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Finite element limit analysis of pullout capacity of planar caissons in clay

Suraparb Keawsawasvong, Boonchai Ukritchon *

Department of Civil Engineering, Chulalongkorn University, Bangkok, Thailand

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ABSTRACT

Rigorous upper and lower bound solutions of pullout capacity for planar caissons in clay are solved by two dimensional plane strain finite element limit analysis. The planar caisson is embedded in a deep clay layer with an undrained shear strength of zero at the mudline that increases linearly with depth. To perform finite element limit analysis, clay is modeled as the triangular element with the rigid-plastic Tresca material in an undrained condition. The planar caisson is modeled as the rigid plate element. Soil-structure interfaces with full tension are used around the contacted length between caisson and clay. Mesh adaptivity is employed to obtain very tight upper and lower bounds on the true pullout load. Parametric studies are carried out for the complete range of input dimensionless variables including adhesion factor and embedment ratio. The results of analyses are summarized in the form of the dimensionless pullout factor which is a function of the dimensionless variables. Empirical closed-form expressions for the dimensionless pullout factor and reverse end bearing factor of a planar caisson are proposed.

1. Introduction

A suction caisson is a reinforced concrete or steel foundation which can sink into the ground by its own weight and then the water is pumped out of the caisson to produce a suction force. This foundation is commonly used for carrying huge axial and lateral loads of large offshore structures. Randolph and Gourvence [1] provide comprehensive overviews of suction caissons and other foundations used in offshore geotechnical engineering. A large number of studies on suction caissons have been carried out in the past to study and understand behaviors of suction caissons. These include field experiments (e.g. [2,3]), centrifuge model tests (e.g. [4]), analysis of a 1G physical miniature caisson model in a laboratory setting (e.g. [5]), finite element analysis (e.g. [6,7]), and limit analysis (e.g. [8–13]). Even though the actual geometry of a suction caisson is cylindrical, numerical analyses using plane strain conditions or planar caissons have been employed to study its vertical and lateral capacities (e.g. [14]).

Vertical pullout capacity is one of the important design parameters when a caisson is subjected to an applied tensile load generated from wave force actions. In the case of undrained conditions, hand calculations of pullout capacity can be conventionally performed by limit equilibrium method (LEM), i.e., the sum of the external skin force and the reverse end bearing force calculated from the standard bearing capacity equation of a surface footing under a compressive (downward) loading together with empirical factors accounting for effects of embedment depth and caisson shape. Thus, uncertainties of the conventional calculation of the reverse end bearing capacity lie in errors from applying depth and shape factors to the standard bearing capacity equation.

This paper presents a numerical solution of pullout capacity of planar caissons in a deep clay layer by state-of-the-art software, finite element limit analysis (FELA), OptumG2 [15]. This software can accurately determine the limit load of a plane strain problem with the power of finite element discretization and the bounding capability of lower and upper bound plastic limit theorems. This numerical technique has been successfully applied to solve various stability problems in geotechnical engineering (e.g. [16]). The result of this study can be used to assess the accuracy of available approximate hand calculations of LEM used in practice.

2. Numerical method

For FELA of OptumG2, the soil is discretized as a triangular element. Lower bound elements use linear interpolation (3 nodes) of unknown stresses and allow stress discontinuity to occur at shared edges of adjacent triangles. Upper bound elements use quadratic interpolation (6 nodes) of unknown displacements which are continuous between elements. Both upper and lower bound elements produce rigorous upper and lower bounds on the true collapse load. In addition, mesh adaptivity is enabled to obtain more

* Corresponding author.
E-mail addresses: suraparb@hotmail.com (S. Keawsawasvong), boonchai.uk@gmail.com (B. Ukritchon).

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accurate lower and upper bound solutions (e.g. [17,18]). For all analyses, the models of a planar caisson were analyzed by OptumG2 using with the automatic mesh adaptivity with the default option of shear dissipation as the adaptivity control. Based on a suggested value in the software manual, five adaptive steps were selected to obtain an accurate solution, where an initial mesh with the number of 5000 elements was automatically adapted and increased to a final mesh with the number of 10,000 elements. Details of FELA in OptumG2 are not covered here, but can be found in Krabbenhoft et al. [15].

The clay is modeled using the rigid-plastic Tresca material with the associated flow rule. The undrained shear strength profile of the clay corresponds to normally consolidated clay in a very deep offshore, where its strength at the mudline (s_{u0}) is zero, but increases linearly with depth by the gradient, ρ. In this study, the unlimited tensile capacity is assumed at the soil-structure interface (i.e. full-tension interface), considering the fact that there is no separation between the cap of the planar caisson and the underlying soil due to the full suction generated by the complete seal of caisson's interior. Because of this assumption, the undrained pullout capacity of caisson is unaffected by the unit weight soil (γ). Therefore, the weightless soil (i.e., $\gamma = 0$) is considered in all analyses.

The planar caisson is modeled as the rigid plate element with weightless material. The geometrical parameters of the caisson include embedded length (L) and width (B), as shown in Fig. 1. The total vertical pullout load (P) is applied at the center of the top cap of the planar caisson. In addition, interface elements are used around the contacted length between the caisson and clay including the top cap and embedded length. The adhesion factor between the clay and caisson (α) is also studied in the full range of 0 (smooth) – 1 (rough). Because of symmetry of the problem, only half of the model is analyzed, as shown in Fig. 2. The bottom boundary of the model is fixed both horizontally and vertically, while the right (centerline) and left boundaries are allowed to move only in a vertical direction. The dimensions of the domain are chosen to be large enough so the failure zone does not intersect the boundaries. Thus, they do not have any effect on the computed results.

There are two independent dimensionless variables in FELA: (1) embedment ratio, $L/B = 0–\infty$; (2) adhesion factor, $\alpha = 0–1$. The solutions of pullout capacity of planar caissons are presented by the dimensionless pullout capacity factor, $N = P/\rho(B/2 + L)^2$, where it is generalized to cover the full range of the embedment ratio.

3. Results

Figs. 3 and 4 show examples of final adaptive meshes and incremental displacement vector for $L/B = 1$. Figs. 5 and 6 show the

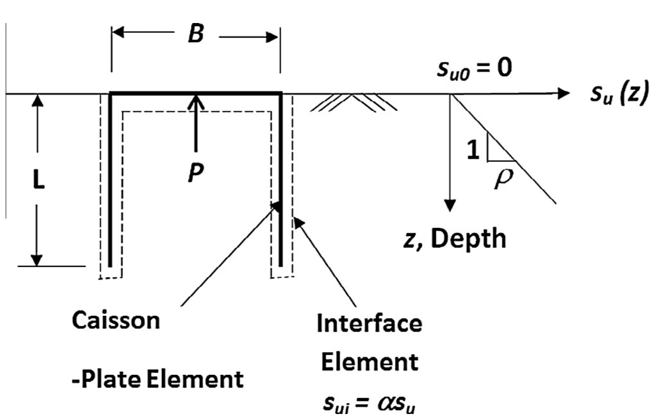

Fig. 1. Problem geometry of the planar caisson.

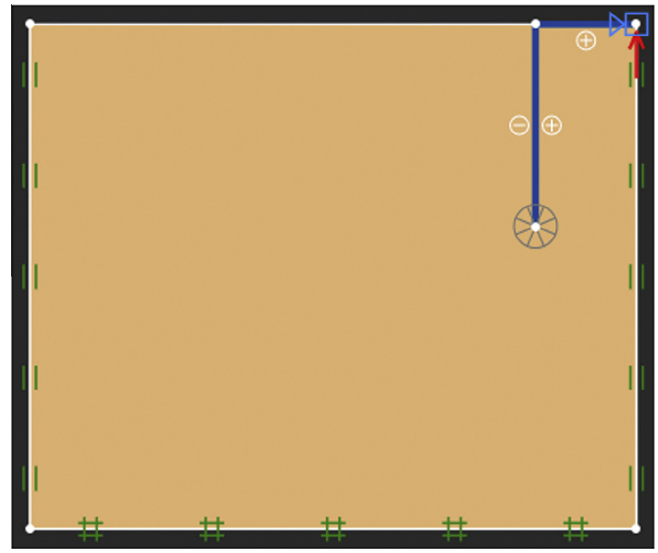

Fig. 2. Numerical model of planar caisson simulation in OptumG2.

results of cases for $\alpha = 1$. The failure mechanism of the planar caisson corresponds to the reverse type of end bearing failure with a radial shear zone located around the tip of the caisson. The failure of rough case has a high degree of local shearing near the wall which induces another inclined shearing zone extending to the mudline. The increase in L/B has an influence on the size of the failure zone. For low embedment ratio, the radial shear zone extends inside the caisson. In contrast, it does not happen for $L/B \geqslant 0.5$, where the soil inside the caisson rises as a rigid body as the caisson is pulled out by the tensile force.

Fig. 7 shows the relationship between N and α. For all values of L/B and α, the difference between the upper and lower bound solutions is very small within 1%. For most cases, the non-linear relationship between N and α is observed, except when $B/L = 0, 0.25$. For the case of pullout capacity of surface footing ($L/B = 0$), the adhesion factor does not alter the pullout factor, where $N = 1.12$. This special case corresponds well with classical bearing capacity with linear increase of strength with depth by Davis and Booker [19] who used the method of characteristics to obtain the exact solution as $N = 1$ for both smooth and rough surfaces.

The solution of vertical pullout capacity of the plate ($B/L = 0$) can be calculated by LEM. Based on the vertical equilibrium equation, the vertical pullout load of the plate is obtained straightforwardly by integrating the interface shear resistance along both sides of the plate, i.e., $N = \alpha$. This solution agrees very well with that of FELA, where it shows the linear relationship between N and α with a gradient of 1 in Fig. 7.

Fig. 8a and b shows the relationship between N and $L/B = 0–1$ and $B/L = 1–0$, respectively. The solution starts from $N = 1.12$ at $L/B = 0$ and then increases nonlinearly with L/B. The highest value of N ranges 4.2–4.9 when $L/B = 0.3–0.4$. Then, the solution decreases nonlinearly with the increase of L/B until $N = \alpha$ at $B/L = 0$. Those results of nonlinearity between N and L/B cannot be observed in Fig. 7.

4. Proposed empirical closed-form solution

Based on the parametric study of α and B/L, fifty data were obtained from FELA and used to develop an empirical closed-form equation for the pullout capacity of a planar caisson. The empirical rational function created from a biquadratic polynomial function is proposed for the dimensionless pullout factor (N_{FELA}) of a planar caisson: