Stability of Buildings Near Shallow Excavations

L’Influence des Fouilles peu Profondes sur la Stabilité des Batiments Adjacents

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ABSTRACT: There are a lot of urban excavations which are done adjacent to existing buildings. Stability of such a system needs to be studied due to reducing effect of the excavation. Numerical results presented by some researchers have shown that at initial steps of a deep excavation or in the case of a shallow excavation adjacent to a foundation, the bearing capacity may decline drastically and as the retaining system are usually neglected in this stage, the foundation and the adjacent building will be unstable. This paper describes a finite element lower bound solution for scrutinizing the change of bearing capacity of strip footings due to shallow excavations. The Mohr-Coulomb yield function and an associated flow rule are adopted for the soil behavior. Three-nodded triangular stress elements are used for meshing the domain of the problem and stress discontinuities occur at common edges of adjacent elements. Variation of bearing capacity versus the change of affecting parameters is analyzed and shown in applicable charts. Effects of two solutions for this problem are also discussed.

RÉSUMÉ: L’exécution des fouilles tout près des ouvrages existants, inévitables dans les zones urbaines, peut affecter la stabilité des fondations adjacentes. Aux premières phases de déblayement des fouilles profondes, avant l’installation des soutènements, ainsi que dans le cas des fouilles peu profondes, la capacité portante des fondations superficielles adjacentes peut subire des diminutions dangéreuses. Cet article présente les résultats d’un modéle des éléments finis, basé sur l’approche par défaut de la théorie du calcul à la rupture, qui permet ĺanalyse détaillée du problème en question. Le critère de plasticité de Mohr-Coulomb avec la loi de normalité a été choisie pour défeinir le comportement du sol. Les éléments sont triangulaires à trois noeuds et les éléments d’extension ont été utilisés aux bords. Les variations de la capacité portante des fondations superficielles en fonction de différents paramèteres du problème sont présentées sous forme des diagrammes sans dimensions. L’efficacité de deux mesures préventive courantes est aussi éxaminée.

KEYWORDS: Bearing capacity, Strip footing, shallow excavation, Lower bound, Finite element.

1 INTRODUCTION

Urban excavations are now inevitable stage of construction in most of the cities which become more challenging near buildings due to reducing effect on stability of adjacent buildings. Stability of buildings near vertical excavations can be considered as a special case of footing-on-slope system which has been investigated by numerous researchers with various methods. Some researchers (du Buhan etal 1998, Georgiadis 2010, Mofidi etal 2014) have found that there are three main failure modes for bearing capacity of footings near slopes versus variation of slope height (figure1). Failure mode (a) can be seen when the slope is stable itself and the footing reaches its limit pressure. Failure mode (b) is known as a overall slope failure and occurs under gravitational loading due to the weight of the soil mass. Failure mode (c) happens when the footing distance to the crest of the slope becomes large and the effect of slope angle gets slight and the system resembles to the bearing capacity of a footing on level ground. This can be observed in diagrams of figure 2 in which the first part of diagrams shows an initial drop in bearing capacity which happens in lower slope heights which is called “Transient portion”, the second part indicates a stable condition in bearing capacity for a specific range of slope height (failure mode “a”) and the third and final part of diagrams shows a final drop in bearing capacity (failure mode “b”).

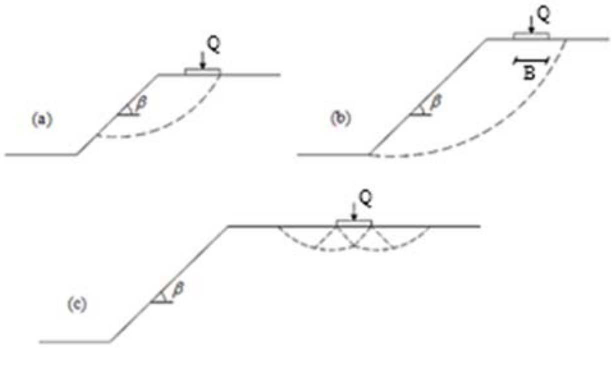


Figure 1. Different typical failure modes for footing-on-slope problem: bearing capacity failure (a, c) and overall slope failure (b).

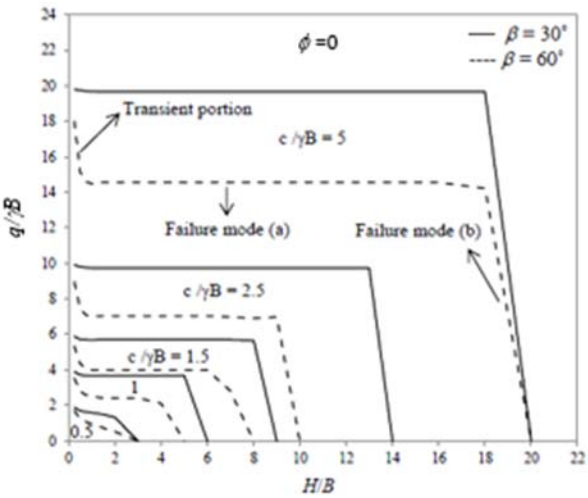


Figure 2. Effect of slope height on bearing capacity of the adjacent footing (Mofidi etal 2014)

A statistical survey of 79 building failures occurred during nearby excavations in Tehran city shows that 16 of them were triggered by shallow excavations (Abdollahi 2016). The foundation ground in this area, from north to south, consists of moderately cemented course grained to fine grained alluviums (c ≈30 to 100 kPa). Another case study (Vitton etal 1993) has shown that a shallow trench (between 1.5 to 1.8 m deep) excavated along the length of the single-story building, resulted in building's collapse in the city of Tuscaloosa, Alabama after about one hour after the excavation process. It is reported that the foundation had been constructed on approximately 2.1 m of soft silty clay with the bottom portion of this soil highly saturated. These statistical researches beside the analytical study presented in current paper highlight the importance of the problem of shallow excavations near buildings. The stability of footing adjacent to a shallow excavation can be considered as a special case for a footing-on-slope problem in which the slope face is vertical and the footing is at the edge of the cut. This paper investigates the effect of shallow excavations on bearing capacity of adjacent footing. In other words, this paper studies the first part of the bearing capacity curves shown in figure 2.

2 PROBLEM DEFINITION

The problem of bearing capacity of a strip footing adjacent to a shallow vertical excavation with a cohesive frictional soil is shown in figure 3.

Geometric parameters include the footing width *B* and height of the slope *H*. It is assumed that the soil obeys the associated flow rule with Mohr-Coulomb yield criterion and has the cohesion of *c*, internal friction angle of ϕ and unit weight of γ. The approach of this paper is to investigate the variation of limit pressure (q) versus parameters which affect the stability of the footing.

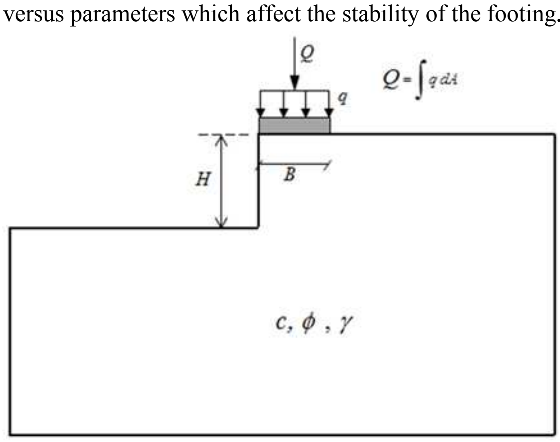


Figure 3. Problem parameters

3 FINITE ELEMENT SOLUTION OF LOWER BOUND LIMIT ANALYSIS

The formulation used in this paper follows that of Sloan (1988) in which the linear finite element method is applied and the domain of problem is discretized by 3-noded triangular elements. Unknowns of the problem are nodal stresses. Extension elements are used to extend the statically admissible stress field into a semi-infinite domain and thus lead to a rigorous lower bound solution. In order to use linear programming technique, the linearized Mohr-Coulomb yield function should be utilized in formulation of lower bound theory. Figure 4 illustrates a typical finite element model used in lower bound analysis for a problem with *B*=2 m and H=2 m. The model consists of 394 elements, 226 nodes and 580 stress discontinuities.

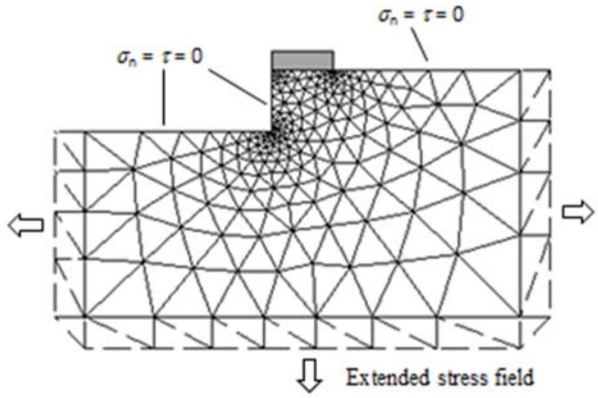


Figure 4. Typical finite element mesh used in lower bound analysis of the problem

By assembling all equalities and inequalities, a discrete formulation of the lower bound theory leads to the following constrained optimization problem:

$$\text{maximize } \mathbf{c}^T \boldsymbol{\sigma}$$
$$\text{subject to } \begin{cases} A_1\boldsymbol{\sigma} = b_1 \\ A_2\boldsymbol{\sigma} \le b_2 \end{cases} \qquad (1)$$

where c is a vector of objective function coefficients, $\boldsymbol{\sigma}$ is the vector of problem unknowns, A_1 is an overall matrix of equality constraint coefficients which derives from elements equilibrium, discontinuities equilibrium and boundary conditions, b_2 is a right-hand vector of equality coefficients, A_2 is an overall matrix of inequality constraint coefficients which derives from yield criterion and b_2 is the corresponding right-hand vector. Using linear finite elements and linearized yield function, the lower estimation of true collapse load can be obtained through linear programming techniques. In current study, a MATLAB code is prepared by authors for computing the bearing capacity of the footings adjacent to shallow excavations.

4 RESULTS AND DISCUSSION

A rational range of parameters has been examined in analyses. The footing width=2m, γ=19 kN/m^3, c=10, 20, 30 kPa, ϕ=25, 30, 35, 40˚ and H/B=0~1 is considered for investigation of bearing capacity of footings adjacent to shallow vertical excavations. The charts showing the change of bearing capacity (q) versus dimensionless parameter of excavation depth (H/B) with variation of soil shear strength parameters (c, ϕ) are presented in figure 5.

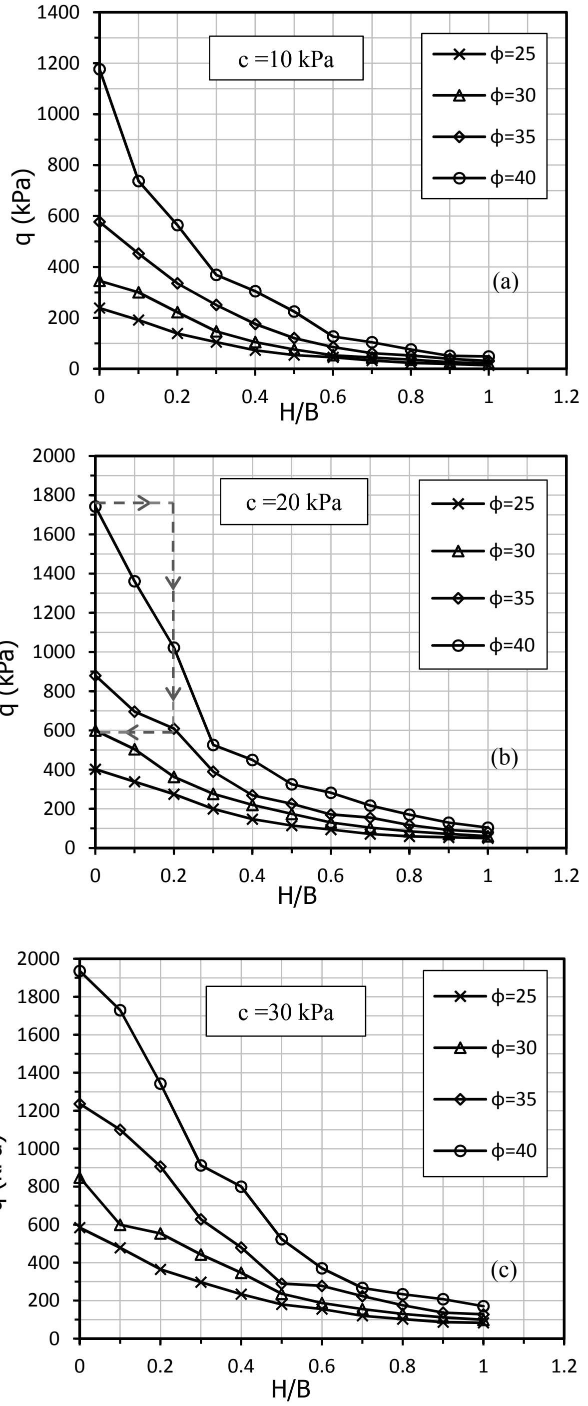
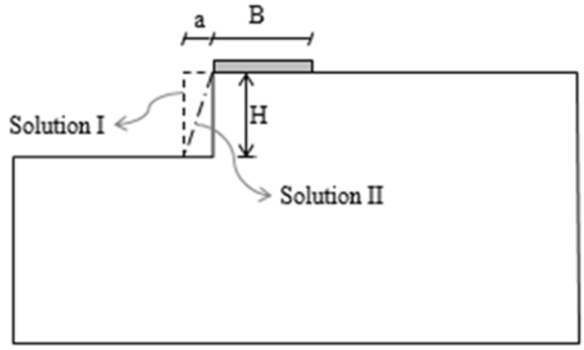


Figure 5. Bearing capacity versus dimensionless excavation height for different values of c ,ϕ (B=2m , γ=19 kN/m3)

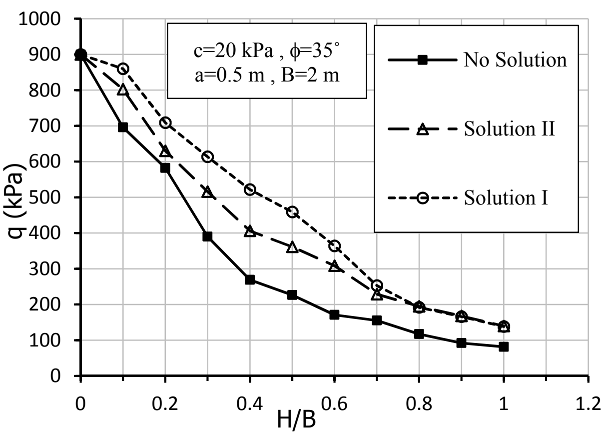
Charts of figure 5 show significant decrease in bearing capacity with increase of H/B particularly to a depth about the half of the footing width. For example, in figure 5(c) and for soil with ϕ=40° the bearing capacity decreases from 1950 kPa when there is no excavation to 550 kPa when the soil adjacent to the footing is excavated to the depth equal to half of the footing width (about 72 % decrease). For the same condition, this value is 76 % for ϕ=35°, 70 % for ϕ=30° and 67 % for ϕ=25°. According to these charts, excavation of the ground adjacent to an existing building may be very risky without any bracing or retaining structures even for shallow depths. These charts also can be helpful when the soil properties are different from what are anticipated or when there is a thin layer of weak soil beneath the foundation. For instance, in figure 5(b) for a case with B=2 m, c=20 kPa and ϕ=40° the ultimate bearing capacity (when there is no excavation) is about q=1750 kPa based on current lower bound solution. When the footing is designed for a level ground by the factor of safety of 3 then the allowable bearing capacity will be q_a=1750/3~583 kPa. If just the internal friction angle of the soil becomes ϕ=35° and the cohesion remains constant and the soil is excavated to 40 cm deep (H/B=0.2), then the ultimate bearing capacity would be about 600 kPa as the dashed line indicates. This means that if ϕ decreases 5 degrees for the aforementioned condition, then the foundation is near to failure because the ultimate bearing capacity approaches the allowable bearing capacity. If the soil friction angle becomes 30° or 25°, then the bearing capacity failure will occur because the ultimate bearing capacity of the footing is less than allowable bearing capacity (q_a=583 kPa). The effect of cohesion decrease can be investigated similarly by going through figures 5(a) to 5(c) with a same ϕ.

5 EFFICIENCY OF SIMPLE PREVENTIVE MEASURES

Some remedial solutions can be proposed in order to avoid the high risk of shallow vertical excavations adjacent to buildings. Two of them are mentioned and discussed here. One is to excavate the soil with a small distance from the foundation (figure 6, solution I) and the other one is to excavate the soil with a slope from the foundation edge (figure 6, solution II).



The effect of these two remedial solutions can be scrutinized through the charts of figure 7.



For problem parameters shown in figure 7, it is observed that both solutions have a notable positive effect on bearing capacity of the foundation. For instance, when the soil is excavated to H/B=0.4 (80 cm deep) the ultimate bearing capacity according to current lower bound method is about 270 kPa. By excavating the soil with a distance of a=0.5 m from the foundation edge (solution I), the bearing capacity increases to about 530 kPa and by excavating the soil with a slope a/H=0.5/2 (solution II) the bearing capacity increases to about 400 kPa. With respect to initial bearing capacity when there is no excavation near the foundation (q~900 kPa), the decrease of bearing capacity for solution I is about 41 % and for solution II it is about 55 % while this decrease is about 70 % when no solution is adopted. These results show that excavating the soil with a remedial measured distance (a) from the foundation edge is more efficient than excavating with the equivalent slope of that distance (a/H). As shallow excavations can be considered as initial stages of deep excavations, the aforementioned solutions can be utilized in shallow urban excavations to reduce the probability of failure in first steps of the project until the designed retaining system be built.

6 CONCLUSION

Finite element lower bound method used in current paper shows that the shallow excavations near strip footings can reduce the bearing capacity of the so called system drastically. Relevant charts indicate that the bearing capacity reduces more than 50 % when the depth of the excavation reaches about half of the footing width. So, the notable effect of shallow excavations on stability condition of adjacent footings highlights the importance of initial steps of excavation projects which should be done with careful consideration. Particularly, when there is a weak soil beneath the foundation removing the soil even to a shallow depth will lead to footing collapse. As current study shows, for reducing the risk of shallow excavations next to the foundations, the soil can be removed vertically with a specific distance from the footing edge or excavation can be done with a slope from the footing edge.

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