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A new method for setting up hoisting point of reinforcement cage of the in-line underground diaphragm wall

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Abstract: The condition of the reinforcement cage during hoisting can be treated as a multi-supported overhanging beam under the combined action of distributed and concentrated loads, where the support corresponds to the hoisting point. Based on the singular function and Laplace transform, the deflection curve equation of the beam is solved, and a new method of setting the optimal lifting point of the in-line reinforcement cage is proposed in combination with the genetic algorithm. The feasibility of the method is evaluated and verified by calculation examples and numerical simulation. The results show that the proposed method can control the deformation of the reinforcement cage during hoisting more effectively than the existing method of determining the hoisting point.

Key words: hoisting point for reinforcement cage; singular function; Laplace transform; genetic algorithm; finite element simulation

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1 Introduction

Due to the limitation of above-ground space resources, the deployment of underground space becomes of growing interest, particularly in large cities^[1]. In deep foundation pit engineering, underground diaphragm wall^[2] is often used as the enclosure structure. The most concern in constructing the underground diaphragm wall is the setting of the hoisting points for erecting the reinforcement cage (Fig. 1). If the number and/or location of the hoisting points used are not appropriate, it will lead to not only the increase in

construction cost but also some safety issue.

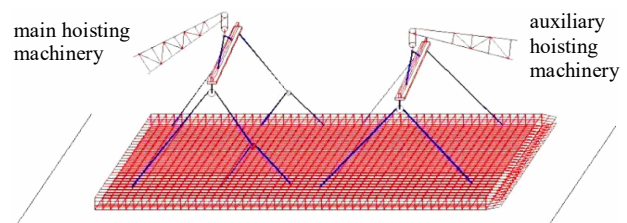


Fig. 1 Schematic diagram of hoisting of reinforcement cage

In recent years, many studies have been carried out on the hoisting point setting of the reinforcement cage in the in-line diaphragm wall^[3-10]. The methods used can be divided into two categories. One is to use the finite element analysis software to establish a reinforcement

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cage model to simulate the hoisting process and determine the positions of optimal lifting points by examining the deflection and internal force variations of reinforcement cage^[11]. For example, Yang et al^[7] carried out the finite element analysis of the in-line steel cage of 55 m using ABAQUS software. Their work demonstrated that the use of additional longitudinal and transverse trusses could improve the stiffness and stability of the overall steel reinforcement cage and the rationality of using four-point lifting scheme. Wang et al^[8] reported a numerical simulation of the multi-angle hoisting of the in-line steel reinforcement cage using ANSYS software, in which the position of hoisting points and the specification of truss bars were optimized. However, due to the complex in the distribution of reinforcement and the working condition in construction site, there are very fewer reinforcement cages that are with high similarity. Thus, the result obtained from the finite element analysis for a specific reinforcement cage may not be applied to other reinforcement cages.

The other is the commonly used engineering method^[9-10], in which the number of vertical and horizontal lifting points is first determined by the length and width of the cage, combined with the engineering lifting experience (there is a corresponding relationship between the side length of the cage and the number of lifting points). The final position of the lifting point is determined by using the principle of moment balance; that is, the sagging bending moment and hogging bending moments are equal in the value. Assume that the six longitudinal lifting points have been determined according to the cage length L (Fig. 2).

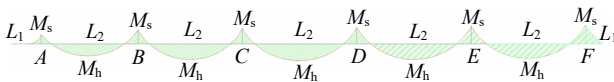


Fig. 2 Longitudinal bending moment calculation diagram

The specific method of determining the position of the lifting points is as follows:

$$M_s = M_h, \quad (1)$$

where M_s is the sagging bending moment, M_h is the hogging bending moment. Note that

$$M_s = qL_1^2 / 2, \quad (2)$$

$$M_h = qL_2^2 / 8 - qL_1^2 / 2, \quad (3)$$

where q is the density of uniform distribution load, L_1 is the overhang span length, and L_2 is the inner span length, respectively. Substituting Eq. (2) and Eq. (3) into Eq. (1), it yields

$$L_2 = 2\sqrt{2}L_1. \quad (4)$$

According to the beam length L , we have the following equation:

$$2L_1 + nL_2 = L, \quad (5)$$

where n is the number of inner spans and $n-1$ represents the number of hanging points. The reinforcement cage between the two hoisting points is regarded as a simply-supported beam model under uniform load, getting maximum deflection by $w_{\max} = 5qL_2^4 / (384EI)$, where $I = bh^3 / 12$, b is the width of the cage, and h is the height of the cage. In what follows, the position of the hoisting point will be fine-tuned according to the hoisting experience, including the distribution of reinforcement bars in the cage and the condition of the embedded parts. This assumes that the self-weight of the reinforcement cage is evenly distributed along the longitudinal direction. However, the actual situation is that the diameter or spacing of the reinforcement bars in each section of the reinforcement cage is different. The diameter of the horizontal reinforcement needs to be increased near the support of the reinforcement cage. This leads to the load that equivalent to the distribution of the reinforcement in the actual reinforcement cage is not simply a uniform load in the longitudinal direction but forms a distributed load with different sizes of m segments, as shown in Fig. 3. Momeni et al^[12] proposed to manufacture reinforcement cages through automated production cells. So, can we develop a program that automatically determines the best hoisting point of the steel cage? In this way, as long as the professionals complete the drawings, the manufacturing and hoisting automation of the reinforcement cage can be realized in the future. To get closer to the reality of the cage, in this paper, the deflection functions of multi-support cantilever beams under the combined action of distributed loads and concentrated loads are deduced by

using singular functions and Laplace transforms. The calculated deflection function is taken as the optimization objective function. Taking the extreme value of deflection as the evaluation index, the optimal lifting point is determined by using a genetic algorithm.

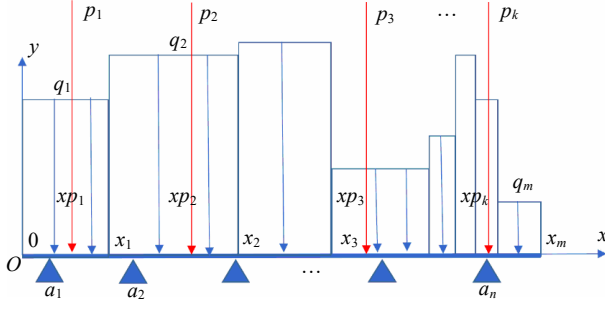


Fig. 3 Schematic diagram of the model

2 Derivation of deflection curves

The overhanging beam simulates the hoisting conditions of the actual reinforcement cage. The first and last hoisting points must be kept at a certain distance from the cage head and end, and they must be set near the area where the transverse truss exists. The values of distributed loads and concentrated loads in different action intervals are different. The distributed loads are used to equate the self-weight of steel bars in a specific area (Ensure that the steel bar diameter and spacing are consistent in the area). Since some reinforcement cages contain I-beams, concentrated loads are used to equate to the weight of the I-beam during hoisting. Meanwhile, they also can equate some special steel bars, which are difficult to be simplified into distributed loads. As shown in Fig. 3, the cantilever beam model is established, with the left endpoint of the beam as the origin of the coordinates. In the figure, a_n is the coordinate of the n th support, equivalent to the hoisting point of the reinforcement cage, x_{m-1} and x_m are the left and right boundary coordinates of the distributed load, q_i is the distributed load, p_k and x_{p_k} are the value and coordinate of the concentrated load, respectively.

The following differential equation^[13-14] is used to calculate the deflection and force of the beam:

$$EIy^{(4)} = q(x), \quad (6)$$

where $q(x)$ is the load density in the solution area. For this model, it is not easy to unify the load profile due to the complexity of the loads acting on the entire beam. Therefore, it can only be divided into several parts to solve, and the deflection function obtained from the solution is a piecewise function. The singular function^[15] can describe the discontinuous load, which is defined as

$$\text{when } n < 0, \quad \langle x - a \rangle^n = \begin{cases} \infty, & x = a, \\ 0, & x \neq a, \end{cases} \quad (7)$$

$$\text{when } n \geq 0, \quad \langle x - a \rangle^n = \begin{cases} (x - a)^n, & x \geq a, \\ 0, & x < a. \end{cases} \quad (8)$$

The distributed load in the interval $[a, b]$ can be expressed as

$$q(x) = -q[\langle x - a \rangle^0 - \langle x - b \rangle^0]. \quad (9)$$

The concentrated load can be expressed as

$$p(x) = -p \langle x - a \rangle^{-1}. \quad (10)$$

Then the load density of the beam can be expressed as follows:

$$q(x) = -\sum_{i=1}^m q_i [\langle x - x_{i-1} \rangle^0 - \langle x - x_i \rangle^0] - \sum_{j=1}^k p_j \langle x - x_{p_j} \rangle^{-1} + \sum_{o=1}^n R_{a_o} \langle x - a_o \rangle^{-1}, \quad (11)$$

where the support reaction force is equivalent to a concentrated load, its value is R_{a_n} , the x coordinate is a_n . q_m is the distributed load value, x_m is the distributed load coordinate, p_k is the concentrated load value, the x coordinate is x_{p_k} . It satisfies the deflection function equation:

$$EIy^{(4)} = -\sum_{i=1}^m q_i [\langle x - x_{i-1} \rangle^0 - \langle x - x_i \rangle^0] - \sum_{j=1}^k p_j \langle x - x_{p_j} \rangle^{-1} + \sum_{o=1}^n R_{a_o} \langle x - a_o \rangle^{-1}. \quad (12)$$

Laplace transform^[16] can be used to transform the differential equations into algebraic equations to simplify the calculation. Laplace transform is performed on both sides of Eq. (12).

Because

$$L\left[\frac{d^4 y}{dx^4}\right] = s^4 Y(s) - \sum_{w=1}^4 s^{4-w} y^{(w-1)}(0), \quad (13)$$

where L is the symbol for Laplace transform, $Y(s)$ is the image function of y , and s is the complex variable^[15].

And point O at the left end of the beam is used as the free end. The boundary condition at this point always satisfies the bending moment and shear force as zero, which is

$$M = 0, Q = 0; y''(0) = 0, y'''(0) = 0. \quad (14)$$

So, the left side of Eq. (12) changes by Laplace transform into

$$EI[s^4 Y(s) - s^3 y(0) - s^2 y'(0)]. \quad (15)$$

Since the Laplace transform formula of singular functions is

$$n \geq 0, L[< x - a >^n] = \frac{e^{-as} n!}{s^{n+1}}, \quad (16)$$

$$n < 0, L[< x - a >^n] = \frac{e^{-as}}{s^{n+1}}, \quad (17)$$

the right side of Eq. (12) changes by Laplace transform into

$$\sum_{i=1}^m \left(-q_i \frac{e^{-x_{i-1}s}}{s^5} + q_i \frac{e^{-x_i s}}{s^5} \right) - \sum_{j=1}^k \frac{p_j e^{-xp_j s}}{s^4} + \sum_{o=1}^n \frac{R_{a_o} e^{-a_o s}}{s^4}. \quad (18)$$

In summary, Eq. (12) after Laplace transformation becomes

$$EI[s^4 Y(s) - s^3 y(0) - s^2 y'(0)] = \sum_{i=1}^m \left(-q_i \frac{e^{-x_{i-1}s}}{s^5} + q_i \frac{e^{-x_i s}}{s^5} \right) - \sum_{j=1}^k \frac{p_j e^{-xp_j s}}{s^4} + \sum_{o=1}^n \frac{R_{a_o} e^{-a_o s}}{s^4}. \quad (19)$$

From Eq. (19), the expression of the image function is

$$Y(s) = \sum_{i=1}^m \left(-q_i \frac{e^{-x_{i-1}s}}{EI s^5} + q_i \frac{e^{-x_i s}}{EI s^5} \right) - \sum_{j=1}^k \frac{p_j e^{-xp_j s}}{EI s^4} + \sum_{o=1}^n \frac{R_{a_o} e^{-a_o s}}{EI s^4} + \frac{y(0)}{s} + \frac{y'(0)}{s^2}. \quad (20)$$

The object function (20) performs the inverse Laplace transform to obtain the deflection function

$$y = y(0) + xy'(0) + \sum_{i=1}^m \left(-\frac{q_i}{24EI} < x - x_{i-1} >^4 + \frac{q_i}{24EI} < x - x_i >^4 \right) - \sum_{j=1}^k \frac{p_j}{6EI} < x - xp_j >^3 + \sum_{o=1}^n \frac{R_{a_o}}{6EI} < x - a_o >^3. \quad (21)$$

To determine the above formula, there are $n+2$ unknown quantity demand solutions, namely

$$R_{a_1}, R_{a_2}, \dots, R_{a_n}, y(0), y'(0).$$

Among them, $R_{a_1}, R_{a_2}, \dots, R_{a_n}$ can be used to guide the selection of the crane and the specifications of the lifting wire rope. We solve $n+2$ unknowns by $n+2$ boundary conditions. Respectively, the deflection in the y -direction of the n supports is zero, and the right endpoint of the beam (i.e., the steel cage tail) is the free end. Therefore, its boundary conditions always satisfy that the bending moment and shear force are both zero, that is,

$$y(a_1) = 0, y(a_2) = 0, \dots, y(a_n) = 0, \\ y''(x_m) = 0, y'''(x_m) = 0.$$

When there are loads and the number of supports corresponding to the working conditions, it is transformed into $n+2$ equations to solve the problem of $n+2$ unknowns, and the corresponding hoisting deflection function of the reinforcement cage is determined.

3 Hoisting point optimization

Using Eq. (21) as the optimization objective function, after inputting the number of supports (corresponding to the number of lifting points) and load distribution, the equations are solved to determine the unknown parameters and the optimal support position (corresponding to the location of the lifting point) is combined to make the maximum value of deflection smallest. Due to the existence of $< x - a_n >^3$, when a specific support position a_n changes, the objective function also changes. In fact, this is a functional extremum value problem.

Genetic algorithm^[17] is the mechanism of gene inheritance and mutation by Holland^[18] based on Darwin's theory of biological evolution, which conducts natural selection through fitness to simulate the spatial random search for optimal solution model method established by the biological evolution process. The genetic algorithm directly operates on the optimization function object, which is different from the traditional maximum principle^[19] of the variational method, and other ways to solve the functional extreme value

problem, which has the limitations of function continuity, derivability, and limited types. It is suitable for solving the optimal hoisting point of the reinforcement cage. The workflow of the genetic algorithm is shown in Fig. 4.

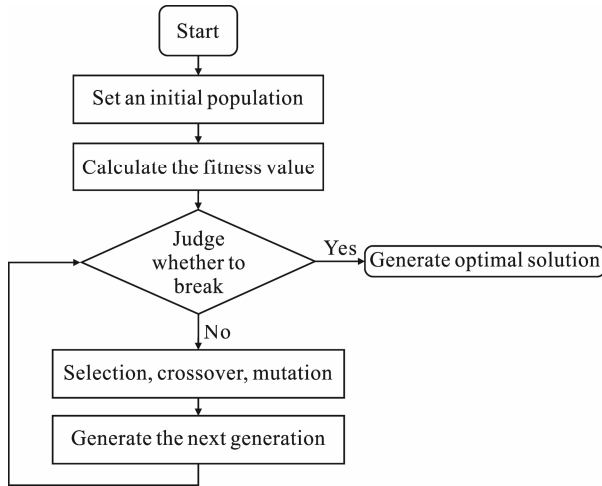


Fig. 4 Workflow of genetic algorithm

This article uses the genetic algorithm that enhances elite retention in the toolbox Geatpy^[20], which comes with Python for optimization. Geatpy is an efficient and valuable object-oriented evolutionary algorithm framework. The operation steps are as follows:

(1) **Parameter encoding:** Population chromosomal element differences ensure that the generated support positions are different using permutation coding, and the value range of the discrete variable is between 0 and the beam length L . The minimum accuracy is taken as 1 cm, which meets the engineering accuracy of the placement error of the lifting point of the reinforcement cage. This code converts the phenotype data into genotype data and can also represent the corresponding decision variable without decoding.

(2) **Genetic algorithm parameters**^[21]: According to the experimental test results of different parameters, the variation scaling factor of differential evolution is set to 0.9, which is used to control the individual variation behavior of the parent, ensure the diversity of the population, and prevent the population from falling into an optimal local situation. The probability of

cross-recombination is 0.9^[22], which serves as the basis for the cross-over behavior of the parent individuals. Both of them set a more significant likelihood to reduce the duplication of the parent in the new generation population. The maximum evolutionary generations and population size must be determined according to the number of lifting points and load complexity. To ensure the optimal effect of the algorithm, they are preset to 100 and 1 000 respectively^[23]. At the same time, since the optimization efficiency of the algorithm is unknown, the other algorithm termination condition is not set, and it only automatically stops when iterating a preset larger evolutionary generation number.

(3) **Select the initial population:** An initial population of 1 000 individuals is randomly generated independently, and each individual corresponds to a set of support positions.

(4) **Crossover, mutation, and evolutionary selection:** The deflection extremum can be calculated by substituting the support position of the initial population into Eq. (21) with $n+2$ boundary conditions. The deflection extremum tensor is used as the basis for the evolution of the population. The 1 000 individuals of the mother generation and the 1 000 individuals of the next generation after cross-mutation were combined to obtain a new population of 2 000. According to the evolutionary selection basis, 1 000 new individuals are selected as the new generation population.

4 Examples

4.1 Uniform load

Taking Ningbo Rail Transit Line 2 Phase II Civil Engineering Standard A (Honglian Station) underground diaphragm wall in-line reinforcement cage as an example, its specific parameters are shown in Table 1.

Table 1 The specific parameters of reinforcement cage

Weight/t	Length/m	Width/m	Thickness/m	E/MPa
66.64	53.5	6.6	0.86	206 000

According to Table 1, we get the moment of

inertia $I = bh^3 / 12 = 3.5 \times 10^{11} \text{ mm}^4$, $q = \text{weight/length} = 12.207 \text{ N} \cdot \text{mm}^{-1}$ and $L_1 = 2.82 \text{ m}$, $L_2 = 7.97 \text{ m}$ by the law of moment balance, so the coordinates of the hoisting point are 2.82, 10.79, 18.76, 26.73, 34.70, 42.67, and 50.64 m, $w_{\max} = 5qL_2^4 / (384EI) = 8.89 \times 10^{-3} \text{ mm}$. The $w_{\max}$ obtained by this method is much smaller than the deformation deflection generated when the actual reinforcement cage is hoisted. This phenomenon occurs due to two reasons. One is that the simplification of the model has limitations. The mechanical properties inevitably change with the simplification of the reinforcement cage from three-dimensional to planar, and the model derived in this paper cannot avoid this problem. The other one is that the value of the moment of inertia is too large, which is calculated by the moment of inertia of the center axis of the rectangle.

Due to the need to verify the optimization effect of this model and algorithm, the same uniform load, flexural rigidity, number of hoisting points, and the length of reinforcement cage are still controlled, and the deflection is used as the effective evaluation criterion. Run the optimization algorithm to get the relationship between the evolutionary generations and the minimum value of the contemporary population $w_{\max}$, as shown in Fig. 5. Due to the larger population size, the minimum value of $8.35 \times 10^{-3} \text{ mm}$ of $w_{\max}$ of the 2nd generation is less than the extreme value of $8.89 \times 10^{-3} \text{ mm}$ of the reinforcement cage deflection after the suspension points are arranged by the moment balance law. Starting from the 21st generation, the hoisting point's position converges to a specific value and the minimum value of $w_{\max}$ is near $4.28 \times 10^{-3} \text{ mm}$. Compared with the moment balance law, the optimization effect reaches 51.9%. Export its lifting point coordinates, which are 3.74 m, 12.62, 20.69, 30.12, 39.46, 48.25, and 51.06 m, the support reaction force on each corresponding hoisting point are 101 648.61, 100 604.49, 106 294.04, 116 570.45, 114 138.17, 73 257.76, and 40 560.99 N, these bearing forces and uniformly distributed loads satisfy the force balance condition, the corresponding

deflection curve is shown in Fig. 6. Using the same bending stiffness, load, and the location of the hoisting point obtained by the new method, a finite element simulation of the plane beam element was performed to obtain the deflection curve as shown in Fig. 7, basically consistent with Fig. 6.

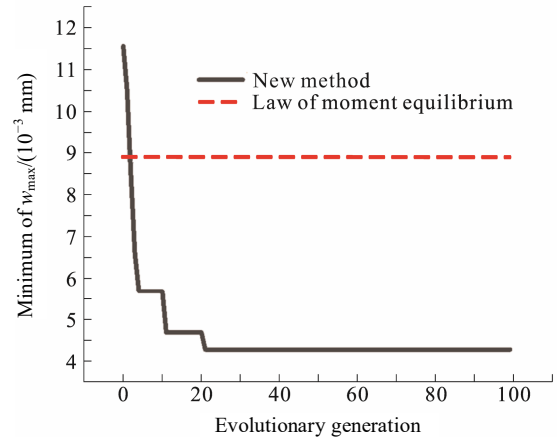


Fig. 5 The relationship between evolutionary generations and the minimum value of $w_{\max}$ in contemporary populations

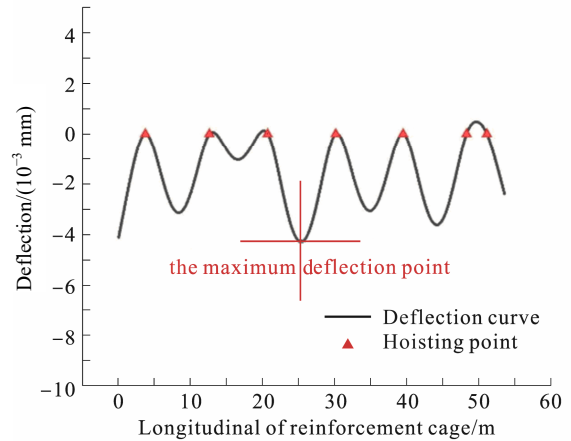


Fig. 6 The deflection curve and hoisting point in the longitudinal direction of the reinforcement cage



Fig. 7 Deflection of the beam under finite element simulation

4.2 General distributed load

When the length and weight of the steel cage are the same, but the distribution of the steel bars is quite

different, there is no difference considering it as uniform load distribution and using the moment balance law to obtain the location of the hoisting point. Therefore, it is necessary to consider the influences of the steel bars to the distributed load. With a specific in-line underground diaphragm wall reinforcement cage project as the background, its particular parameters are shown in Table 2 and Fig. 8. The longitudinal primary reinforcement of the reinforcement cage is arranged in upper and lower double rows, using HRB400 grade $\Phi 25$ and $\Phi 22$ steel bars, respectively. The properties of the horizontal reinforcement are HRB400 grade $\Phi 20$ and $\Phi 16$. The deflection curve equation is applicable in the online elastic range, the distributed load can be determined by sequentially including various steel bars for load stacking. The diameter, spacing of horizontal steel bars, and the length of the corresponding area initially determine the position and value of the distributed load. Longitudinal main bars uniformly increase the distributed load value, and the non-full-length longitudinal main bars increase the original distributed load value within the length range. The load distributions of the steel cage are shown in Table 3–5.

Table 2 A certain in-line underground diaphragm wall reinforcement cage project

Length/m	Width/m	Thickness/m	E/MPa
30.5	6	0.663	206 000

Table 3 Longitudinal distributed load of reinforcement cage

Number	Coordinate interval/mm	Load/($\text{N}\cdot\text{mm}^{-1}$)
1	0–6 000	5.986
2	6 000–8 000	8.916
3	8 000–27 500	9.439
4	27 500–30 500	8.916

Table 4 Transverse distributed load of reinforcement cage

Number	Coordinate interval/mm	Load/($\text{N}\cdot\text{mm}^{-1}$)
1	0–3 600	47.29
2	3 600–6 000	44.68

Table 5 Transverse concentrated load of reinforcement cage

Number	Coordinate/mm	Load/kN
1	10	31.32
2	1 050	0.67
3	1 200	0.67
4	1 800	0.67
5	1 950	0.67
6	3 000	0.67
7	4 050	0.67
8	4 800	0.67
9	4 950	0.67
10	6 000	31.32

Two improvement schemes are given for the treatment of the moment of inertia. First, the formula for

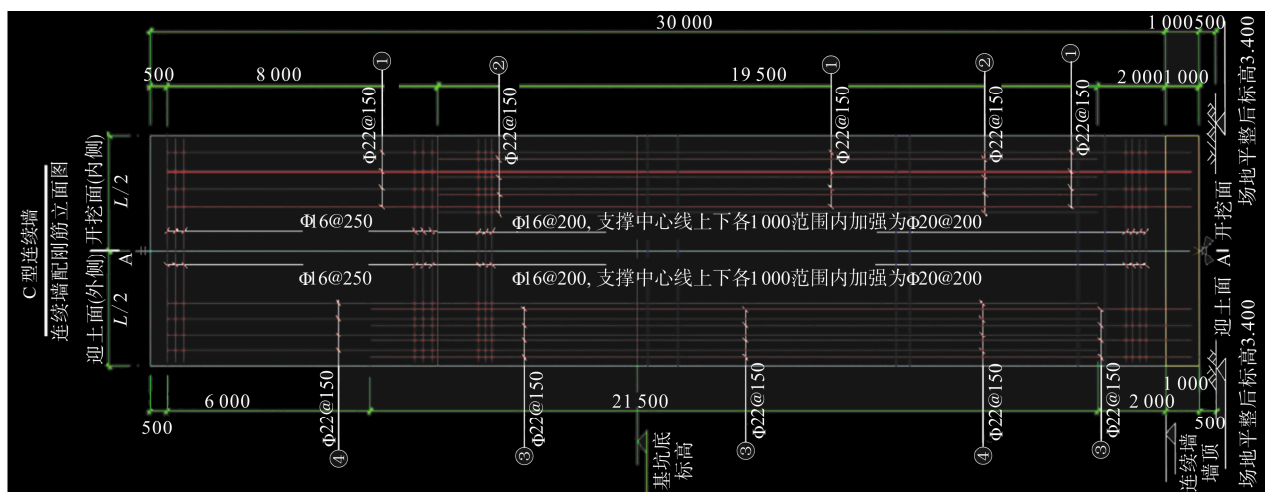


Fig. 8 Rebar cage reinforcement diagram (in Chinese)

calculating the moment of inertia of the rectangular section is still used. Still, it needs to combine many engineering-measured data to set the safety factor to reduce the equivalent bending stiffness. Second, for it's the longitudinal main bars that provide the main flexural stiffness, we use Eq. (22) to calculate the moment of inertia (this paper adopts this method).

$$I = \sum_{i=1}^N \frac{\pi D_i^2}{4} \times \left(\frac{h}{2}\right)^2, \quad (22)$$

where N is the number of longitudinal main reinforcement bars, D_i is the diameter of the longitudinal reinforcement, and h is the thickness of the steel cage. Substitute the data to get $I = 2.2 \times 10^9 \text{ mm}^4$, which is 11/730 of $I = bh^3 / 12 = 146 \times 10^9 \text{ mm}^4$. Although only the deflection is taken as the optimization index, it can be closer to the actual deflection value.

Set the maximum evolutionary generation and population size to 50 and 1 000, then run the algorithm. The positions of the longitudinal hoisting points are 1.08, 7.15, 15.19, 21.36, and 27.72 m, respectively. The transverse positions are 1.07, 2.19, 3.88, and 4.91 m.

This algorithm does not have the limitation of the load type. For reinforcement cages with relatively regular structures and small differences in steel distribution, that is, under uniform load conditions, it can be used as a reference for subsequent adjustment of the hoisting point position determined by the moment balance method. For reinforcement cages with apparent differences in steel distribution, it needs to be simplified to a generally distributed load, and this algorithm can determine the position of the hoisting point.

5 Finite element modeling and analysis

To verify the correctness of the new method for determining the hoisting point, we used ABAQUS to simulate the state of the reinforcement cage when it is hoisted to 0° , 30° , 45° , and 60° to explore its deformation and internal force changes. Reference Fig. 8 for the establishment of the model, that is, the detailed reinforcement configuration corresponding to Table 2. Summing up the hoisting point positions obtained for the law of moment equilibrium, field program, and the new method in Table 6. Due to the large gap between the hoisting point position of the law of moment equilibrium and the other two, in the numerical simulation, the longitudinal hoisting point position is only selected in the field program and the new method, and the transverse position is fine-tuned to the same according to the arrangement of horizontal bars due to their proximity.

The linear elastic B31 beam element is used for reinforcement, and the S4R reduced integral shell element is used for I-steel. Simpson is selected for the shell thickness integral rule, and the thickness integral point is 5. Material properties of steel: elastic modulus $E = 2.06 \times 10^2 \text{ GPa}$, Poisson's ratio $\mu = 0.3$, mass density $\rho = 7\,850 \text{ kg} \cdot \text{m}^{-3}$. In the simulation, the node degree of freedom coupling is used to simulate the welding of reinforcement, and the tie of node-surface is used to set the contact between I-steel and reinforcement. The boundary condition of the hoisting point is to

Table 6 Summary of horizontal and transverse hoisting points

m

The serial number of the hoisting point	Longitudinal			Transverse		
	Law of moment equilibrium	Field program	New method	Law of moment equilibrium	Field program	New method
1	2.29	1.0	1.08	0.57	1	1.07
2	8.77	8	7.15	2.19	2	2.19
3	15.25	14	15.19	3.81	3.8	3.88
4	21.73	21	21.36	5.43	5	4.91
5	28.21	27.71	27.72			

restrict the displacement freedom of X , Y , and Z , and release the angular displacement freedom of R_X , R_Y , and R_Z . The hoisting situation of the reinforcement cage at 0° , 30° , 45° , and 60° is simulated by adjusting the acceleration of gravity, the specific parameter settings are shown in Table 7.

Table 7 Parameters of gravity component corresponding to hoisting angle

Hoisting angle/ $^\circ$	Gravity component 1	Gravity component 2	Gravity component 3
0	0.00	0	-9 810.00
30	0.00	-4 905.00	-8 495.71
45	0.00	-6 936.72	-6 936.72
60	0.00	-8 495.71	-4 905.00

The deflection and stress changes in the hoisting process of the reinforcement cage at different angles are shown in Fig. 9–10, and the maximum deflection, stress, and optimization rate are summarized in Table 8 and drawn in Fig. 11. With the increase in hoisting angle, the maximum deflection and maximum stress of the cage gradually decrease. Therefore, the horizontal position is the most dangerous position for the hoisting, which should be the focus of hoisting process control, and the new method is just based on the horizontal position of the reinforcement cage. Compared with the field program, the maximum deflection and maximum stress of the reinforcement cage are greatly optimized by the new method, especially the stress optimization effect,

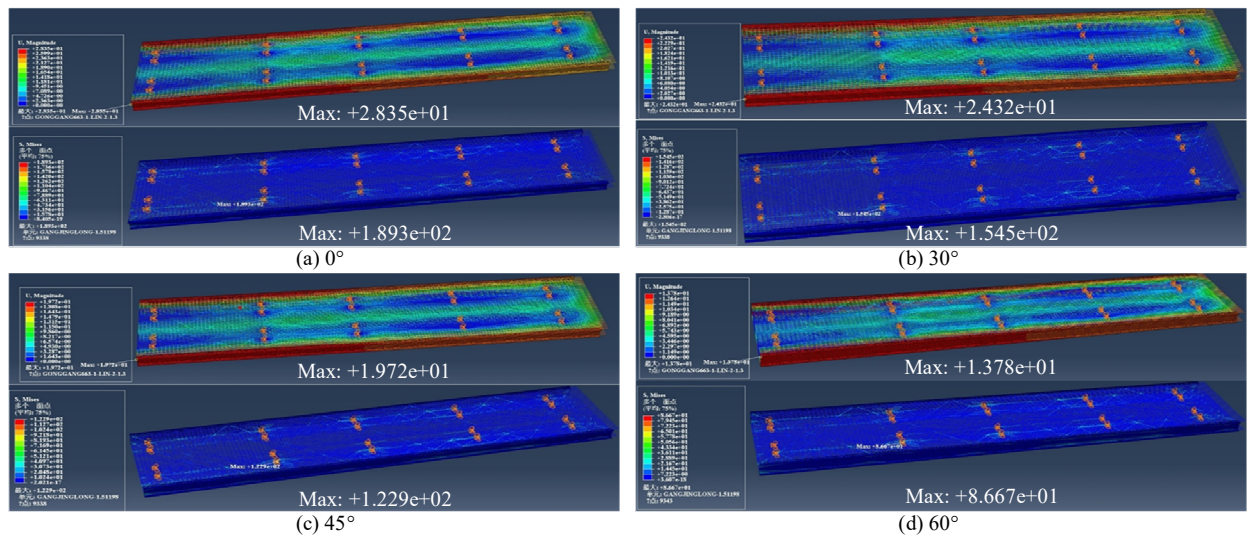


Fig. 9 Deflection and stress of reinforcement cage hoisting at different angles under field program

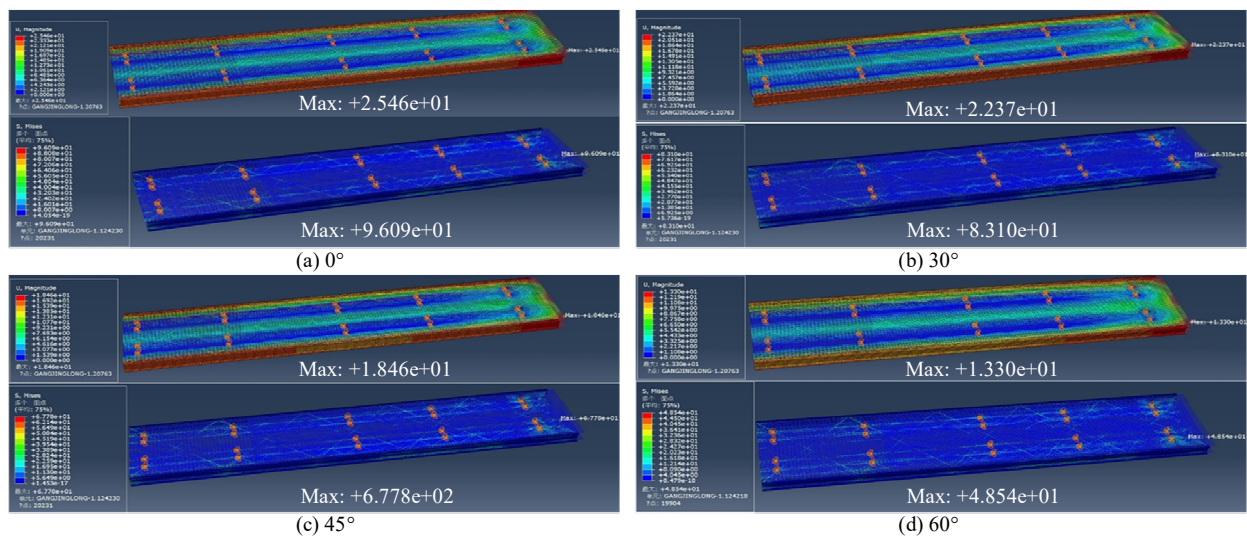
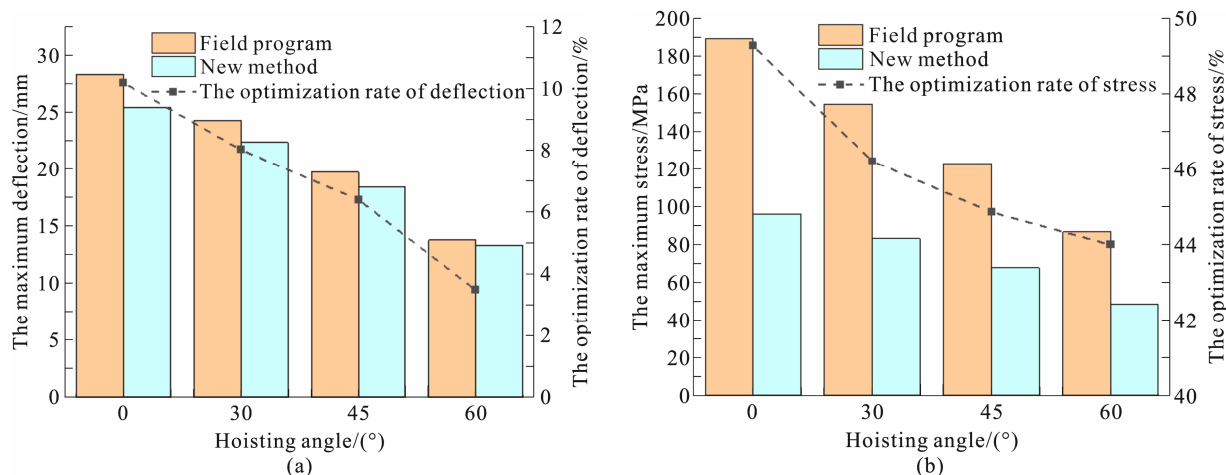


Fig. 10 Deflection and stress of reinforcement cage hoisting at different angles under the new method

Table 8 Statistical table of maximum deflection, maximum stress, and optimization rate

Hoisting angle/(°)	Maximum deflection/mm		Deflection optimization rate/%	Maximum stress/MPa		Stress optimization rate/%
	Field program	New method		Field program	New method	
0	28.35	25.46	10.19	189.3	96.09	49.24
30	24.32	22.37	8.02	154.5	83.10	46.21
45	19.72	18.46	6.39	122.9	67.78	44.85
60	13.78	13.30	3.48	86.67	48.54	43.99

**Fig. 11** Changes of maximum deflection, maximum stress and optimization rate

reaching more than 40%. The maximum stress point in the field program appears near the longitudinal second and transverse fourth lifting point, and the maximum value is 189.3 MPa. The new method transfers it to the end of the reinforcement cage and reduces it to 96.09 MPa. It is beneficial to the hoisting of the cage. The steel bars will be added near the hoisting point to increase the strength. Due to the large internal force and welding damage, the steel solder joints at this position are more prone to open welding. For HRB400 steel bars used in the reinforcement cage, the standard yield strength is 400 MPa, and the maximum stress meets the specification requirements.

Under the field program, the overall maximum displacement appears at the I-steel at the end of the reinforcement cage, while the maximum displacement in the new method appears at the longitudinal main reinforcement near the I-steel without horizontal reinforcement. The maximum deflections are 28.35 mm and 25.46 mm, respectively. The node displacement

along the horizontal reinforcement path at the maximum deflection is selected to obtain the lateral deflection variation curve of the reinforcement cage as shown in Fig. 12. The existence of the I-steel leads to larger transverse deflection on both sides of the reinforcement cage, and smaller deflection between 1-2 and 3-4 transverse hanging points. The overall deflection curve is in the shape of the 'camel', and the deflection of the cage in the new method is smaller than that in the field program. Combined with the requirements of the diaphragm wall regulations, the allowable deviation of the wall verticality should be less than 1/200 of the wall body, and the local protrusion of the wall should not be greater than 100 mm (source: Technical specification for diaphragm wall of foundation pit engineering, DB 33/T 1233—2021, in Chinese). The maximum deflections of the reinforcement cage are both less than the critical value required by the specification. It proves that the location of the hoisting point determined by the new method conforms to the hoisting specification, and the

effect is better than the field program.

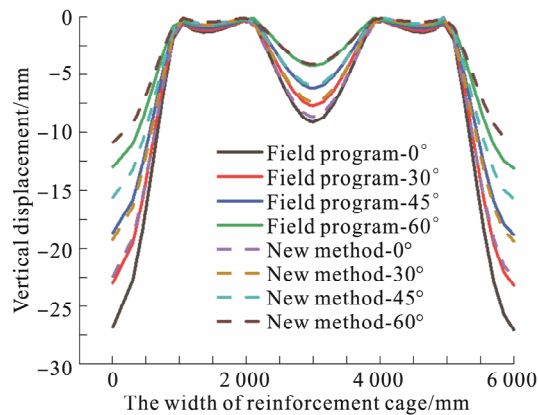


Fig. 12 The relationship between width and vertical displacement in the field program and the new method

6 Conclusions

In this paper, according to the characteristics of the I-shaped reinforcement cage, the shortcomings of the existing engineering methods are analyzed, and a new method for setting the lifting point based on singular function, Laplace transform and genetic algorithm is proposed. Firstly, this method can simulate the case of an arbitrary combination of concentrated loads and distributed loads, which corresponds to the hoisting process of complex reinforced cage members. Secondly, the genetic algorithm is used to find the best bearing position of the extended beam to obtain the optimal lifting point position, which has a fast random search and high scalability (this method has been made into a web client as shown in Fig. 13, language: Chinese). Two sets of calculation examples also verify the optimization effect. The corresponding numerical simulation demonstrates that 0° is the crucial point in the hoisting process of the reinforcement cage, which verifies the rationality of the horizontal extended beam model in the new method. It is proved from two aspects of deformation and stress that the position of the hoisting point determined by the new method conforms to the specification, and the effect is better than that of the field scheme based on the bending moment balance law. This method can provide theoretical guidance for the

determination of the hanging point position of the one-shaped steel cage in the future, provide scientific data for the revision of relevant regulations in the future, and provide reliable control methods for the information construction of the diaphragm wall.

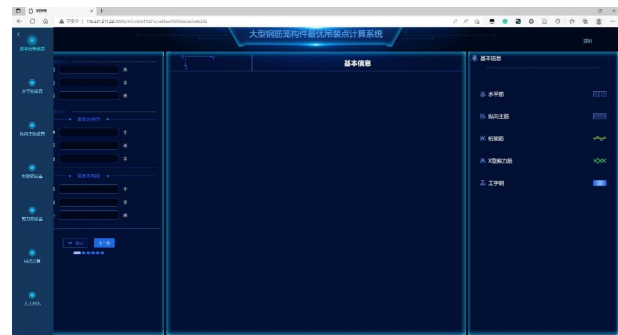


Fig. 13 Web client of the reinforcement cage computing system

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一种设置地下连续墙钢筋笼吊点的新方法

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摘要: 钢筋笼吊装过程中的状态可以看作是在分布荷载和集中荷载共同作用下的多支承悬挑梁, 其中支承点对应于吊点. 本文基于奇异函数和拉普拉斯变换, 求解了梁的挠度曲线方程, 并结合遗传算法, 提出了一种设置直列式钢筋笼最优吊点的新方法. 通过算例和数值模拟验证了该方法的可行性. 结果表明, 与现有的吊点确定方法相比, 该方法能更有效地控制钢筋笼在吊装过程中的变形.

关键词: 钢筋笼吊装点; 奇异函数; 拉普拉斯变换; 遗传算法; 有限元模拟

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