Mechanical Analysis and Application of Lattice-Type High-Pile Cap Tower Crane Foundation During Construction in Complex Geological Conditions

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Abstract. This study investigates the stability and mechanical performance of a lattice-type high-pile cap foundation for an STT323 tower crane in soft soil conditions at a Shanghai office complex. The foundation, elevated 10 m with a 5.5 m×5.5 m cap, employs lattice columns (cross-sectional side length: 480 mm) composed of angle steel and batten plates. A finite element model was developed to evaluate deformation and stress under ±X/Y directional loads, incorporating a maximum geometric imperfection of 475 mm (4.75% offset ratio). Results demonstrate a maximum cap displacement of 6.26 mm, compressive stress of 112 MPa, and tensile stress of 22.3 MPa, with stress ratios between 7.4% and 37.3%, all within safety limits. Stress concentrations were observed at column bases, while horizontal and diagonal bracing effectively mitigated lateral deformation. On-site monitoring confirmed compliance with permissible deformation thresholds during crane operation. This work provides a practical framework for designing lattice-type high-pile cap foundations in similar geotechnical projects.

Keywords: Tower Crane, Lattice-type High-pile Cap, Soft Soil, Finite Element Analysis, Stability Design.

1 Introduction

High-pile caps, rigid structures comprising multiple foundation piles and caps, are widely used in ports, bridges, and deep excavation projects.[1] This study addresses the challenge of designing a lattice-type high-pile cap foundation for a tower crane in soft soil conditions, where soil creep and deformation during excavation necessitate advanced stability measures, the combined effects of high water content (typically >40%), low shear strength (<25 kPa), and significant compressibility (compression index Cc >0.3) create time-dependent ground behavior, which induces cumulative differential settlements jeopardizing the lattice structure's alignment accuracy.[2,3] By integrating lattice steel columns, bracing systems, and finite element modeling, the proposed design ensures structural integrity under complex loads.

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2 Project Overview

Taking a comprehensive office building in Shanghai as an example, the tower crane of the STT323 model is adopted, and its technical parameters are shown in Table 1 as follows.

Table 1. Working Environment Parameters of the Tower Crane with the Model of STT323

Parameter Name	Parameter Value
Max. Lifting Ht.(Indep. State)	54 m
Calc. Ht.(Indep. State)	60 m
Max. Slewing Radius	75 m
Tower Truss Structure	Square steel tube
Tower Truss Width	2 m
Max. Lift at Jib End	3 t

During the operation process, the self-weight of the tower crane, the weight of the lifted load, and the wind load, etc., are transmitted to the pile cap through the tower body, and then distributed to each pile foundation by the pile cap. The standard values of the loads on the top surface of the pile cap are shown in Table 2.

Table 2. Standard Values of the Loads Transmitted from the Tower Crane to the Top Surface of the Foundation

Statement	Parameter Name	Parameter Value
Intrinsic Parameters	Tower Crane Self-weight	1005 kN
	Hoisting Load	185 kN
Working State	Vertical Load	1190 kN
	Horizontal Load	34.3 kN
	Overturning Moment	3909 kN·m
Non-working State	Vertical Load	1005 kN
	Horizontal Load	147 kN
	Overturning Moment	1683 kN·m

The pile foundation relies on the side friction resistance of the pile and the end resistance of the pile to resist the load, and transfers the load to the soil layers around the pile, so as to keep the foundation stable. The parameters of the soil layers are obtained from the foundation investigation report, as shown in Table 3 below.

Table 3. Soil Layer Parameters Obtained from the Foundation Investigation Report

Layer	Soil Type	Buried Depth	Std. Of Skin Friction	Std. Of End Resistance
②1	Silty Clay	3 m	15 kpa	

④	Silty Soil with Siltiness	9.6 m	20 kpa	
⑤$_{1-1}$	Clay	18.7 m	30 kpa	
⑤$_{4}$	Silty Clay	41.4 m	50 kpa	
⑦$_{2-1}$	Silty Clay	44.5 m	65 kpa	1500 kpa
⑦$_{3-2}$	Silty Sand	47.7 m	75 kpa	2300 kpa
⑧	Silty Clay	62.0 m	65 kpa	/

3 Design of Lattice-Type High-Pile Cap

The tower crane adopts a lattice-type high-pile cap as its combined foundation. The reinforcement configuration and calculated length of pile foundations, the reinforcement layout and structural detailing of the cap, as well as the material composition and geometric configuration of lattice columns collectively govern the global load-transfer mechanism and stability performance of the high-pile cap system. The design is carried out for the three parts of the pile cap, lattice column and pile foundation respectively according to the force transmission path from top to bottom[2,4] . The design parameters of the tower crane foundation under normal working conditions are shown in Table 4, where shaded cells highlight parameters deviating from GB50007-2011 code baseline values due to site-specific creep effects.

Table 4. Technical Parameters for the Design of Lattice-type High-pile Cap

Pile Cap Design			
Pile Cap Height	1500 mm	Cap L×W Dimensions	5500 mm
Long. Reinforcement at Cap Bottom	HRB400 Φ22@150	Trans. Reinforcement at Cap Bottom	HRB400 Φ22@150
Long. Reinforcement at Cap Top		Trans. Reinforcement at Cap Top	
Vertical Connecting Reinforcement of Cap		HRB400 Φ22@450	
Lattice Column Design			
Lacing Form of Lattice Column	Lacing Plate	Cross-Section Side Length of Lattice Steel Column	480 mm
Lattice Steel Column Length	14 m	Clear Distance between Lacing Members	260 mm
Anchorage Length in Bored Pile	3.5 m	Design Tensile/Compressive Strength of Limb Material	295 N/mm^2
Lattice Column Limb Material	L160X16	Cross-Sectional Area of Limb Material	49.07 cm^2
Radius of Gyration about Min. Axis	3.14 cm	Parallel Axis Moment of Inertia	1175.08 cm^4
Centroid-Outer Edge Distance	4.55 cm	Yield Strength of Limb Material	355 N/mm^2
Lattice Steel Column Lacing Material	440×300×16	Cross-Sectional Area	4800 mm^2

Lacing Plate Design Bending Strength	355 N/mm^2	Design Shear Strength of Lacing Plate	295 mm^2
Fillet Weld Leg Size	12 mm	Calculated Weld Length	580 mm
Design Weld Strength	160 N/mm^2		
Pile Foundation Design (Bored Pile)			
Pile Body Diameter	850 mm	Main Reinforcement Bars	16Φ22
Length of Encrypted Stirrups	4000 mm	Form of Encrypted Stirrups	8@100
Length of Non-Encrypted Stirrups	28650 mm	Form of Non-Encrypted Stirrups	8@200

4 Analysis of the Construction Process of High-Pile Caps Under Special Conditions

The construction procedures for high-pile caps are as follows: First, the bored construction of the pile foundation is conducted. After inserting the steel reinforcement cage, lattice columns are placed, followed by concrete pouring. Once the concrete strength of the pile foundation reaches 80% of its designed strength, earthwork excavation is initiated. Following this initial excavation, the concrete surrounding the lattice columns is removed, and scissors braces along with diagonal braces between the lattice columns are constructed to establish a stable intermediate connection. Given that the engineering site within the range of the lattice columns primarily consists of soft, silt-like soil with high water content, it is highly susceptible to deformation or creep during the foundation pit excavation process. This inevitably leads to variations in the pile foundation at the site. During the construction phase, the bases of two lattice columns of the high-pile cap foundation for a tower crane experienced a shift, while the tops remained stable. The maximum amount of shift reached 475 mm, corresponding to a shift degree of 4.75%. Ensuring the stability of high-pile caps under complex geological conditions presents a significant challenge.[3,4]

According to the Standard for Design of Steel Structures and the Technical Standard for Tower Crane Concrete Foundation Engineering, the high-pile cap can be classified as a member exhibiting geometric initial defects.[5,6] The cross-section type of this member falls under category B, with the representative value of the initial defect taken as the maximum offset of 475 mm, corresponding to an offset degree of 4.75%. The lowest-order overall buckling mode is utilized, and an equivalent analysis is conducted by applying an imaginary horizontal force to each layer of the lattice column to determine the additional bending moment. At this time, there are the formulas:

$$\Delta_i = 0.0475 h_i \sqrt{0.2 + \frac{1}{n}} \tag{1}$$

$$H_{ni} = 0.0475 G_i \sqrt{0.2 + \frac{1}{n}} \tag{2}$$

$$Ms = \sum_i H_{ni} h_i \tag{3}$$

In this study, we denote the total number of standard sections as 'n' and the gravitational force at the top of each standard section as 'Gi'. It is important to note that the gravitational force of the top-layer tower crane and the high-pile cap significantly exceeds that of the other layers. Therefore, we will only consider the gravitational force 'Gn' at the top layer. Additionally, 'hi' represents the distance from the top of each layer of the tower crane standard section to the fixed end at the junction with the bottom floor slab.

Given the complexity of manually calculating the above formula, the finite element analysis method is employed. Component models of the lattice columns and the pile cap are created with identical dimensions (as illustrated in Figure 1). The lattice columns, scissors braces, and diagonal braces are all represented using beam elements. The diagonal and scissors braces release 90% of the beam-end constraints while transferring 10% of the beam-end bending moment. The pile cap is modeled using thick-plate elements, followed by meshing. The lattice columns and the high pile cap are coupled at the nodes.

Since the lattice columns are inserted 3.5 m into the steel reinforcement cage at the top of the pile foundation, the concrete has reached the designed strength, and the floor slab concrete is immediately constructed later, it can be simulated as a fixed support, and the offset amounts of the lattice columns in two directions are adjusted. For the load values, according to the standard load values in the tower crane instruction manual, the design values are calculated by multiplying them by the dead-load factor of 1.3 and the live-load factor of 1.5 respectively. These loads are respectively applied in the four directions of ±X and ±Y along the tower-crane high-pile cap. The bending moment acts on the main node at the center of the pile cap through the designed master-slave nodes.

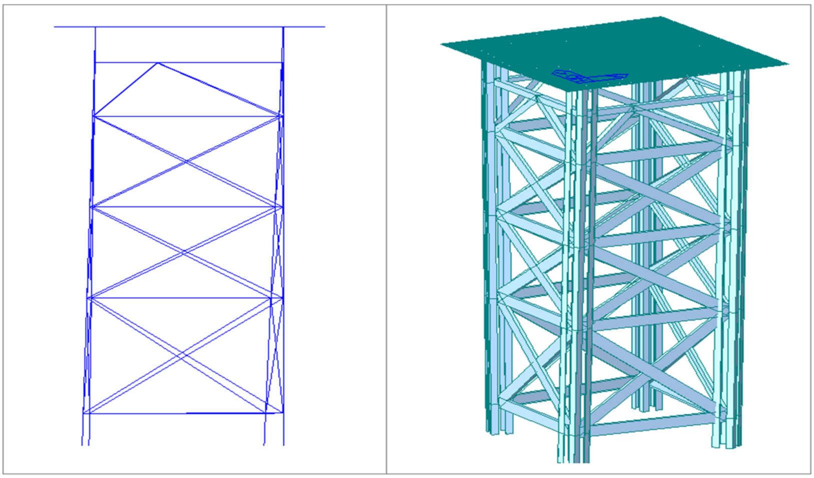

Fig. 1. Rendering of the Finite Element Model of the High-Pile Cap

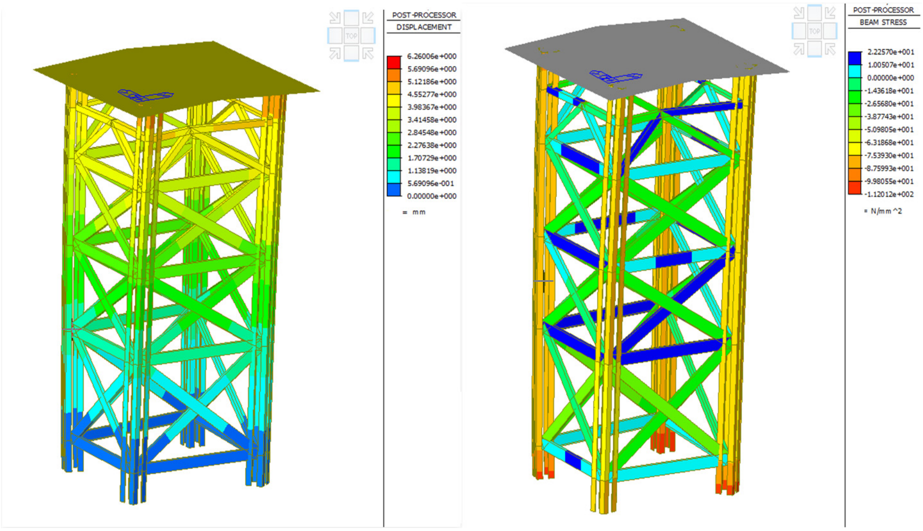

Fig. 2. Overall Analysis Nephogram of the High-Pile Cap (The Displacement Contour Nephogram is on the Left and the Stress Nephogram is on the Right)

By analyzing the finite element model, the overall deformation and stress of the high-pile cap can be obtained. The displacement contour nephogram in the standard combination state and the stress nephogram in the basic combination state are respectively used for display, as shown in Figure 2. The maximum displacement deformation of the lattice-type high-pile cap is 6.26 mm, the maximum compressive stress amplitude is 112 MPa, the maximum tensile stress amplitude is 22.3 MPa, and the stress ratio is 7.4%-37.3%. The safety margin is relatively high, meeting the requirements of the construction site.

Separate and in-depth analyses are carried out for each component of the high-pile cap, namely the vertical lattice columns, horizontal cross-braces, diagonal scissors-braces, and top reinforcing braces. The displacement and deformation of these components are studied respectively, and the results are shown in Figure 3 and Figure 4. The results are summarized in Table 5. The vertical lattice columns, serving as the main compression-bearing components, have the maximum stress occurring at the bottom column-foot positions. The horizontal cross-braces and diagonal scissors-braces, as the main tension-bearing components, restrict the lateral deformation of the vertical lattice columns to maintain their overall stability, and the maximum stress appears at the bottom-most scissors-braces.

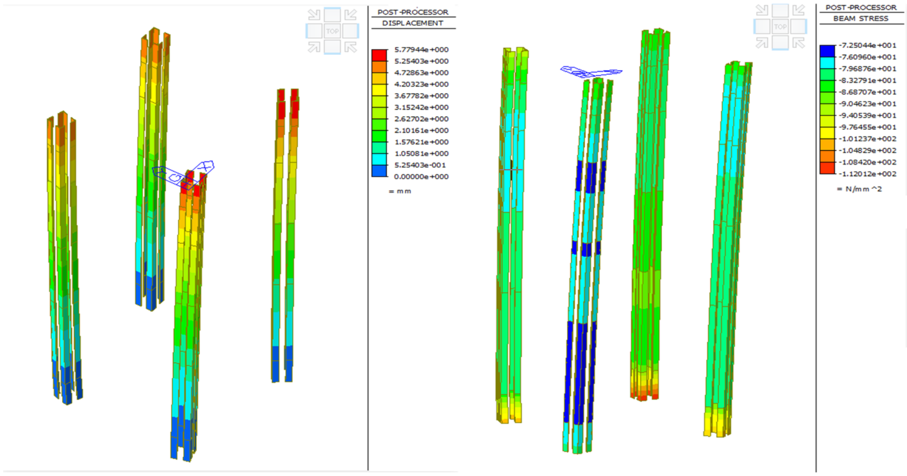

Fig. 3. Analysis Nephogram of the Vertical Lattice Columns (The Displacement Contour Nephogram is on the Left and the Stress Nephogram is on the Right)

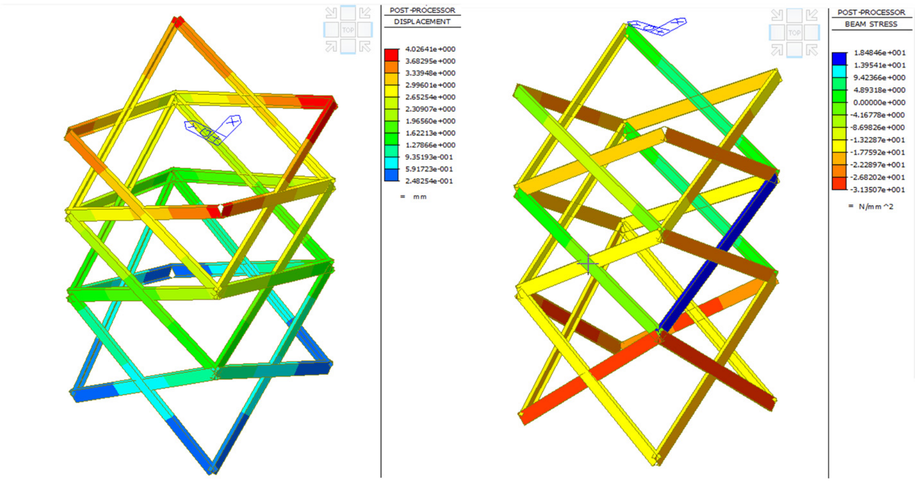

Fig. 4. Analysis Nephogram of the Horizontal Cross-braces (The Displacement Contour Nephogram is on the Left and the Stress Nephogram is on the Right)

Table 5. Analysis Results of the Displacement and Deformation of Each Component of the High-Pile Cap

Component	Max. Displacement	Max. Tensile Stress	Max. Compressive Stress	Stress Ratio
Vertical Lattice Columns	5.78 mm	0 MPa	112.0 MPa	37.33%

Horizontal Cross-braces	4.03 mm	22.26 MPa	0 MPa	7.42%
Diagonal Scissors Braces	4.03 mm	18.48 MPa	31.35 MPa	10.45%
Top Reinforcing Braces	5.03 mm	19.50 MPa	21.48 MPa	7.16%

5 Conclusions and Applications

The analysis results have been applied in a comprehensive office complex in Shanghai (as shown in Figure 5). On-site, a total station and a theodolite were used to measure the deformation. During the operation period of the tower crane (both in working and non-working states), the deformation did not exceed the simulated values, achieving zero-alarm operation. The results of this analysis can be applied to similar engineering cases to realize the construction of the lattice-type high-pile cap foundation for tower cranes in complex geological conditions.

Fig. 5. Construction Drawings of the On-site Practical Example

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