UPPER BOUND LIMIT ANALYSIS OF THE UPLIFT BEARING CAPACITY OF SUCTION CAISSON FOUNDATION BASED ON REVERSE PRANDTL MECHANISM

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Abstract: In order to study the upper bound solution of bearing capacity of suction caisson foundation under vertical uplift load, a reverse Prandtl failure mechanism is constructed. On the basis of upper bound theorem of limit analysis, this paper introduces the viewpoint of reverse bearing capacity and the Prandtl failure mode for study. The reverse Prandtl failure mechanism means that the active area under the foundation becomes the passive area and the logarithmic spiral direction is opposite. Accordingly, the upper bound solution of bearing capacity of suction caisson foundation is derived by establish the corresponding kinematically admissible velocity field. At the same time, the upper bound solution is calculated by using the Matlab program and compared with the previous experimental data and other upper bound solution. The results show that the error between the upper bound solution and the experimental value is basically around 20% and it can prove that the reverse Prandtl failure mode is reasonable.
***Key words**: suction caisson foundation; Prandtl failure mode; ultimate bearing capacity; upper bound theorem*

Introduction

Suction caissons have been widely used in as foundations in offshore oil and gas industry and have recently extended to offshore wind turbines. However, there are still no wide spread engineering specifications on design and calculation of uplift bearing capacity for the suction caisson foundation. Existing methods for estimating the pullout capacity of suction are mainly based on experiments or finite element analysis (Rao et al.1997, Deng and Carter 2002, Feng 2016, Zhai 2017 and Du et al. 2017). Andersen et al.(1993) carried out four field tests to study the pullout behavior of suction caissons in soft clay and concluded that the ultimate capacity may be calculated by assuming a reverse bearing capacity failure. They also suggested that an upper limit could be solved by assuming a failure mechanism which is similar to the approach to compute the bearing capacity of the shallow foundation as introduced by Terzaghi (1943). The upper bound theorem have been proved to be a powerful tool for the analysis of the plastic collapse associated with shallow foundations, buried caissons and circular foundations (Chen 1975, Yang 2001 and Wang 2008). However, limited attempts have been reported to estimate the pullout capacity of the suction caisson foundation using the upper bound solution.

In this paper, the reverse Prandtl failure mode was adopted to represent the failure mechanism of suction caisson subjected to pullout loading. An upper bound method for calculating uplift bearing capacity of suction caisson foundation based on the reverse Prandtl failure mode. The proposed equation was verified using the experimental data from published literatures and it shows that the results from proposed equations agree well with the experimental results.

Theory

The distinct failure mechanism, referred to as the M1, is utilized in the analysis. M1 is the reverse Prandtl failure mechanism. The Prandtl reverse failure mechanism means that the active wedge under the caisson becomes the passive wedge at the vertical pullout loads, at the same time, the direction of the principal stress is horizontal and the minor principal stress is vertical. The angle between the direction of horizontal plane and the failure surface is $45°-\phi/2$, so it is different from Prandtl failure mechanism(The angle is $45°+\phi/2$), and the logarithmic spiral direction is opposite. The upper bound theorems, which assumes a perfectly plastic soil model with an associated flow rule, states that the internal power dissipated by any kinematically admissible velocity field can be equated to the power dissipated by the external loads and so enables a strict upper bound on the true limit load to be deduced.

Reverse Prandtl Failure Mechanism

The configuration of the suction caisson foundation here was described through two parameters-the radius *R*, the Caisson buried depth *L*. An overall schematic illustration of M1 is shown in Fig.1, the kinematic mechanism and the associated velocity field is shown in Fig.2. Since the movement is symmetrical about the footing, it is only necessary to consider the movement on the left-side of M1.The wedge ABC, with weight G_1, move with velocities v_0 but making an angleϕ, the friction angle of soil, with the linear failure surfaces AC. The Logarithmic spiral ACD, with weight G_2, move with velocity v but making an angleϕ, with the curved failure surfaces CD. The wedge ADE, with weightsG_3, moves with velocity v_1. The suction caisson foundation moves vertically with velocity v_p. Soil may slide either along the foundation surface, referred to as interface shear with limiting shear stress $a\,c$. At the same time, the soil weight above the bottom of caisson was considered in the upper bound solution of M1. And the soil weight above the bottom of caisson equivalent to q.

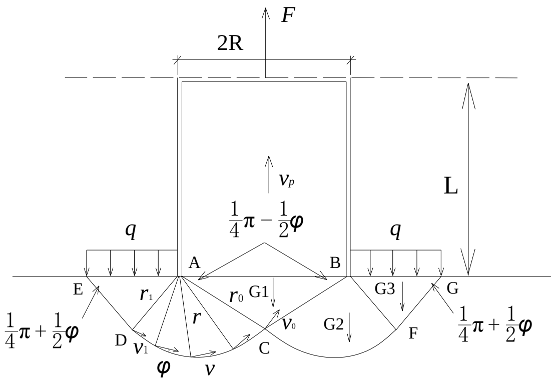

Fig.1 Reverse Prandtl failure mechanism

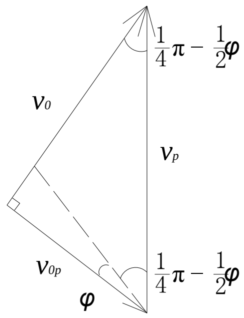

Fig.2 velocity hodographs

Formulation of Upper Bound Solution

Equating the work rates of external loads to the total internal energy dissipation rates, we can obtain the general equation of the ultimate bearing capacity using upper bound method, which is

$$
\begin{aligned}
F = & -2 f_6 e^{-\pi\tan\phi}\left[f_7+1\right]q+\frac{1}{3}\gamma\pi R^3\tan\left(\frac{\pi}{4}-\frac{\phi}{2}\right) \\
& -\frac{1}{2}\gamma R f_5\left\{\begin{aligned}&-f_1+\tan\left(\frac{\pi}{4}-\frac{\phi}{2}\right)f_2+\frac{1}{3}\sec^2\left(\frac{\pi}{4}-\frac{\phi}{2}\right)* \\ &\left[\left[\frac{1-e^{-2\pi\tan\phi}}{4\tan\phi}+\cos 2\left(\frac{\pi}{4}-\frac{\phi}{2}\right)f_3-\sin 2\left(\frac{\pi}{4}-\frac{\phi}{2}\right)f_4\right]\right]\end{aligned}\right\} \\
& -\frac{2}{3}\gamma R f_6 e^{-\frac{3}{2}\pi\tan\phi}\left[f_7+1\right]+\gamma\pi R^2 L+\frac{1}{2}c\cos\phi f_5+c f_5\left(\frac{1-e^{-\pi\tan\phi}}{2\tan\phi}-f_1+\tan\left(\frac{\pi}{4}-\frac{\phi}{2}\right)f_2\right) \\
& +\frac{1}{2}c\cos\phi f_5 e^{-\pi\tan\phi}\left[3f_7+2\right]+c f_5\left(\frac{1-e^{-\pi\tan\phi}}{2\tan\phi}-\frac{1}{2}f_1+\frac{1}{2}\tan\left(\frac{\pi}{4}-\frac{\phi}{2}\right)f_2\right)+2\pi RLac
\end{aligned} \tag{1}
$$

Comparison with experimental values

Singh et al.(1991), Shi et al.(2003), Jiao et al.(2006), El-Gharbawy and Olson(1998) and Chen and Cassidy(2012) have performed the vertical uplift tests for suction caisson foundations under the undrained condition. The results of these tests and the upper bound solutions for the ultimate uplift force are shown on Fig.3. It can be seen from Fig.3 that the M1 solutions agree reasonably well with the test results, with differences in the range from 3% to 44%. The upper bound solution used in this paper are less than the upper bound solution of completely Prandtl failure mechanism of Wang(2008) and closer to the test results. The comparisons presented that the suggested upper bound solutions can be applied to suction caissons for estimating the uplift bearing capacity under the undrained condition.

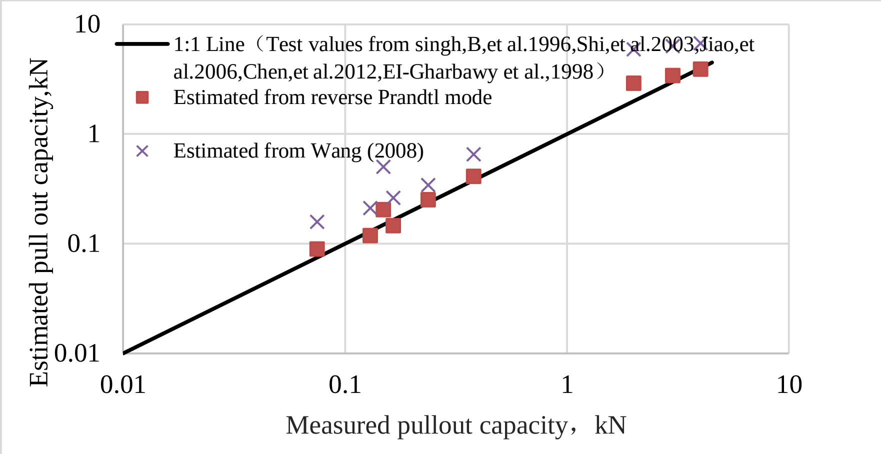

Fig.3 Verification of upper bound solutions for undrained vertical uplift capacity

Conclusions

In this paper, the reverse Prandtl failure mode was adopted to represent the failure mechanism of suction caisson subjected to pullout loading. And the upper bound solution agrees reasonably well with the test results, with differences in the range from 3% to 44%. The upper bound solution used in this paper is less than the upper bound solution of completely Prandtl failure mechanism of Wang（2008） and closer to the experimental value. It can be proved that both failure mechanisms are reasonably and more consistent with the actual force condition.

Acknowledgement

The preparation of the paper had received financial support from national key research and development program（No. 2017YFC0703408), the National Natural Science Foundation （No.51678145）and . the National Natural Science Foundation （No.51478109）.The financial support was greatly appreciated.

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Appendix A

$$f_1 = \int_0^{\frac{\pi}{2}} e^{-3\theta\tan\phi}\cos\theta \,\mathrm{d}\theta = \frac{e^{-\frac{3}{2}\pi\tan\phi} + 3\tan\phi}{1+\left(3\tan\phi\right)^2} \quad (A.1)$$

$$f_2 = \int_0^{\frac{\pi}{2}} e^{-3\theta\tan\phi}\sin\theta \,\mathrm{d}\theta = \frac{1-3\tan\phi e^{-\frac{3}{2}\pi\tan\phi}}{1+\left(3\tan\phi\right)^2} \quad (A.2)$$

$$f_3 = \int_0^{\frac{\pi}{2}} e^{-4\theta\tan\phi}\cos 2\theta \,\mathrm{d}\theta = \tan\phi \frac{e^{-2\pi\tan\phi} + 1}{1+\left(2\tan\phi\right)^2} \quad (A.3)$$

$$f_4 = \int_0^{\frac{\pi}{2}} e^{-4\theta\tan\phi}\sin 2\theta \,\mathrm{d}\theta = \frac{1}{2}\frac{1+e^{-2\pi\tan\phi}}{1+\left(2\tan\phi\right)^2} \quad (A.4)$$

$$f_5 = \pi R^2 \sec^2\left(\frac{\pi}{4}-\frac{\phi}{2}\right) \quad (A.5)$$

$$f_6 = \pi R^2 \tan^2\left(\frac{\pi}{4}-\frac{\phi}{2}\right) \quad (A.6)$$

$$f_7 = \tan\left(\frac{\pi}{4}-\frac{\phi}{2}\right)e^{-\frac{\pi}{2}\tan\phi} \quad (A.7)$$