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New design equation for undrained pullout capacity of suction caissons considering combined effects of caisson aspect ratio, adhesion factor at interface, and linearly increasing strength

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ABSTRACT

Undrained pullout capacity of suction caisson in clays with homogeneous and linearly increasing strengths with depth was investigated by two-dimensional axisymmetric finite element analysis. Effects of the caisson aspect ratios, the complete range of adhesion factors at soil-caisson interface, and the full range of dimensionless strength gradients on the dimensionless pullout factor of suction caissons were comprehensively examined. Based on a nonlinear regression to the derived finite element solutions, a new design equation of the undrained pullout capacity of suction caissons was proposed, considering the practical ranges of caisson aspect ratios, the complete range of adhesion factors at soil-caisson interface, and a general profile of both homogeneous and linearly increasing strengths with depth. The proposed equation was validated through a comparison of existing solutions and published experimental data.

1. Introduction

In recent years, suction caissons, known as skirted or bucket foundations, have been commonly employed as one of the most effective anchored and mooring systems for floating platforms and offshore facilities in deep water [42]. A suction caisson is a large steel thin-walled cylindrical structure that is open at the bottom and closed at the top. A typical diameter of a suction caisson ranges from 3 to 8 m, while its ratio of length to diameter is within 3–6 employed as suction anchor [42]. It is installed into the seabed first by penetrating under its own weight, and then by pumping water out of the caisson to create a suction that forces the caisson into the seabed. Under a completely sealed top cap after installation, the suction developed inside the caisson is still maintained during operation, thereby providing the uplift resistance attributed from the reverse end bearing of soils below its skirt. Thus, suction caissons have the major advantage to resist large uplift as well as lateral loads generated from hydrodynamic (wave and current) and wind loadings acting on offshore structures. Comprehensive overviews and examples of design problems of suction caissons and other foundations used in offshore geotechnical engineering can be found in Randolph and Gourvenec [42] and Houlsby [21].

Because of its practical importance, a large number of studies on suction caissons have been investigated in order to have a better understanding of their behaviors and field performance in various aspects (i.e., bearing and pullout capacities, combined loadings, installation, different soil types, static and cyclic loadings, plane strain and axisymmetric conditions, etc.), including field experiments (e.g., [3,12]), centrifuge model tests (e.g., [7,8,32,34]), 1 g physical models in laboratory (e.g. [6]), limit equilibrium method (LEM) (e.g., [10,22,42]), finite element analysis (e.g. [4,18,40,47,61]) and analytical limit analysis (e.g., [4,61]), finite element limit analysis (e.g., [24,35,54,55,57]), artificial neural network and other artificial intelligence techniques (e.g., [1,17,37,44]), and statistical-based methods (e.g., [46]).

Of particular interest in those various studies of suction caissons is the vertical pullout capacity that is one of the most important design parameters of this type of foundation. So far, there have been very few attempts to develop a closed-form expression of pullout capacity of suction caisson using both finite element analysis and limit analysis, as cited previously. Most available closed-form expressions of vertical pullout capacity of suction caissons has been derived by LEM (e.g., [10,22,42]), and thus this method still remains one of the most popular hand calculations for a conventional prediction of the vertical pullout capacity of a suction caisson. For an

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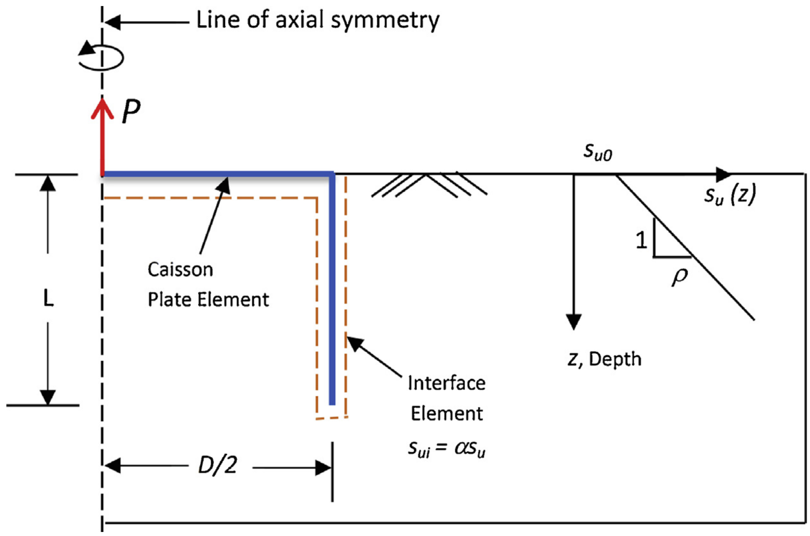

Fig. 1. Problem notation of undrained vertical pullout capacity of suction caissons.

undrained condition and assumption of a completely sealed cap of suction caissons, the vertical pullout capacity of a suction caisson in a cohesive soil by LEM is estimated from the vertical static equilibrium as the sum of the external friction force around its externally cylindrical area and the reverse end bearing force acting over its full basal area. The latter is based on the standard bearing capacity equation of a surface footing under a compressive (downward) loading, with a modification using empirical factors accounting for effects of embedment depth and caisson shape. Consequently, most available equations for undrained pullout capacity of suction caissons (e.g., [10,22,42]) have the major limitation associated with some simplifications on results of finite element or limit equilibrium studies, in which correction factors for the caisson's depth and shape are utilized. In addition, their applications are very restricted to a homogeneous strength profile, and are unable to consider the effect of interface roughness at soil-caisson interfaces, commonly known as adhesion factor.

Recently, finite element limit analysis was employed by Keawsawasvong and Ukritchon [24] and Ukritchon and Keawsawasvong [54] to investigate the undrained pullout capacity of planar and cylindrical suction caissons, respectively. In their studies, the shear strength profile is limited to a linear increase with depth but zero strength at the seabed in which this strength profile corresponds to a normally consolidated clay. Based on their studies, it was found that the accuracy of conventional hand calculations of pullout capacity of suction caissons by LEM is questionable due to uncertainties in shape and depth factors that were applied to the reverse end bearing capacity. In addition, the effects of adhesion factor at the soil-caisson interface and linear increase of strength profile cannot be accurately accounted for LEM. Assumptions using average strength must still be made for the limit equilibrium equations while LEM's solutions of the reverse end bearing are unclear as to whether they correspond to either smooth or rough interfaces of the suction caisson. Ukritchon et al. [57] developed a lower bound finite element limit analysis to extensively investigate the effects of adhesion factor at soil-footing interface and linear increase in shear strength with depth on undrained bearing capacity of strip footings. Moreover, Ukritchon and Keawsawasvong [55] employed the finite element limit analysis to investigate the undrained bearing capacity of shallow foundations and reported that a use of the traditional shape factor of 1.2 for converting a solution of bearing capacity of a strip footing to that of circular footing is seriously in error and unsafe for the case of a shallow foundation on a normally consolidated clay with a linear increase of strength with depth and zero strength at the ground surface. Therefore, this finding serves as an excellent example demonstrating unsafe uncertainties associated shape factors commonly employed in a conventional prediction of undrained bearing capacity of shallow foundations.

Despite being an alternative to a predictive tool in complex geotechnical problems due to its simplicity, the artificial neural network, other intelligence models (e.g., [1,17,37,44]) and statistical based methods (e.g., [46]) suffer the major drawback of being a black box model, in which there is no closed-form expression of a variable relationship available for a design in practice. In particular, the relationship among considered variables cannot be established reasonably while the models must be trained with sufficient number of data with a tendency to overfitting, where they are limited a particular range of model variables. As a result, the reliability of those artificial, intelligence and statistical models are very questionable and theoretical based researchers are still skeptical in the model development of a black box system. Consequently, for a practical standpoint, an accurate and reliable calculation of vertical pullout capacity of suction caissons is still desirable since it is the most important design parameter for the stability evaluation of suction caissons against an applied uplift loading. So far, there is no design equation of undrained pullout capacity of suction caissons considering combined effects of practical ranges of the caisson aspect ratio, the complete range of adhesion factor at the soil-caisson interface, and the full range of linearly increasing strength with depth.

This paper is concerned with the development of a reliable and accurate and closed-form approximate solution for the undrained pullout capacity of suction caissons in practice. The development of an analytical solution of the problem by hand calculations of limit analysis seems not to be possible due to the problem complexities in constructing accurate upper and lower bound solutions. Thus, a numerical approach using finite element analysis (FEA) with the axisymmetric condition is adopted and employed to accurately generate numerical solutions of the problem in which the approximate closed-form solution is subsequently developed from these numerical data. In order to make a new contribution to the research of suction caissons, this study considers a parametric study of the complete range of linear increase in undrained shear strength of clay with depth, complete range of adhesion factor at soil-caisson interface, and practical range of caisson aspect ratio. Based on a nonlinear regression to the finite element solutions, a new design equation of the undrained pullout capacity of suction caissons is proposed, in which the caisson aspect ratio, the adhesion factor at