Finite element analysis on bearing capacity of post-grouting bored pile with the HS-small model and the HS model

Airong Zheng*

CCCC Tianjin Port Engineering Institute Ltd., Key Laboratory of Geotechnical Engineering, Ministry of Communications, PRC, Key Laboratory of Geotechnical Engineering, Tianjin, 300222, China

*Corresponding author’s e-mail: airong717@163.com

Abstract. Based on static load test results, with consideration of the small-strain stiffness characteristic of soils, the bearing capacity of bored piles with pile-toe and pile-shaft post-grouting have been analyzed using HS-small model and HS model of Plaxis program. The analysis reveals that: the small-strain stiffness of soil is not negligible in analyzing pile and soil interaction; with post-grouting, the interface between pile and surrounding soil are strengthened and the performance of bored pile is improved with increased bearing capacity and reduced settlement.

1. Introduction

The hardening soil model is used to do the finite element simulation of static load pile testing. The settlement amount of piles tends to be larger than the measured value and this is true especially at the early loading stage. In order to solve this problem and considering that the soil stiffness is large when small strain exists, this paper will compare calculation results of the small strain hardening soil model (HS Small) and the general hardening soil model (HS) and analyze the influence of small strain stiffness on the simulation of pile’s bearing capacity.

2. Selection of constitutive model of soil body

2.1. HS model and HS-small model

The hardening soil model is based on the plastic theory and it takes the dilatancy of soil and introduces a capped yielding surface into consideration. It is an advanced model which can simulate behaviors of different soil types, including the soft and hard soil [1]. Its yielding surface is not fixed in the principal stress space. It expands because of the generation of plastic strains. The hardening soil model includes two main hardening types of soil: the shearing stiffness and the compression stiffness. The former one is mainly used for the irreversible plastic strain brought by the simulation of principal deviator loads while the latter one is used to simulate the irreversible plastic strain brought by the primary compression during the oedometer loading and the isotropic loads in different directions.

The small strain hardening soil model is used when the soil stiffness is significantly higher than the stiffness under the general engineering strain level (Figure 1[2]) under the small strain level. It will consider the soil deformation performance according to the small strain stiffness and general hardening soil model. Its quasi-elastic tangent shear modulus is obtained by the secant shear modulus of the integral deformation curve according to the actual shear stress increment. When the tangent shear modulus is smaller than the cyclic loading shear modulus G₀ref, it will be set to a constant and
the following stiffness deformation will meet the hardening plastic performance of the hardening soil model, which is shown as Figure 2. On the basis of the hardening soil model parameter, this model adds the small strain shear modulus $G_{0\text{ref}}$ (when the strain is less than $1\times10^{-6}$) related to the strain and the shearing strain $\gamma_{0.7}$ when the shear stiffness is $0.7$ times of the small strain shear stiffness. These two parameters can all be obtained through experiments.

![Figure 1. Characteristic stiffness-strain behavior of soil with typical strain ranges for laboratory tests and structures](image)

![Figure 2. Characteristic stiffness-strain behavior of soil in the HS Small model](image)

### 2.2. Model comparative analysis

Supposed that soil layers around the pile are uniform, the pile length is 10m, the pile diameter is 0.8m and the material parameters are shown in Table 1. The soil around the pile will be compared by the load settlement curves of the small strain hardening soil model and the general hardening soil model, which are shown in Figure 3. Compared with the general hardening soil model, after the small strain stiffness of the soil is considered, the settlement amount calculation results of either the clay or the sand are significantly reduced at the early loading stage. Besides, the final settlement amount also has a measurable reduction. This means that HS Small model can play a great role in solving large settlement amount of static load pile testing numerical simulation.

| Material | Clay | Sandy soil | Pile |
|----------|------|------------|------|
| Constitutive model | HS | HS Small | HS | HS Small | Liner |
| $\gamma$ /kN/m$^2$ | 18 | 18 | 18 | 18 | \(25^\circ\) |
| $E_{50}$, $E_{\infty}$/MPa | 50 | 50 | 50 | 50 | |
| $E_{\text{ur}}$/MPa | 150 | 150 | 150 | 150 | 32500 |
| $c$ /kN/m$^2$ | 30 | 30 | 1 | 1 | |
| $\phi/^{\circ}$ | 24 | 24 | 35 | 35 |
|-----------------|----|----|----|----|
| $r_{0.7}$       | 0.0002 | 0.0002 |
| $G_0/\text{MPa}$ | 200 | 200 |

Note: $\gamma$ means the unit weight, $E_{50}$ means the three-axis load stiffness, $E_{\text{osed}}$ means the load stiffness of the consolidometer, $E_{\text{uc}}$ means the three-axis cyclic loading stiffness, $c$ is the cohesive force and $\phi$ is the frictional angle. For all the following calculations, $r_{0.7}=0.0002$.

3. Finite element analysis on pile testing of post-grouting bored pile

Pile-bottom sediment and pile-surrounding slurry cake are two inherent defects which can affect the pile-end resistance and pile-surrounding frictional force of grouting piles with shaft wall protection by drilling mud. The post-grouting technology is widely used because it has good prevention effects on pile-bottom sediment and pile-surrounding slurry cake.

In order to further compare HS Small and the Harding Soil Model, the pile-end and pile-surrounding association post-grouting piles SD-TP2 and SD-TP4 respectively use two models to conduct the finite element calculation. The length of post-grouting piles is 27.5m, and the diameter of them is 1.0m. The pile-end grouting quantity is 1000kg, and the pile-surrounding grouting quantity is 600kg.

According to the spherical cavity expansion theory, the pile-end grouting reinforced body is a ball with the center of the grouting pressure source [3]. The pressure source is the grouting valve stretching 400mm out of the pile end. Diameter $D$ of the pile-end grouting reinforced body is [4]:

$$D = \frac{1}{3} \sqrt[3]{\frac{6V}{\pi} + \frac{3d^3}{2}}$$

In the formula, $n$ means the pile-end porosity factor, $d$ means the diameter of the grouting pile and $V$ is the grouting quantity.

During the pile-surrounding grouting process, slurry bubbles will be formed near the grouting place and the cement concretion body will totally replace the slurry cake layer. In addition, the “Diameter Expansion Effect” will appear and the interface between pile and soil will be expanded outside to the place between the pile-surrounding cement concretion body and the soil body. The intensity of the soil around the pile will also be improved through the “Seepage Consolidation Effect”, “Filling Compaction Effect” and “Splitting Reinforcement Effect” of the grouting [5]. Suppose that the
reduction coefficient of the interfacial strength is 0.9, the material parameters are shown in Table 2 and Table 3, and the axisymmetric numerical model is shown as Figure 4.

Table 2. Material properties

| Name of the material              | Material Model | $\gamma$/kN/m$^2$ | $E$/MPa | $\nu$ |
|-----------------------------------|----------------|------------------|---------|-------|
| Pile                              | Liner Elastic  | 25               | 32500   | 0.15  |
| Pile-surrounding reinforced body  | Liner Elastic  | 21               | 10000   | 0.2   |
| Pile-end reinforced body          | Liner Elastic  | 21               | 22000   | 0.2   |

Table 3. Soil properties

| Name of the material | Depth | $\gamma$ | $E_{50}$ | $E_{ur}$ | $c$ | $\phi$ | $G_0$ |
|----------------------|-------|----------|----------|----------|-----|--------|-------|
| ④ Silty clay         | 2.3   | 19.4     | 7.1      | 21.3     | 23  | 15.1   | 28.4  |
| ⑤ Fine sand          | 6     | 19.3     | 21       | 63       | 1   | 35     | 84    |
| ⑦ Silty-fine sand    | 6     | 19.2     | 35       | 105      | 1   | 35     | 140   |
| ⑧ Silty clay         | 4     | 20.1     | 19.1     | 57.3     | 28  | 21.4   | 76.4  |
| ⑧,1 Sandy powder soil| 2     | 19.5     | 31.5     | 94.5     | 28  | 35     | 126   |
| ⑧,3 Clay             | 2     | 18.4     | 10.7     | 32.1     | 58  | 14.8   | 42.8  |
| ⑨ Fine sand          | 5.5   | 19.8     | 42.5     | 133.5    | 1   | 35     | 170   |
| ⑩ Silty clay         | 4     | 19.8     | 20.7     | 62.1     | 28  | 21     | 82.8  |
| ⑪ Fine medium sand   | 4     | 20.3     | 40       | 120      | 1   | 35     | 160   |
| ⑫ Clayey silt        | 3     | 20.1     | 23.9     | 71.7     | 28  | 21     | 95.6  |

Reinforced soil

| ④ Silty clay         | 19.4  | 10.7    | 32.1    | 35      | 17   | 42.8   |
| ⑤ Fine sand          | 19.3  | 42      | 126     | 60      | 38   | 168    |
| ⑦ Silty-fine sand    | 19.2  | 70      | 210     | 60      | 38   | 280    |
| ⑧ Silty clay         | 20.1  | 28.7    | 86.1    | 42      | 23   | 114.8  |
| ⑧,1 Sandy powder     | 19.5  | 47.3    | 141.9   | 42      | 38   | 189.2  |
| ⑧,3 Clay             | 18.4  | 16.7    | 50.1    | 87      | 16   | 66.8   |
| ⑨ Fine sand          | 19.8  | 85      | 255     | 60      | 38   | 340    |

Figure 4. The FEM analytical model
The load settlement curve of the grouting pile and the axial force distribution results are shown as Figure 5 and Figure 6. The numerical analysis results of the HS Small constitutive model are well consistent with the measured value, which proves the effectiveness of this method in analyzing the bearing capacity of the post-grouting piles. However, under the same loads, the settlement amount is significantly larger when HS constitutive model is used, which further validate the necessity of considering the small strain stiffness of the soil.

4. Conclusion
(1) The small strain hardening soil model is used when the soil stiffness is significantly higher than the stiffness under the general engineering strain level under the small strain level. It will consider the soil deformation performance according to the small strain stiffness and general hardening soil model.

(2) Considering the small strain stiffness of the soil, the HS Small constitutive model is used and the settlement amount of the numerical simulation in static load pile test during the early loading stage
will also be reduced. The calculation results are closer to the measured results, which further validate the necessity of considering the small strain stiffness of the soil.

(3) With post-grouting, because of the enhancement of the strength of soil around the pile and the improvement of conditions of the interface between pile and soil, the settlement amount of the pile-end and pile-surrounding association grouting pile is significantly reduced and the bearing capacity is greatly improved.

References
[1] Schanz T. (1998) Zur Modellierung des Mechanischen Verhaltens von Reibungsmaterialien. Habilitation: Stuttgart Universität.
[2] Alpan I. (1970) The geotechnical properties of soils. Earth-Science Reviews, 6: 5–49.
[3] Huang Min, Zhang Ke-xu and Zhang Er-qi. (2002) The behavior of grouting pile inserted into sand or gravel layer under axial load. China Civil Engineering Journal. 35(3): 77–81.
[4] Zhu Xiang-rong, Zhang Han and Kong Qing-hua. (2006) Research on ultimate bearing capacity of post grouting bored pile. Building Science. 22(6): 18–21.
[5] Zhu You-pa, Wu Shun-chuan and Fang Zu-lie. (2004) Property analysis of rock and soil masses properties after cement-grouting. Journal of University of Science and Technology Beijing. 26(3): 240–3.