increase of undrained shear strength with the depth (s_u) but zero strength at the seabed as:

$$s_u = s_{u0} + \rho z = \rho z \quad (1)$$

where s_{u0} = strength at the seabed = 0, ρ = linear strength gradient, z = the depth below the seabed.

Note that this strength profile corresponds to a typical case of a normally consolidated clay in deep water, where suction caissons are used to moor floating platforms. The clay obeys the rigid-perfectly plastic Tresca material with the associated flow rule.

It is also assumed that: (1) suction caissons behave as rigid structures since internal stiffeners are usually installed to prevent buckling failure; (2) the analyses do not consider the effect of caisson installation on the surrounding soil or the caisson is assumed "wished-in-place"; and (3) the rigid top cap of a caisson is completely sealed after installation.

Adhesion factor (α) at the soil-caisson interface is also considered in this study for the complete range from 0 (smooth) to 1 (rough) and defined as:

$$\alpha = s_{ui}/s_u \quad (2)$$

where s_{ui} = undrained shear strength at soil-caisson interface, s_u = undrained shear strength of surrounding soil.

Due to the assumption of a completely sealed cap, a full suction is achieved and hence there is no separation between the cap of caisson and the underlying soil. Thus, a fully bonded soil-caisson interface is assumed. This assumption was used in previous numerical studies of pullout capacity of suction foundations (e.g., [7,10–13,15–17]). For undrained conditions, the undrained pullout capacity of the caisson is unaffected by the unit weight of soil (γ). Therefore, the weightless soil (i.e. $\gamma = 0$) is considered in all analyses.

In this study, the soil behavior in the seabed is assumed to be pressure-independent (undrained); therefore, plastic deformation is incompressible. Consequently, due to kinematic constraints provided by the caisson skirt, the soil plug behaves as a rigid block. Thus, the assumption of zero-strength at the seabed surface (s_{u0} = 0) does not cause numerical difficulty in calculations.

3. Details of numerical models in FELA

The state-of-the-art FELA software, OptumG2 [18] was employed to accurately determine the limiting undrained pullout load of suction caissons. FELA employs the power of finite element discretization for handling complex load and geometry and plastic limit theorems for bracketing the exact limit load while numerical bound solutions are obtained from solving formulated optimization problems. Details of FELA are extensively discussed in Sloan [19]. The following summarizes aspects of numerical modelling of FELA in OptumG2 specially related to the current study of suction caissons.

Since the geometry of a caisson is a cylindrical shell, the axisymmetric condition is used in FELA, where only one half of domain is considered in the analysis as shown in Fig. 2. For both upper and lower bound analyses, the rigid plate element with weightless material was employed to model the cylindrical shell

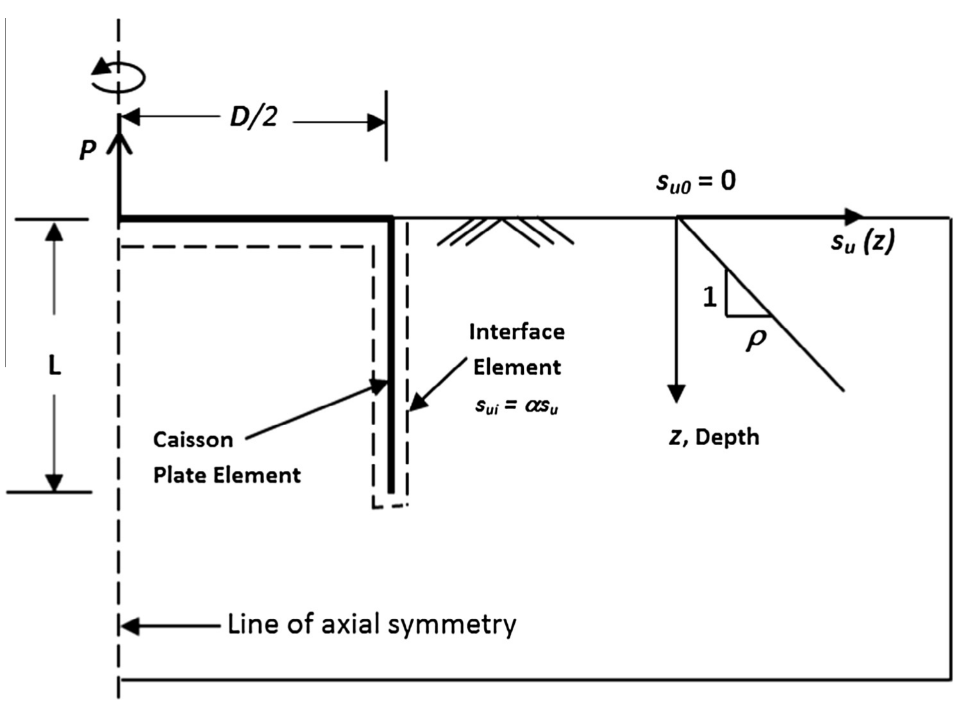

Fig. 1. Problem notation of cylindrical suction caisson.