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Basal stability analysis of braced excavations with embedded walls in undrained clay using the upper bound theorem

Maosong Huang*, Zhen Tang, Juyun Yuan

Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China
Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 200092, China

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ABSTRACT

The embedded wall has beneficial effects on the basal stability of braced excavation in clay. Conventional basal stability analysis methods cannot evaluate the lateral resistance afforded by the wall reasonably. This paper presents a new failure mechanism to evaluate the basal stability of excavations with embedded walls in undrained clay based the upper bound theorem. The proposed mechanism consists of a rigid block and three shear zones, and the horizontal reinforcing effects of wall penetration blow the excavation base are considered. The embedded wall is regarded as an elastic beam and deforms consistently with the velocities of adjacent soil in the shear zone. The elastic strain energy stored in the wall is incorporated in the upper bound calculation to increase the stability of excavation. The proposed mechanism has also been extended to the basal stability of excavations in anisotropic and non-homogeneous clay. The applicability of the proposed mechanism was validated by comparison with the results of numerical limit analysis and FEM, as well as five field cases near or at failure. Two failure field cases in anisotropic clay were also studied using the proposed mechanism. The results showed that the proposed method is capable to yield reasonable estimation by using both isotropic and anisotropic shear strength.

1. Introduction

For deep excavations in soft clay, the factor of safety against base heave failure plays a key role in assessing the amount of ground movement generated by the plastic deformation of clay around the excavation. The retaining walls used to penetrate the excavation base with certain depth to prevent the base heave failure and limit the ground movements. For calculations of basal stability, it is desirable to consider the effects of wall embedment on the basal stability. The study of the basal stability of excavations in soft clay has been investigated by several authors in literature. Most authors have performed numerical or analytical approaches.

The most widely used numerical approach for basal stability analysis may the finite element method (FEM). The FEM provides a comprehensive framework to evaluate multiple facets that affect the basal stability and thus results in an accurate estimation. The non-linear elastoplastic finite element analysis conducted by Hashash and Whittle (1996) showed the wall embedded depth and support conditions can significantly affect the failure models and the stability of excavation base. Goh (1990) and Faheem et al. (2003) adopted the elastoplastic FEM with shear strength reduction technique to study the basal stability of excavations. Parametric study showed that the basal stability of excavations increases with the embedded depth and the stiffness of wall. Ukritchon et al. (2003) used the numerical limit analysis to study the stability the braced excavations, whose results agreed well with those by Goh (1990) and Faheem et al. (2003). The results of numerical analysis had shown the close dependency of the basal stability on wall embedded depth and stiffness. However, the numerical approaches have not been widely used in practice engineering due to the difficulties in selecting suitable constitutive models and the time-consuming convergence process.

Most analytical approaches for calculating stability are through limit equilibrium analysis or upper bound limit analysis. Fig. 1(a) shows two failure mechanisms of limit equilibrium analysis, as presented by Theoretical (1943) and Bjerrum and Eide (1956). These two methods assumed that the failure of the excavation base is analogous to the failure of a wide footing located at the excavation base. This assumption provided a convenient way to calculate the basal stability factor by introducing the bearing capacity expressions. Obviously, these two methods neglect the effects of wall penetration. The modified versions of those two methods to account for the embedded depth of wall were proposed by Terzaghi (1943) and Eide et al. (1972), as shown in

* Corresponding author at: Department of Geotechnical Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China.
E-mail address: mshuang@tongji.edu.cn (M. Huang).

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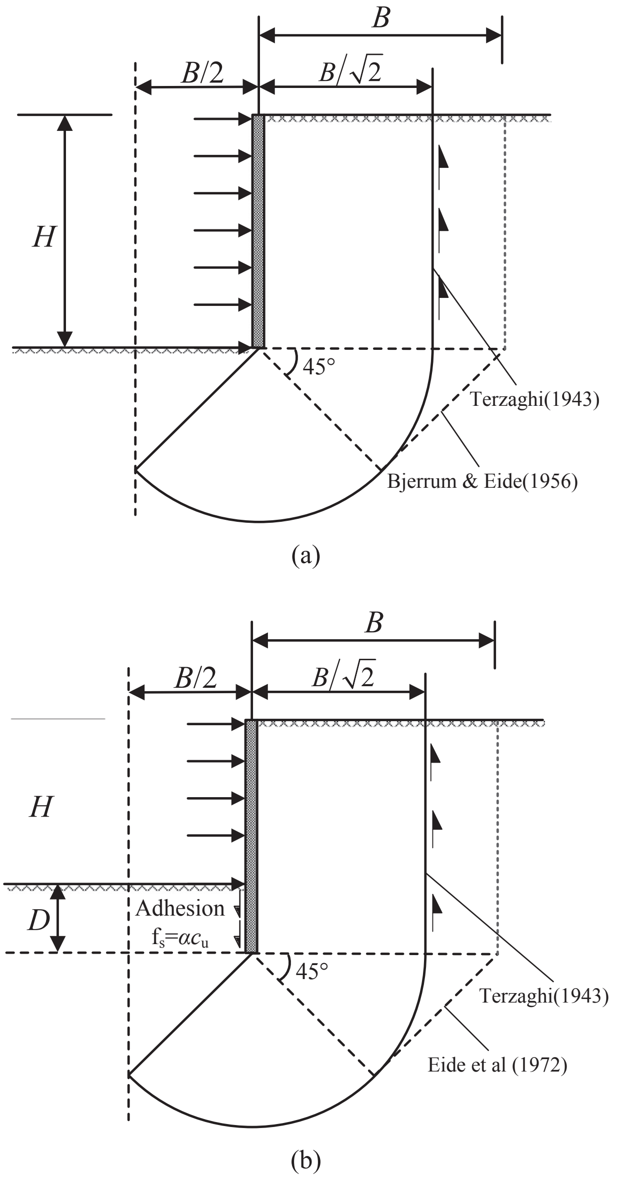

Fig. 1. Conventional basal stability mechanisms: (a) without consideration of wall embedded; (b) with consideration of wall embedded.

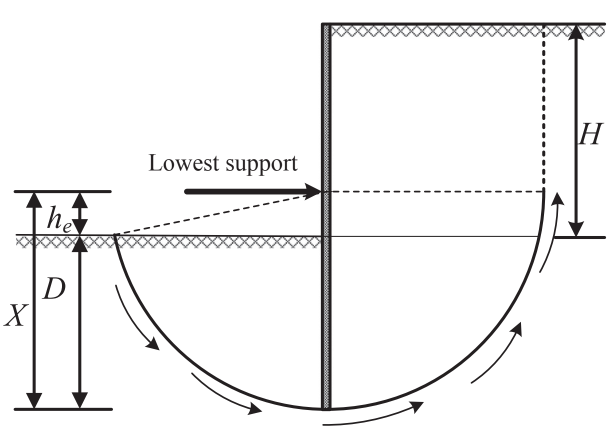

Fig. 2. Failure mechanism of the slip circle method.

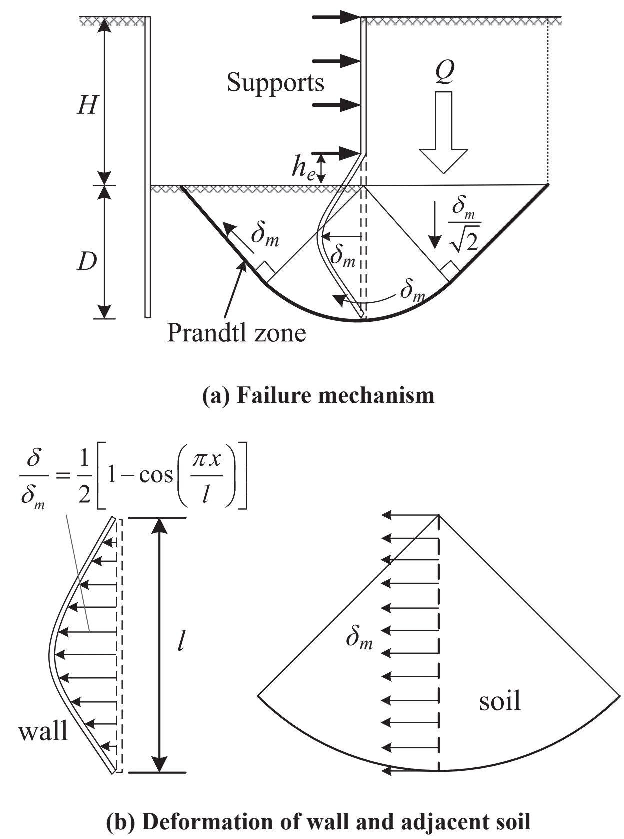

Fig. 3. Failure mechanism proposed by O'Rourke (1993).

Fig. 1(b). The two modified mechanisms do not consider the lateral resistance afforded by the wall. Therefore, these two modifications can only be applied in the case of fully rigid walls, which is unrealistic in practical engineering. The slip circle method (Hsieh et al., 2008) is widely used in practical engineering, which defines the ratio of resisting moment to the driving moment of the lowest support as the factor of safety for basal stability, as shown in Fig. 2. The resisting moment afforded by the wall is also not incorporated in the slip circle method. Moreover, the slip circle method deduces a constant stability factor with different wall embedded depth in the case of homogeneous clay. The analytical approaches based on upper bound theory are also widely used, such as Su et al. (1998), Liao and Su (2012), Chang (2000), Faheem et al. (2003) and Huang et al. (2011). These approaches either neglected the wall embedment or regarded the wall as fully rigid, and thus had the same limitations with those from the limit equilibrium analysis.

O'Rourke (1993) proposed a distinctive analytical approach based on conservation of energy, as shown in Fig. 3. The failure mechanism consists of a Prandtl zone and an embedded wall, the wall increases the stability due to the elastic energy stored in flexure. As seen in Fig. 3, the wall deforms inconsistently with the adjacent soil, thus the velocity boundary conditions of soil-wall interface are not satisfied. Actually, this approach did not necessarily provide a rigorous basal stability estimation of excavation with embedded wall.

In the framework of upper bound approach and Tresca's yield criterion, the velocity fields should satisfy the incompressibility condition and any imposed velocity boundary condition. Ingenuity is required in upper bound approach from the need to devise velocity fields satisfying kinematic admissible conditions and yet producing a sufficiently low value of the upper bound of the stability factor. Most failure mechanisms of basal stability analysis presented in literature consist of rigid blocks and uniform shear zones with either straight or circle velocity fields. Among these failure mechanisms, some consist of a uniform