

Numerical Analysis of Settlement of Bridge Pile Group Foundation

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ABSTRACT

In bridge engineering, the large settlement of pile not only changes the alignment of bridge deck, but additional internal forces will be generated which depress the safety of the whole bridge. In order to analyze the soil–pile interaction problem of pile group foundation, a space finite element model was built by ANSYS. Meanwhile, the parallel computation technique was adopted to improve the analysis efficiency. The influence of settlement of pile group foundations about vertical load, filling soil height, pile length and pile diameter are compared, which aim to decrease the settlement by felicity measures. To ensure the safety of bridge, it is suggested to use space finite element software to analyze the settlement of bridge pile group foundation at weak soil conditions.

KEYWORDS: Pile group foundation; Soil–pile interaction; Parallel computation.

INTRODUCTION

Pile foundations are widely used in bridge engineering. If the settlement of pile is large, not only the ride comfort will be depressed for the alignment change of bridge deck, but additional internal forces will be generated which endanger the safety of the whole bridge. The settlement of pile foundation involves many factors, such as the nature and properties of soils around piles, the height of filling soil, the length and diameter of pile and so on. Some of the factors take uncertainty and some of the others can not be directly expressed by formulas, which increase difficulties to get the settlement of pile foundation of bridge.

In actual engineering, the settlement of pile foundation is obtained by the pile test, which takes better precision to predict short-term values of settlement. But the method cost too much, need long cycle time and will not effect to reflect the long-term characteristic of pile foundation. Analytical methods and numerical analysis are better ways to simulate the settlement of pile foundation at present. Analytical methods mainly contain simplified method, load transfer method, elastic analysis method, layer-wise summation method and so on. These methods involve a lot of simplified approaches or engineering experience, which are not useful to all cases. Numerical analysis method can take many factors into account, which contains boundary element method, finite element method, finite strip method, hybrid method and so on, but the finite element method is most popular. Ellison studied the load and settlement relationship of single pile by FEM. Desai analyzed piles in cohesionless soils and indicated the curves of pile movements versus applied load take practical value for pile foundation design. Ottaviani analyzed vertically loaded pile groups by three-dimensional FEM and pointed out piles internal forces were not equal under vertically loads for the rigid platform. Wang X-D based on the finite layer method and finite element method modeled the response of individual piles within the pile groups using load-transfer functions. Huang C-L used contact surface element between piles and soils to get the distribution of deformation and stress.

Although the researches of single pile settlement were gradually developed, the settlements of pile group foundation do not get a good solution because of its complexity. Based on general finite element software ANSYS, the settlement of pile group foundation was studied, and parallel computation method was adopted to improve the calculation efficiency. The influencing factors of settlement were contrasted, which will do help to decrease the settlement by felicity measures.

SOILS CONSTITUTIVE RELATION

Soils are granular materials collection, and the constitutive model that is stress-strain relationship is very complex. In numerical analysis, the soils are usually simulated as linear elastic model, nonlinear elastic model, or elastoplastic model. The Drucker-Prager (DP) yield criterion is an approximation to the Mohr-Coulomb law in ANSYS, which is developed from the Von Mises yield criterion. The yield surface does not change with progressive yielding, hence there is no hardening rule and the material is elastic-perfectly plastic. The higher the hydrostatic stress the higher the yield strength, but the change of temperature is not included. In finite element analysis for soils or rock, using DP criterion can obtain more accurate results.

The yield criterion for DP is

$$\sigma_e = 3\beta\sigma_m + \sqrt{\frac{1}{2}\{S\}^T [M] \{S\}} = \sigma_y \quad (1)$$

Where $\{S\}$ is deviatoric stress; $\sigma_m = \frac{\sigma_x + \sigma_y + \sigma_z}{3}$ is mean stress; $[M]$ is constant coefficients matrix.

The expression of material constant β and yield parameter σ_y is

$$\beta = \frac{2 \sin \phi}{\sqrt{3}(3 - \sin \phi)} \quad (2)$$

$$\sigma_y = \frac{6c \cos \phi}{\sqrt{3}(3 - \sin \phi)} \quad (3)$$

Where ϕ is angle of internal friction; c is cohesion value.

SOIL–PILE INTERACTION

In finite element analysis, soils are modeled as eight nodes hexahedron SOLID45 element, and piles are modeled as SOLID65 element, which can change the pile reinforcement ratio by real constants modification.

Soil-pile interaction is particular, because the two materials are very different from each other and usually do not match deformation compatibility conditions on their contact surfaces. Soil and pile maybe relatively slip, which belongs to boundary condition nonlinear problems. Thus contact element should be taken into consideration. The elastic modulus of piles is above 100 times of soils' in most situation, so the soil-pile interaction is the rigid-to-flexible fact-to-face contact problem. The pile rigid surface referred to the target surface and is modeled with TARGE170, meanwhile the surface of the soils deformable body is referred to the contact surface and is modeled with CONTA 173

Put the loads beyond piles (including the bridge internal forces and self-weight of filling soil) on the top of piles to simulate the load case at the bridge normal operation. The diagrammatic sketch of pile foundation model is showed in Fig. 1.

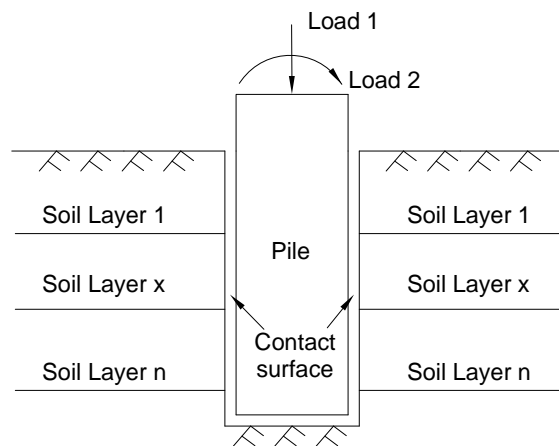


Figure 1: Diagrammatic sketch of pile foundation

PARALLEL COMPUTATION

Parallel algorithm is a generic term which is suitable for parallel operation of the algorithm. It is a form of processes in which many processes are carried out simultaneously, and used to solve some specific large problems. The calculation scale of settlement analysis by space FEM is large when consider the soil-pile interaction. On single computer the calculation takes too much time, so it is not suitable for the bridge pile group foundation design. The parallel computation is the only method to solve the problem. Parallel computers can be mainly classified into four categories: symmetric multi-processor (SMP) system, massively parallel processor (MPP) system, distributed shared memory (DSM) system and cluster. The former three kinds need to develop specialized computer hardware and software, which cost too much and have poor universality. Cluster takes the non-customized commercialization system with high performance-price ratio, thus it becomes to the mainly support of parallel computation. Cluster of workstation (COW) is a group of linked independent computers. The components of a cluster are commonly connected to each other through fast local area networks. Each computer can run tasks independently or work together closely by commands, which means easy to form, low cost and good expansibility. Parallel computation will execute when each node computer idles. In software, ANSYS can support multi core and processor parallel computation since version 8.1. In order to improve the computation efficiency of pile group foundation, three computers are used to form a COW, and the ANSYS parallel environment is established.

ENGINEERING SAMPLE

The settlement analysis of pile group foundation is based on one self-anchored cable-stayed suspension bridge. The general engineering situations are as follows: dimensions of bearing platform are $18.6\text{ m} \times 8.6\text{ m} \times 4\text{ m}$, the reaction of bridge under dead-load is 77430 KN, the piles are bored with rectangle arrangement and the center distance of piles is 5.0 m (Fig.2). The design parameters of soils are shown in Tab. 1.

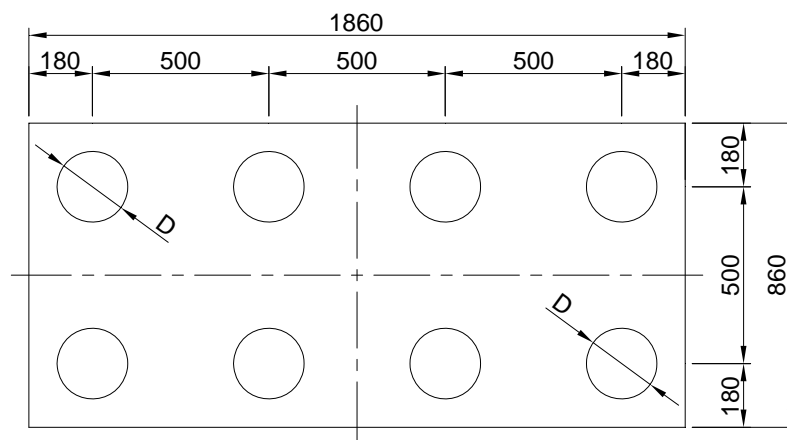


Figure 2: Plan graph of pile group foundation (unit: cm)

Table 1: Design parameters of soils

No.	Name	Thickness (m)	Bulk density (KN/m ³)	Internal friction angle (°)	Modulus of compressibility (MPa)	Allowable bearing capacity (KPa)
1	Silty clay	5.7	18.8	19.1	5.5	120
2	Medium coarse sand	7.9	19.6	20.3	14.6	234
3	Gravel	6.4	21	25	19.0	719
4	Strong decomposed rock	12.8	22	40	154	994

Based on the contact algorithm and general finite element software ANSYS, a space FE model was built to analyze the pile settlement problem. In order to decrease the uncertainty of soil boundary conditions, the soil scope is six times of the pile diameter, while the boundary conditions will do insignificant effect on the pile foundation by St. Venant's principle. The bottom and side of soils are fixed and the top free. The contact surfaces of soil and pile are mapped with same mesh to improve the precision of finite element analysis. The mesh around piles is smart, but far from piles is coarse. The finite element model of pile group foundation is shown in Fig. 3. Fig. 4 is the sectional view of soil and pile surface. The analysis in which large deformation effects are included employ Newton-Raphson procedure to solve the nonlinear problem, and parallel computation method is adopted to improve the efficiency. The convergence criterions are adjusted by the solution time.

Calculation parameters of piles are: bulk density 25 KN/m³, linear expansion coefficient 1.0E-5, elastic modulus 30 GPa, Poisson ratio 0.2.

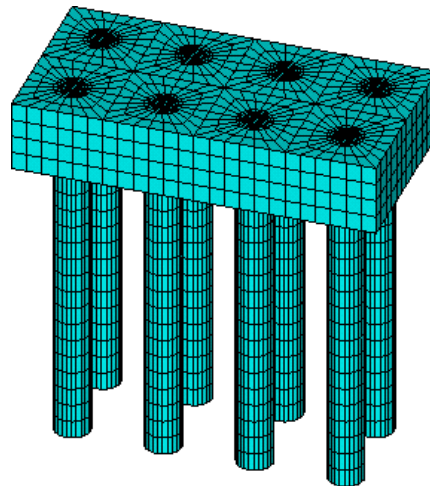


Figure 3: Mesh of pile group foundation model

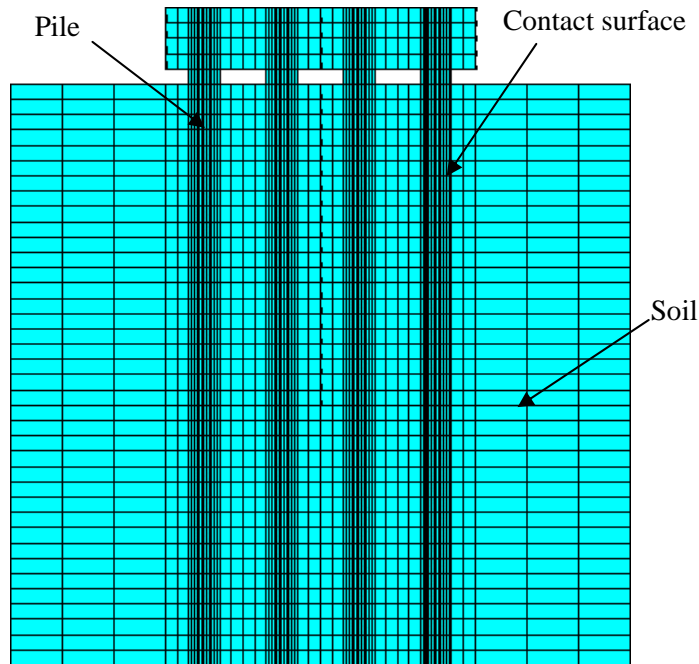


Figure 4: Sectional view of soil and pile surface

RESULTS ANALYSIS

The influence factors of settlement in pile group foundation about vertical load, filling soil height, pile length and pile diameter are compared (Fig. 5~9).

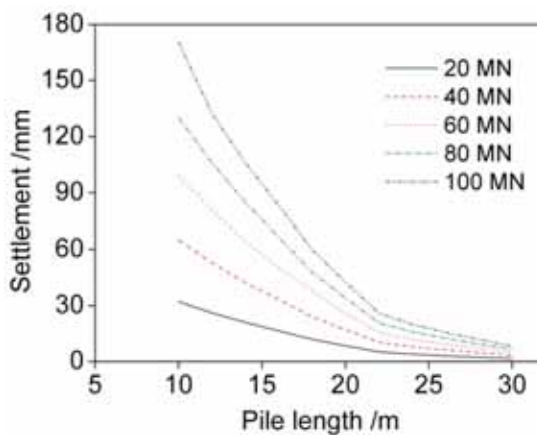


Figure 5: Relationship of settlement and pile length under vertical load

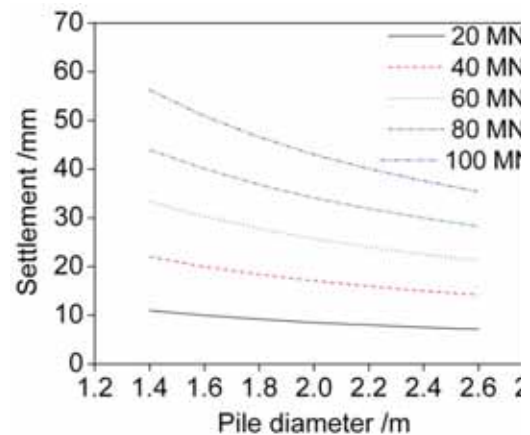


Figure 6: Relationship of settlement and pile diameter under vertical load

Fig. 5 shows the relationship of settlement and pile length under vertical load, where the settlement values have ignored the self-weight influence of soils and pile group foundation. The change of pile length is from 10 m to 30 m with 2.0 m pile diameter, and the vertical load is from 20 MN to 100 MN. When the pile length is less than 22 m, that is the piles are wholly at the weak soils, the settlement is large and rapidly reduced by the increase of pile length. It indicates that the friction between pile and soil is the main factor to bear vertical load. When the piles reach into strong decomposed rock, the settlement is small and changes slowly with the increase of pile length. The change of pile diameter is from 1.4 m to 2.6 m with 20 m pile length (Fig. 6). The settlement values decrease slowly by the increase of pile diameter.

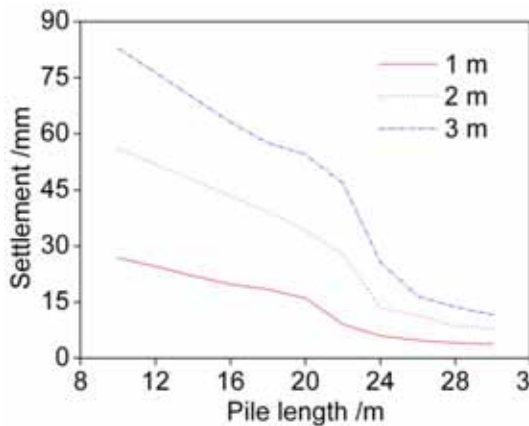


Figure 7: Relationship of settlement and pile length under filling soil height

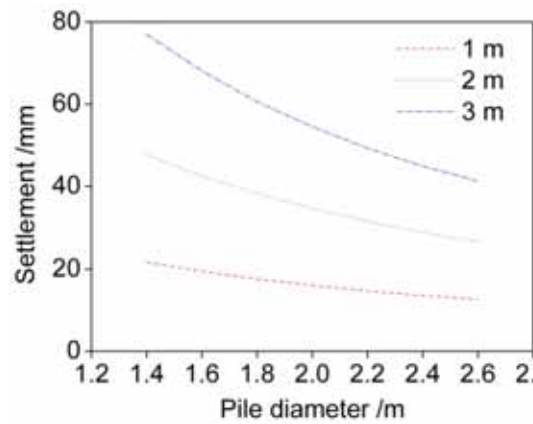


Figure 8: Relationship of settlement and pile diameter under filling soil height

Fig. 7 shows the relationship of settlement and pile length under filling soil height, and Fig. 8 shows the relationship of settlement and pile diameter, where the height changes from 1 m to 3 m and the others are same as Fig. 5 and Fig. 6. Filling soil height has obvious effect on settlement values, and even it is equally important to vertical load. The amount of soil compression will be enlarged by the increase of filling soil height, which results in the increase of pile settlement.

Not only the settlement values of pile group foundation can be obtained from the FE model, but also the pile stress states can be acquired. Table 2 shows the axial stress of pile under designed vertical load with 2.0 m pile diameter. The axial force gradually decreases from the top to the bottom of pile. When the pile length becomes longer, the settlement becomes smaller. As the contact area of pile and soil is large, the soils can afford more reaction forces on piles. It indicates that increasing pile length can improve the foundation carrying capacity.

Table 2: Axial stress of pile under designed vertical load (unit: MPa)

	0 ($\times l$)	1/4 ($\times l$)	1/2 ($\times l$)	3/4 ($\times l$)	1 ($\times l$)
$l=10$ m	-3.16	-3.12	-2.91	-2.79	-2.19
$l=15$ m	-3.11	-3.09	-2.88	-2.73	-1.89
$l=20$ m	-3.07	-3.06	-2.85	-2.87	-1.83
$l=25$ m	-2.98	-2.97	-2.77	-2.85	-0.81
$l=30$ m	-3.04	-3.02	-2.83	-2.74	-0.75

CONCLUSIONS

From the settlement study of pile group foundation, the conclusions are summarized as follows:

1 Based on FEM and the face-to-face contact algorithm, the soil-pile interaction problem will get good precision results.

2 The computational efficiency can be greatly improved by the computer network of COW and corresponding parallel algorithm, which will help to widely apply FEM to analysis pile group foundation problems.

3 To ensure the safety of bridge, it is necessary to use space finite element software to analysis the settlement of bridge pile group foundation at weak soil conditions and get the reasonable pile length and diameter.

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