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Estimate end bearing resistance of a circular foundation using small strain and large deformation finite element modelling

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Abstract

Accurately predicting the end bearing resistance of the foundation is important for its design and application. This research compares the results of a circular foundation end bearing resistance in uniform clay from small strain finite-element (SSFE) analysis and large-deformation finite-element (LDFE) analysis, with focus on the effect of soil stiffness. Results show that the soil stiffness has little influence on the bearing capacity of a shallow foundation with a shallow failure mechanism; for a deeply buried foundation, however, a deep flow mechanism is developed, and the failure zone is influenced by the soil stiffness. It is found that, for a shallow foundation, artificially increasing the soil stiffness in SSFE analysis allows for obtaining the end bearing capacity at a smaller displacement without sacrificing accuracy; while employing increased soil stiffness for deeply buried foundations may lead to inaccurate results. For penetrating problems, e.g., pile installation and CPT (cone penetration test), SSFE analysis may underestimate the end bearing resistance factor without considering the installation effect.

Key words: *bearing resistance; soil stiffness; small strain finite-element analysis; large-deformation finite-element analysis*

1 Introduction

The bearing capacity problem was initially investigated for a strip (infinitely long) foundation using the plasticity approach [1] and further developed and employed for various shapes of foundation (e.g., circular, square, and rectangular foundations) considering shape factors [2, 3].

Soil stiffness is a crucial factor in many geotechnical applications, such as settlement analysis, cone penetration analysis and so on. Existing publications have indicated that the stiffness of clay soil has no influence on the undrained bearing capacity through small strain finite element (SSFE) analysis [4, 5]. However, some other research has shown that there are significant variations in the bearing capacity of foundations, such as strip footings [6], rectangular foundations [7], and bucket foundations [8], based on large deformation finite element (LDFE) analysis. In summary, significant uncertainty exists, with conflicting evidence regarding how soil stiffness impacts foundation bearing capacity.

This paper presents a numerical study of the end bearing resistance of a circular foundation in uniform clay with SSFE and LDFE analyses, where both shallow and deep foundations are considered. The soil flow mechanism is investigated in detail, and the influence of soil stiffness on the bearing capacity is numerically quantified.

2 Numerical modelling

Both SSFE and LDFE analyses are undertaken in this study to investigate the end bearing resistance of a circular foundation. For large deformation problem, the RITSS method (remeshing and interpolation technique with small strain [9]), falling in the category of Arbitrary Lagrangian and Eulerian (ALE) method, is developed and implemented in the commercial software ABAQUS. The flowchart of RITSS procedure is shown in Figure 1, where the whole analysis is divided into a series of incremental small strain analysis combined with frequent remeshing of the entire domain, followed by updating all field variables (i.e., stresses and material properties) from the old mesh to the new mesh. Small strain analysis is conducted with the foundation pre-embedded at a certain depth, and a displacement of $0.2D$ is set to reach its limit force.

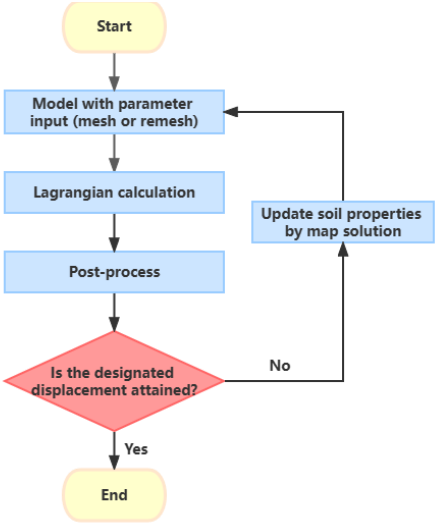


Figure 1: Overall numerical scheme of RITSS.

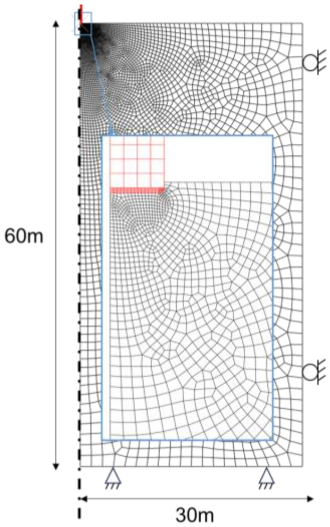


Figure 2: Typical mesh for numerical model.

Numerical model used in this study is shown in Figure 2. The circular foundation has a diameter of D = 1 m, and the largest penetration depth is 20D (to assess variations in end bearing capacity with burial depth). The foundation is simplified as a rigid body. The axisymmetric soil domain is chosen as 30 m in radius and 60 m in depth to minimize the influence of the boundary conditions. Hinge and roller conditions are applied along the base and two sides of the soil domain, respectively. Linear four-node quadrilateral elements (CAX4) with four internal Gauss points are used in the numerical model. A fine mesh is generated around the foundation to ensure the accuracy of end bearing resistance.

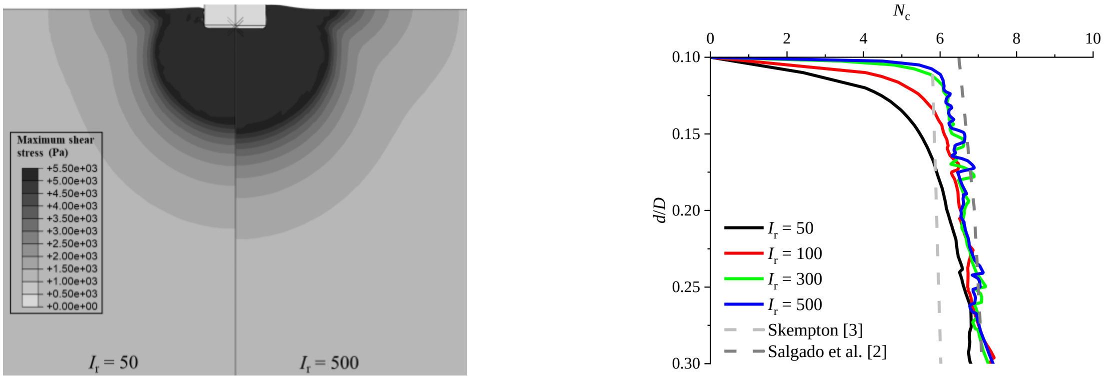
The soil is modelled as a linear elastic-perfectly plastic material obeying a Tresca yield criterion. Undrained soil condition is considered with a Poisson's ratio of ν = 0.495 and undrained shear strength s_u = 5 kPa. For simplification, the soil is taken as weightless, and only smooth (i.e., frictionless or α = 0, where α is the adhesion factor) soil-structure interface is simulated.

For clay soils, the rigidity index, I_r (= G/s_u, where G is the shear modulus), typically ranges between 50 and 500. To explore the impact of the rigidity index I_r on end bearing resistance, parametric analyses are conducted through SSFE and LDFE analyses, where I_r is varied across values of 50, 100, 300, and 500.

3 Numerical results

3.1 Shallow foundation

The effect of soil stiffness on the bearing capacity of a shallow circular foundation (pre-embedded 0.1D) is investigated through SSFE analysis. Figure 3a shows the failure mechanisms of the foundation for I_r = 50 and 500. The contour of maximum shear stress ($(\sigma_1 - \sigma_3)/2$, where σ_1 and σ_3 are the maximum and minimum principal stresses, respectively) displays that the plastic zone is developed beneath the tip extending to the soil surface, and the ranges of mobilized soil are comparable. SSFE analyses with various rigidity index I_r of 50, 100, 300 and 500 are conducted to explore the effect of soil stiffness. Figure 3b shows the bearing capacity factor, N_c, over normalized displacement, d/D. It can be seen that soil stiffness affects the initial load-displacement response but has little effect on the ultimate bearing capacity of a shallow circular foundation. The results from this study agree well with that from finite element limit analysis [2] and slightly larger than the empirical results [3]. This suggests that artificially increasing the value of I_r allows for obtaining the end bearing capacity at a smaller displacement without sacrificing accuracy.



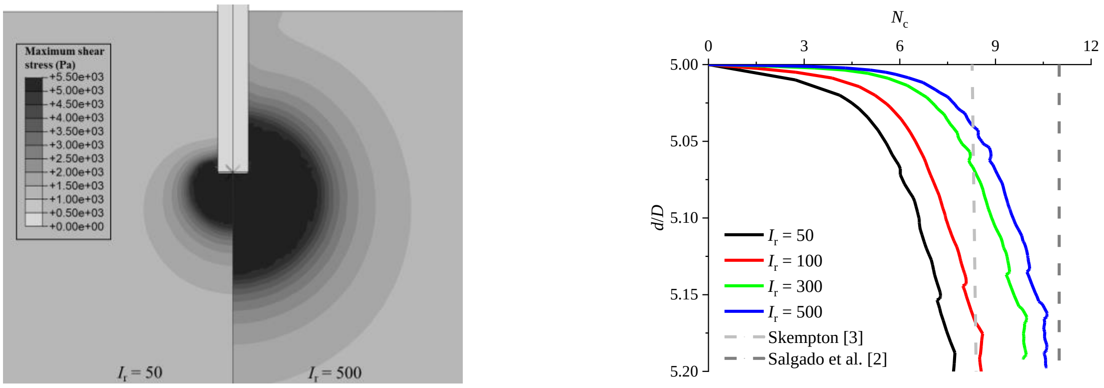
(a) (b)

Figure 3: Bearing capacity of a shallow foundation (SSFE): (a) failure mechanism; (b) bearing factors.

3.2 Deep foundation

The effect of soil stiffness on the bearing capacity of a deep circular foundation (or pile) ($d/D > 5$) is investigated through both SSFE and LDFE analysis. The soil flow mechanisms for the foundation pre-embedded at a depth of $d/D = 5$ from SSFE analysis for $I_r = 50$ and 500 are shown in Figure 4a. It is shown that the plastic area is localized around the foundation tip, and the yielding zone of $I_r = 500$ is significantly larger than that of $I_r = 50$. The bearing capacity factors for various I_r are depicted in Figure 4b. It is shown that the soil stiffness has a significant influence on the bearing capacity of a deeply buried circular foundation. This is because a foundation placed in soil with larger stiffness induces increased radial displacement, resulting in a higher pressure in the expansion of a cylindrical cavity. The findings from existing publications [2, 3] without considering the stiffness effect are incorporated for comparison, where discrepancy can be found.

This indicates that, for a deeply buried foundation, using increased value of I_r (for reaching the end bearing capacity at a small displacement) may lead to inaccurate results. Hence, LDFE analysis is necessary to determine the bearing capacity with certain realistic soil stiffness.

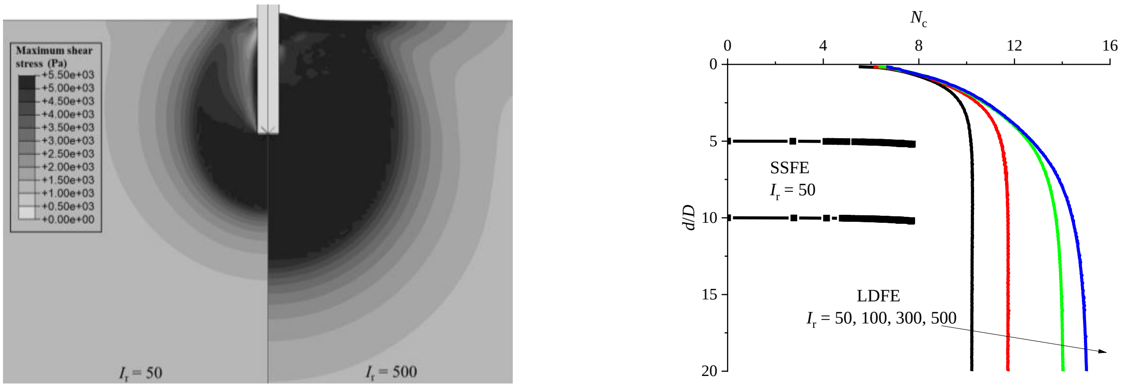


(a) (b)

Figure 4: Bearing capacity of a deep foundation (SSFE): (a) failure mechanism; (b) bearing factors.

Figure 5a shows the failure mechanisms at a penetration depth of $d/D = 5$ for $I_r = 50$ and 500, where the foundation is penetrated from soil surface through LDFE analysis. It is shown that the yielding zone of $I_r = 500$ is larger than that of $I_r = 50$, as is the extent of soil heaving. It can be seen that a deep failure mechanism occurs for $I_r = 50$, where the mobilized area is localized around the tip; while a shallow failure is observed for $I_r = 500$, where slip surfaces extend outwards and upwards to the ground surface.

Figure 5b shows the penetration resistance factor profiles over normalized penetration depths. The value of N_c gradually increases with the penetration depth and achieves a steady-state condition at a depth of $d/D = 5$ for $I_r = 50$, where a transition mechanism from shallow failure to deep failure occurs; while N_c continues to increase until $d/D = 15$ for $I_r = 500$. It can be seen that the critical depth for a deep failure mechanism increases as soil stiffness rises. As shown in Figure 5b, the end bearing resistance factor N_c increases by approximately 45% for a deep circular foundation, as soil rigidity I_r increases from 50 to 500. SSFE analyses for a pre-embedded foundation (d/D = 5 and 10) with I_r = 50 are also included in Figure 5b for comparison, where N_c = 8 from SSFE analysis, while N_c = 10 from LDFE analysis.



(a) (b)

Figure 5: Penetration behaviour (LDFE): (a) failure mechanism (d/D = 5); (b) bearing capacity factors.

4 Conclusions

Numerical simulations using Small Strain Finite Element (SSFE) and Large Deformation Finite Element (LDFE) methods are performed to investigate the effect of soil stiffness on the bearing capacity of a circular foundation. It is found that the soil stiffness has little influence on the bearing capacity of a shallow foundation with a shallow failure mechanism. However, for a deeply buried foundation, a deep flow mechanism is developed, and the failure zone is influenced by the soil stiffness. As the rigidity index increases from 50 to 500, the deep end bearing resistance is enhanced by up to 45%.

The observation regarding the impact of soil stiffness on end bearing resistance also holds practical significance for numerical modelling. For a shallow foundation, artificially increasing the soil stiffness in SSFE analysis allows for obtaining the end bearing capacity at a smaller displacement without sacrificing accuracy. However, employing increased soil stiffness for deeply buried foundations may lead to inaccurate results. For penetrating problems, e.g., pile installation and CPT (cone penetration test), SSFE analysis may underestimate the end bearing resistance without considering the installation effect. The findings presented here help practitioners in accurately determining soil stiffness parameters when conducting numerical modelling of foundation bearing capacity problems.

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