Finite Element Analysis of Flexural Performance of Prestressed Concrete Pipe Piles

Qingjie Zhou1, Zhimin Dong1,*, Jianwen Li1 and Fang Han1

1School of Civil Engineering, Changchun Institute of Technology, Changchun.130012, Jilin, China

*Corresponding author e-mail:dongzhimin527@126.com

Abstract. Prestressed concrete pipe piles, due to the long body length, are easily deformed during the construction, transportation and installation, and such deformation will affect the utilization of pipe piles and even result in broken piles. In order to ensure the construction safety of prestressed pipe piles, it’s necessary to study the flexural performance and deformation of pipe piles under loads generated from the utilization stage. This paper, by virtue of ABAQUS, analyzes the contribution of wall thickness of prestressed concrete pipe piles, the diameter of spiral bar and diameter of prestressed reinforcement to the flexural deformation of pipe piles, and the corresponding results can serve as the theoretical basis of designing and laying prestressed concrete pipe piles.

KeyWords: Prestressed Concrete Pipe Piles, Finite Element, Flexural, Deformation

Pile foundation, one kind of deep foundation forms commonly applied in high-rise buildings, is an important component of architecture, and is critical to the quality of safety of architecture. Pretensioned spun concrete piles, consisting of end plate, hoop and circular or trunk pile body, are hollow slender barrel-shape precast concrete members by prestress pretensioning method and centrifugal compaction.

Prestressed concrete pipe piles, due to quick speed of construction, high bearing capacity, strong penetration, reliable quality and other advantages, have been widely applied in the practical engineering projects. However, considering the damage to pile body due to flexural deformation of long prestressed concrete pipe piles during the lifting, transportation and piling [1,2], it’s critical to calculate the construction performance of slender barrel-shape members.

Considering the above-mentioned disadvantages, finite element analysis (FEA) has been carried out on the flexural test of prestressed concrete pipe piles. In order to ensure the contribution of wall thickness of prestressed concrete pipe piles, the diameter of spiral bar and diameter of prestressed reinforcement to flexural performance- the flexural deformation of pipe piles, this paper applies FEA software to analyze the stress performance and deformation performance of prestressed concrete pipe piles, and the corresponding results can serve as the basis of experimental study to a certain degree.

1. Working Conditions of Test Pieces for FEA
1.1. Calculation Diagram

Prestressed concrete pipe piles can be lifted only when the applied concrete strength is up to 70% of the design strength. During the lifting and transportation, pipe piles shall maintain stable, and free from any damage. The lifting point shall be determined in strict accordance with the design requirements and meet the principle that the absolute value of maximum span flexural moment is smaller than that of negative flexural moment at the lifting point [3], as shown in Figure 1.

![Figure 1. Rational Positions of Pile Lifting Points](image)

1.2. Working Conditions of Test Pieces

Dimensions of test pieces for FEA: prestressed concrete pipe piles shall be 6.0m long and OD 400mm. In order to analyze the influence of wall thickness of pipe piles, the diameter of spiral bar and diameter of prestressed reinforcement to the flexural deformation of pipe piles respectively, the parameter working conditions via FEA have been designed. Spiral bar shall be made of Φ4, Φ5 and Φ6 cold-drawn low-carbon steel wires, prestressed reinforcement shall be made of Φ9.0 and Φ10.7 prestressed steel bars respectively and the wall thickness of pipe piles shall be 95mm and 115mm respectively. Total 3 groups and 9 test pieces for FEA shall be designed, with the calculated parameter working conditions shown in Table 1.

| Working condition | Specimen number | Diameter of spiral bar | Diameter of prestressed reinforcement | Wall thickness /mm |
|-------------------|-----------------|------------------------|---------------------------------------|--------------------|
| 1 group           | 1               | 4                      | 9                                     | 95                 |
|                   | 2               | 5                      | 9                                     | 95                 |
|                   | 3               | 6                      | 9                                     | 95                 |
| 2 group           | 4               | 4                      | 10.7                                  | 95                 |
|                   | 5               | 5                      | 10.7                                  | 95                 |
|                   | 6               | 6                      | 10.7                                  | 95                 |
| 3 group           | 7               | 4                      | 9                                     | 115                |
|                   | 8               | 5                      | 9                                     | 115                |
|                   | 9               | 6                      | 9                                     | 115                |

2. Finite Element Simulation
2.1. Material properties and constitutive relation of concrete
Concrete, with hydraulic cement as the main cementing material, is an artificial mixture with coarse and fine aggregates made of different mineral components as the substrate and then mixed together[5], and the material properties and constitutive relation model of concrete can substantially influence the non-linear analysis of reinforced concrete structure. Concrete constitutive relation refers to the stress-strain relationship of concrete under loads. The concrete constitutive relation is normally built on the base of constitutive relation of current continuum mechanics, and then combined with mechanical properties to determine all parameters in the constitutive relation [6-9].

2.2. Material properties and constitutive relation of reinforcement
The prestressed concrete pipe piles used in this test are respectively made of prestressed reinforcement and non-prestressed spiral bar. The constitutive relation of prestressed reinforcement in the finite element model shall be ideal elastic model, with its pre-yield stress smaller than 1420MPa, which is deemed as in the complete elastic status, and the stress-strain relationship after yield being a straight line [10].

3. Analysis of Finite Element Results
This paper analyzes the deformation of prestressed concrete pipe piles under different working conditions via FEA, and the schematic diagram of flexural deformation of pipe piles under loads is shown in Figure 2. It analyzes and compares the factors influencing the deformation of pipe piles, and draws the contribution of wall thickness of pipe piles, the diameter of spiral bar and diameter of prestressed reinforcement to the flexural deformation of pipe piles according to the working conditions in Table 1.

![Schematic Diagram of Flexural Deformation of Pipe Piles](image)

**Figure 2.** Schematic Diagram of Flexural Deformation of Pipe Piles

3.1. Contribution of the Changes of Diameter of Spiral Bar to the Deformation of Pipe Piles
The maximum deformation of test piece 1, 2 and 3 in this finite element model is shown in Table 2. According to the analysis results, All test piece 1, 2 and 3 deform slightly under the equivalent load, which can meet the utilization requirements. The deformation of pipe piles decreases minimally along with the increase of diameter of spiral bar. When the pipe piles are under slight horizontal effect, all kinds of materials are in the elastic behavior, with spiral bar mainly serving the role of framework to bear the force generated by partial load on the pipe piles.

The analysis in Table 2 shows that the deformation of pipe piles decreases along with the increase of diameter of spiral bar, but the change of diameter of spiral bar is minimal to the deformation of pipe piles.

| Specimen | Deformation /10^3mm | Increment /10^3mm | Percentage /% |
|----------|---------------------|-------------------|---------------|
| 1        | 4.527               |                   |               |
| 2        | 4.525               | 0.002             | 0.04%         |
| 3        | 4.524               | 0.001             | 0.02%         |

3.2. Contribution of the Changes of Diameter of Prestressed Reinforcement to the Deformation of Pipe Piles
Test pieces in the 2nd group pipe piles are prestressed reinforcement with the diameter changed on the base of 1st group pipe piles. The diameter of spiral bar is respectively 4mm, 5mm and 6mm, while the diameter of prestressed reinforcement changes from 9.00mm to 10.7mm accordingly, with the deformation value of pipe piles shown in Table 3. Table 3 shows that when the pipe piles deform in the elastic phase, the diameter of prestressed reinforcement increased by 1.7mm, and the deformation reduces by 0.66%, 0.54% and 0.56% respectively.

**Table 3. Deformation Analysis against the Change of Diameter of Prestressed Reinforcement**

| Specimen | Diameter | Deformation /10^3mm | Increment /10^3mm | Percentage /% |
|----------|----------|---------------------|------------------|---------------|
| 1/4      | 1        | 9.0                 | 4.527            | 0.030         | 0.66%         |
|          | 4        | 10.7                | 4.497            |               |               |
| 2/5      | 2        | 9.0                 | 4.525            | 0.030         | 0.54%         |
|          | 5        | 10.7                | 4.495            |               |               |
| 3/6      | 3        | 9.0                 | 4.524            | 0.031         | 0.56%         |
|          | 6        | 10.7                | 4.493            |               |               |

According to Table 3, the diameter of prestressed reinforcement increases and the deformation of pipe piles decrease accordingly. But such decrease of deformation is minimal.

**3.3. Contribution Of the Changes of Wall Thickness of Pipe Piles to the Deformation of Pipe Piles**

Test pieces in the 3rd group pipe piles are test pieces in the 1st group pipe piles with the wall thickness changed. On the conditions that the diameter of spiral bar and prestressed reinforcement remains unchanged, the wall thickness of prestressed concrete pipe piles changes from 95mm to 115mm accordingly, with the deformation value of pipe piles shown in Table 4. Table 4 shows that when the pipe piles deform in the elastic phase, the wall thickness of prestressed concrete pipe piles increases by 20mm, the deformation decreases by 29.78%, 29.77% and 29.80% respectively.

**Table 4. Deformation Analysis against the Change of Wall Thickness of Pipe Piles**

| Specimen | Wall thickness /mm | Deformation /10^3mm | Increment /10^3mm | Percentage /% |
|----------|--------------------|---------------------|------------------|---------------|
| 1/7      | 1                  | 95                  | 4.527            | 1.348         | 29.78%        |
|          | 7                  | 115                 | 3.179            |               |               |
| 2/8      | 2                  | 95                  | 4.525            | 1.347         | 29.77%        |
|          | 8                  | 115                 | 3.178            |               |               |
| 3/9      | 3                  | 95                  | 4.524            | 1.348         | 29.80%        |
|          | 9                  | 115                 | 3.176            |               |               |

Table 4 shows that the wall thickness of pipe piles increases and the deformation of pipe piles decreases accordingly. Meanwhile, the wall thickness plays a huge role in the deformation of pipe piles.

**4. Conclusion**

(1) When the elasticity of prestressed concrete pipe piles deform slightly under loads, the influence of parameters to the deformation of pipe piles varies accordingly, namely wall thickness of pipe piles, diameter of prestressed reinforcement and diameter of spiral bar.

(2) Though the influence of diameter of spiral bar on prestressed concrete pipe piles is minimal, all kinds of materials are in the elastic behavior, with spiral bar mainly serving the role of framework to
bear the force generated by partial load on the pipe piles, and reinforcement meeting the requirements in the code.

(3) When prestressed concrete pipe piles are under loads and all materials are in elastic behavior, the diameter of prestressed reinforcement affects the deformation of prestressed concrete pipe piles slightly, but when the wall thickness of prestressed concrete pipe piles remains unchanged, and parameters of other materials change, the change of diameter of prestressed reinforcement to the deformation of prestressed concrete pipe piles shall be considered prior to the diameter of spiral bar.

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