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Optimized Design of a Squeezed-Branch Pile Group Based on an Improved Particle Swarm Algorithm

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Abstract: To reduce the differential settlement of pile group foundations, a squeezed-branch pile group optimization method based on an improved particle swarm algorithm is proposed in this paper. This method translates the problems of optimization design in the squeezed-branch pile group into the pile-bearing-plate distribution using the theory of variable-stiffness leveling. In the optimization process, the pile group is divided into groups according to the top axial force of the pile. The finite element analysis software is used to solve the pile group under the control of the particle swarm optimization algorithm, with the objective functions of bearing-plate number, vertical bearing capacity, settlement value and settlement difference as the constraint conditions. An engineering example is used to verify this method. The results show that the optimized design can reduce the settlement difference by 39%, while the number of the bearing plate is reduced by 56%, which makes the deformation and force of the pile group more uniform and is conducive to the normal use of the structure.

Keywords: squeezed branch pile; particle swarm algorithm; numerical modelling; variable-stiffness leveling

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Citation: Chen, J.; Hui, Y. Optimized Design of a Squeezed-Branch Pile Group Based on an Improved Particle Swarm Algorithm. *Sustainability* **2023**, *15*, 2060. https://doi.org/10.3390/su15032060

Academic Editors: Yi Bao, Yazhou (Tim) Xie, Shan Li and Wenwei Wang

Received: 25 November 2022
Revised: 17 January 2023
Accepted: 18 January 2023
Published: 21 January 2023

1. Introduction

As a new type of variable cross-section pile, the squeezed-branch pile was developed from the conventional circular pile. It has a central rounded shaft with at least one branch attached to it. The branch penetrates the relatively hard soil layer using a hydraulic squeezed machine. The soil surrounding each branch is applied to the pile's top static load. Due to its benefits including a high bearing capacity and low settlement, the squeezed-branch pile is widely used in high-rise buildings. Although the squeezed-branch pile group foundation was constructed with equal stiffness, the differential settlements cause the superstructure to distort and crack, which has a significant impact on a building's ability to be used normally [1]. In view of these problems with the traditional design of pile group foundations, Franke et al. [2] proposed the concept of the variable-stiffness design of pile groups. By adjusting the pile length, the foundation settlement tends to be uniform, reducing the internal force of the foundation and the secondary stress of the superstructure.

Numerous academics have undertaken in-depth research to construct the pile group foundation's variable-stiffness and leveling design, mostly using the theoretical-analysis method, model-test method, and numerical simulation method. In terms of theoretical analysis, Leung et al. [3,4] established the shape function of pile-length optimization in the pile group foundation, optimized the 5 × 5 pile group foundation, and analyzed the overall stiffness and differential settlement of the pile group before and after optimization. Chan et al. [5] used a genetic algorithm to optimize the vertical bearing capacity and the uneven settlement of the cap. Zhang et al. [6] combined the pile-group-foundation-displacement function with the pile-length-optimization function, compared different pile-layout schemes, and studied the axial direction of the pile group foundation's variation law of stiffness ratio and differential settlement ratio. Rasim et al. [7] used the GWO algorithm to optimize the pile group foundation under vertical load. Han et al. [8] carried out an improved two-way asymptotic structure optimization method, based on the continuum-topology-optimization theory, to produce the variable stiffness and leveling of a piled raft foundation using friction piles.

In terms of model tests, Zhang et al. [9] analyzed the relationship between the plane layout, geometric size and settlement of piles by comparing models of variable-stiffness piled-raft foundations. Qian et al. [10] compared seven sets of physical-variable stiffness and physical-simulation tests and found that changing the pile length has a more significant effect on the variable stiffness and leveling. In terms of numerical simulations, Dang et al. [11] studied the influences of pile length, pile number, load distribution and raft thickness on the settlement and deformation of piled raft foundations.

In another study using numerical simulation methods, Sheil and McCab [12] proposed a set of equations which can be used to predict the stiffness efficiency of the pile group based on a finite element analysis (FEA) parametric study of several variables that affect stiffness efficiency. Based on a parametric study of three-dimensional FEA simulations of jet-grouted rafts, Algin [13] presented a multi-objective-optimization analysis using the surface response method to achieve the most economical design solution.

The majority of the pile group foundation optimizations discussed above use the methods of variable pile length, pile diameter, and variable pile spacing to modify the overall layout of the pile groups to achieve the goal of reducing the differential settlement of pile groups. However, this variable-stiffness-adjustment method is aimed entirely at the constant cross-section pile group foundation. For the squeezed-branch pile group foundation, the variable-stiffness-leveling method is still seldom researched.

Therefore, this paper first analyzes and simplifies the variable-stiffness principle of the pile group in order to address the issue of uneven settlement on the top of the squeezed-branch pile group. It develops an optimization model for the squeezed-branch pile group, with the number of branches, vertical bearing capacity, maximum settlement value and settlement difference as the objective function and constraint conditions. Secondly, the particle swarm algorithm (PSO) was improved to make it more suitable for solving the optimization problem of pile groups with squeezed branches and plates. Finally, the ABAQUS FEA software was redeveloped through the Python language [14] and an automatic optimization platform for the squeezed-branch pile group was created, to achieve variable rigidity leveling of the squeezed-branch pile group foundation.

2. Optimization Model of Squeezed-Branch Pile Group

As a component of the superstructure–foundation system, the foundation of a high-rise building is constrained by the combined action of three aspects. Liu et al. [15] presented the equation for the total balance as follows:

$$([K]_{\mathrm{st}} + [K]_{\mathrm{F}} + [K]_{\mathrm{s}})\{u\} = \{F\}_{\mathrm{st}} + \{F\}_{\mathrm{F}} \tag{1}$$

where $[K]_{\mathrm{st}}$ is the superstructure-stiffness matrix, $[K]_{\mathrm{F}}$ is the base-stiffness matrix, $[K]_{\mathrm{s}}$ is the support-stiffness matrix of the foundation soil, $\{u\}$ is the displacement vector at the bottom of the foundation, $\{F\}_{\mathrm{st}}$ is the load vector of the superstructure, and $\{F\}_{\mathrm{F}}$ is the load vector of the foundation. When the pile group foundation is in the design stage, the stiffness matrices $[K]_{\mathrm{st}}$ and $[K]_{\mathrm{F}}$ of the superstructure and foundation, respectively, are determined, and the corresponding loads $\{F\}_{\mathrm{st}}$ and $\{F\}_{\mathrm{F}}$ are also determined accordingly. Therefore, only by adjusting the support-stiffness matrix of the foundation soil $[K]_{\mathrm{s}}$ can the displacement vector at the bottom of the foundation $\{u\}$ be made uniform.

For conventional piles, pile-side resistance and pile-bottom resistance make up the majority of the support stiffness of foundation soil. Because the squeezed-branch pile adds the bearing plate as a member of the pile body, its foundation-soil-supporting stiffness matrix can be expressed as follows:

$$[K]_{\mathrm{s}} = [K]_{\mathrm{s(p)}} + [K]_{\mathrm{s(s)}} + [K]_{\mathrm{s(d)}} \tag{2}$$

where $[K]_{\mathrm{s(p)}}$ is the pile-bottom stiffness matrix, $[K]_{\mathrm{s(s)}}$ is the pile-side stiffness matrix, and $[K]_{\mathrm{s(d)}}$ is the branch stiffness matrix.

By adjusting the stiffness matrices of the pile side, pile bottom, and bearing plate, the purpose of reducing the differential settlement of the pile group can be achieved. However, if the three aspects are adjusted at the same point in the optimization process, there are many factors involved and optimization is not easy to achieve. For this reason, it is necessary to grasp the key part of the optimization problem. As the load borne by the branch of the squeezed-branch pile accounts for about 55–65% of the total load [16], the stiffness matrix of the branch is selected as the key factor in the optimization problem, and the optimization problem is simplified as follows:

(1) The pile length L, pile diameter r and pile spacing S of the squeezed-branch piles are not changed during the optimization process.
(2) The diameter D of the branch, the height of the branch h, and the ratio t of the branch diameter to the pile diameter are fixed.
(3) The spacing of the branch set on the pile body of the squeezed-branch plate meets the specification requirements.

After simplifying the overall balance equation of the squeezed-branch pile group foundation, the soil-support-stiffness matrix $[K]_{\mathrm{s}}$ is only related to the branch stiffness matrix $[K]_{\mathrm{s(d)}}$. For a squeezed-branch pile group, the stiffness matrix of the branch is proportional to the number of branches. Therefore, the stiffness matrix of the branch can be changed by adjusting the number of branches to adjust the settlement of the pile group foundation, in order to achieve the purpose of reducing the differential settlement of pile groups.

Through the principle of variable stiffness adjustment, the optimization problem of a squeezed-branch pile group is transformed into the distribution problem of the pile branch, and the optimization model with the number of branches on each pile as the design variable is established. The total volume of the pile foundation is typically regarded as the objective function of optimization in pile group optimization, because it allows for cost management and straightforward calculation. However, when the total volume is selected as the optimization objective function of a squeezed-branch pile group, a change in the number of pile group branches has little effect on the overall volume; this may lead to difficulties in the optimization process. For this reason, the number of total branches of the pile group is selected as the objective function of the optimization problem. This not only reflects the difficulty of construction, but also makes it possible to comprehensively consider the influence of factors such as time and cost.

A method for combining and reoptimizing pile groups is proposed, due to the significant amount of calculation required for individual optimization of each pile, which is not conducive to actual construction. The pile group foundation is modeled and calculated in ABAQUS FEA software according to the original design scheme, and the axial force FN_i of each pile top is obtained through post-processing operations. As shown in Figure 1, the maximum value FN_{max} and the minimum value FN_{min} of the pile-top axial force are selected as two special values, and the average value FN_{avg} of the pile-top axial force is calculated. Next, the three special values divide the pile-top axial force into two regions. After averaging the special values n times, a total of $2^n + 1$ special values are generated. The axial force of the pile top is divided into 2^n regions, and the whole pile group is also divided into 2^n groups. The number of pile groups 2^n can be determined according to the number of piles contained in the piled raft foundation and the uneven degree of foundation stress.

The number of squeezed-branch pile-bearing plates in the same group is consistent and replaced by a design variable. After grouping, the objective function of the squeezed-branch pile group optimization problem becomes:

$$\begin{aligned} &\text{Find} && X = \{x_1, x_2 \ldots x_s\} = \{np_1, np_2 \ldots np_s\} \\ &\text{Minimize} && f(X) = \sum_{i=1}^{s} np_i n_i \end{aligned} \tag{3}$$

where X is the solution of the squeezed-branch pile group optimization problem, x_i is the design variable for the i group of piles, $f(X)$ is the objective function, s is the number of pile groups, n_i is the number of piles contained in group i, and np_i is the number of branch sets for group i piles.

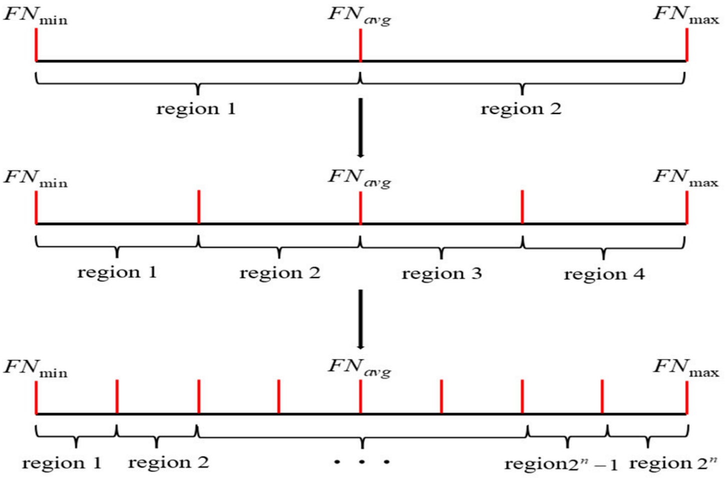


Figure 1. Division map of pile top axial force.

For the optimization problem of the squeezed-branch pile group, the objective function should be solved under constraint conditions. After considering the vertical bearing capacity, maximum settlement value, and settlement difference of the pile group, the constraint conditions are established as follows:

$$\begin{aligned} \text{Subject to}: \quad & N_i \le R(i = 1, 2, \ldots, s) \\ & S_{\max} \le [\mathrm{S}] \\ & S_{\max} - S_{\min} \le S_u \end{aligned} \tag{4}$$

where N_i is the vertical-load value of each single pile in the i group of piles, R is the characteristic value of the vertical bearing capacity of a single pile in the pile group, $S_{\max}$ is the maximum settlement of the raft calculated by the FEA software, and $[S]$ is the maximum allowable settlement value of the piled raft foundation, which can be determined according to the design level of the building in conjunction with the code. $S_{\min}$ is the minimum settlement of the raft, while S_u represents the maximum allowable settlement difference of the piled raft foundation after optimization, which may be determined by the specific project.

3. Improved Particle Swarm Algorithm

To produce the variable stiffness leveling of the pile foundation, the particle swarm algorithm is used. The PSO is a cluster intelligence optimization algorithm for nonlinear function optimization, proposed by Kennedy, J. and Eberhart, R.C. in 1995, which is inspired by the behavioral characteristics of a flock of birds during foraging. The PSO forms an initial population by randomly generating particles of certain sizes and finding the corresponding fitness value according to the objective function of the optimization problem. The initial population flies within the feasible solution to find the maximum or minimum fitness value; the direction and distance of the particle flight are determined by the velocity.

Assuming that the total number of particles in d-dimensional space is N, the displacement of particle i in dimension d at time t is $x_i^t = (x_{i1}^t, x_{i2}^t, \ldots, x_{id}^t)$, and the fitness value of particle i is calculated as follows:

$$F(x_i) = f_{\max} - \left[f(x_i) \times \left(1 + \sum_{j=1}^{3} \frac{v_j(x_i)}{[g_i]} \right) \right] \tag{5}$$

$$v_j(x_i) = \begin{cases} g_j(x_i) - [g_j], & if\ g_j(x_i) > [g_j] \\ 0, & else \end{cases} \tag{6}$$

where $F(x_i)$ is the fitness value of particle i, $f_{\max}$ is a relatively large number to ensure that the fitness value is positive, $v_j(x_i)$ is the degree of violation of each constraint condition by particle i, $g_j(x_i)$ is the value of constraint condition j in particle i, $[g_j]$ is the constraint value for each constraint condition.

Using the fitness function $F(x)$ to calculate particle-fitness value, the position where the particle is currently searching for the largest fitness value is noted as the optimal position $pbest_i^t = (p_{i1}^t, p_{i2}^t, \ldots, p_{id}^t)$. The position where all particles in the whole swarm are currently searching for the largest fitness value is denoted as $gbest^t = (g_1^i, g_2^i, \ldots, g_d^i)$. The velocity of particle i is $v_i^t = (v_{i1}^t, v_{i2}^t, \ldots, v_{id}^t)$. The velocity and displacement of particle i in dimension d at time $t+1(v_{id}^{t+1}$ and $x_{id}^{t+1})$ are simply derived from Equations (7) and (8).

$$v_{id}^{t+1} = wv_{id}^t + c_1 r_1 (pbest_{id}^t - x_{id}^t) + c_2 r_2 (gbest_d^t - x_{id}^t) \tag{7}$$

$$x_{id}^{t+1} = v_{id}^{t+1} + x_{id}^t \tag{8}$$

where w represents the inertia weight coefficient, c_1 and c_2 are the cognitive and social acceleration constants, and r_1 and r_2 are two random numbers that form a uniform distribution [0, 1].

For solving the problem of minimizing the objective function, the PSO updates the $pbest_i^t$ and $gbest^t$ using Equations (9) and (10).

$$pbest_i^{t+1} = \begin{cases} pbest_i^t, & if\ F(pbest_i^t) < F(x_i^t) \\ x_i^t, & else \end{cases} \tag{9}$$

$$gbest^{t+1} = \begin{cases} gbest_i^t, & if\ F(gbest^t) < F(x_i^t) \\ x_i^t, & else \end{cases} \tag{10}$$

To solve the pile group foundation optimization problem using a discretization approach, Equation (8) needs to be improved. Particle-position-update probability is calculated by mapping the particle velocity to $[-1, 1]$ via the Tanh function. The value $T(v_{id}^{t+1})$ denotes the probability that the position update velocity of particle i in dimension d takes 1, -1, 0; the relationship between $T(v_{id}^{t+1})$ and v_{id}^{t+1} is shown in Equation (11). Given the large absolute value of v_{id}^{t+1}, there is a high probability that $T(v_{id}^{t+1})$ will take on a value of 1 or -1. Meanwhile, the particle-velocity formula remains unchanged; the position is updated according to Equation (12).

$$T(v_{id}^{t+1}) = \frac{e^{v_{id}^{t+1}} - e^{-v_{id}^{t+1}}}{e^{v_{id}^{t+1}} + e^{-v_{id}^{t+1}}} \tag{11}$$

$$x_{id}^{t+1} = \begin{cases} x_{id}^t + 1, \ \text{rand}() < T\left(v_{id}^{t+1}\right), v_{id}^{t+1} \geq 0 \\ x_{id}^t - 1, \ \text{rand}() < \left| T\left(v_{id}^{t+1}\right) \right|, v_{id}^{t+1} < 0 \\ x_{id}^t, \quad \text{otherwise} \end{cases} \tag{12}$$

where rand() is a function that generates a random number between 0 and 1.

At the initial stage of iteration, the PSO needs to enhance the particles' global search capability to guarantee that the particles can search the entire solution space at this stage. However, in the late iteration phase, the local search ability of the particles needs to be consolidated, increasing the probability of the algorithm searching for the global optimal solution by boosting the particles' ability to search in the local solution space.

The particles' global and local search abilities are related to the inertia weight coefficient w, cognitive-acceleration constants c_1 and social-acceleration constants c_2 in Equation (13). When w and c_1 take large values, it is beneficial to enhance the particles' global search ability, while when w and c_2 take small values, it is beneficial to enhance the particles' local search ability.

To improve the optimized performance of the PSO, an adaptive adjustment strategy was used to dynamically correct the inertia weight coefficient and acceleration constants c_1 and c_2, which was calculated as follows:

$$\begin{cases} w = w_0 - 0.4 \times \left(\frac{pso_t}{pso_{\max}}\right) \\ c_1 = 2 \times w \\ c_2 = 2 - c_1 \end{cases} \tag{13}$$

where w_0 is the initial inertia weight coefficient, pso_t is the number of current iterations of the particle swarm, and $pso_{\max}$ is the total number of iterations specified.

Finally, the PSO is stopped when a specified number of generations is reached and the optimal position of the particle swarm is solved for the optimization problem.

The basic procedure for the overall optimization of a squeezed-branch pile group is as shown in Figure 2.

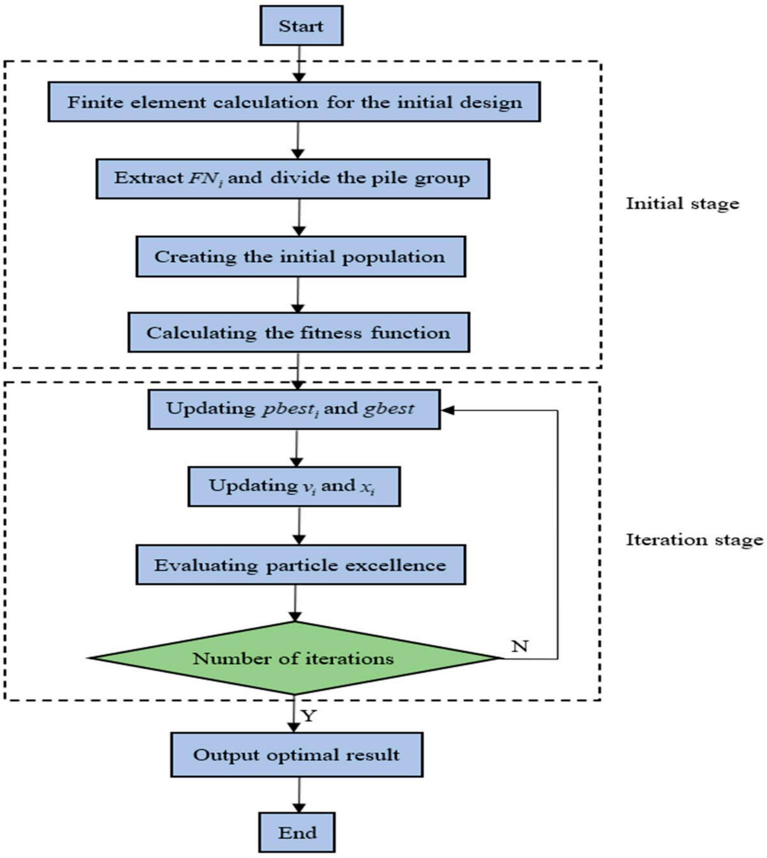


Figure 2. Procedure of squeezed-branch pile group optimization.

a. FEA is performed on the original design plan, and the axial force of each pile is extracted.
b. An appropriate number of groups is selected; the pile group foundation is divided into regions.
c. The single-pile form of squeezed and expanded branch plates that can be selected in each group is determined.
d. Initial populations are created and fitness value is calculated.
e. The optimal individual particle position $pbest_i$ and the optimal particle-population position $gbest$ are updated.
f. The velocity and position of the particle are updated, and particle quality is evaluated.
g. Steps e to f are repeated until the specified number of evolutionary generations is reached, and $gbest$ is found in the population of particles corresponding to the optimal design of the squeezed-branch pile group.

4. Engineering Example

The squeezed-branch pile group model was created using the three-dimensional (3D) simulation software Abaqus. To achieve the adjustment of variable stiffness leveling of the squeezed-branch pile group foundation, an auto-optimization platform was established using secondary development in Python language.

4.1. Calculation Settings

In the FEA simulation process, the soil is assumed to be a continuous, homogeneous and isotropic elastic plastic material, and the Mohr–Coulomb constitutive model is used. The foundation of pile rafts is regarded as a continuous homogeneous elastic body, and the linear elastic constitutive model is used. The specific parameters of the pile–soil model are shown in Table 1.

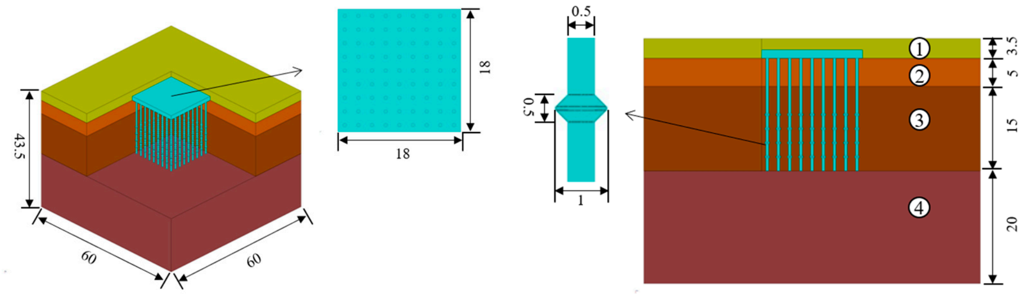
Table 1. Model parameters for FEA calculation of soils.

Category	**γ/(kN·m^{-3})**	**E/(MPa)**	**μ/(kPa)**	**c/(kPa)**	**φ/(°)**
pile	25	3.0×10^4	0.15	-	-
pile cap	25	3.15×10^4	0.15	-	-
Soil 1	18.0	24.6	0.3	8.2	8.3
Soil 2	18.5	27.1	0.3	15.4	18.0
Soil 3	19.0	36.0	0.3	28.0	20.8
Soil 4	19.3	40.0	0.3	30.0	22.5

It was necessary to set up contact between the pile and the soil by considering the relative sliding between the pile and the soil under the action of vertical load. To improve accuracy, the finite-sliding method was used for simulation. The normal and tangential directions of the contact surface were hard contact and a penalty-stiffness-algorithm-friction model, respectively. In this paper, $\tan(0.75\varphi)$ is used for the value of the friction coefficient, where φ is the friction angle in the soil.

4.2. Example Model

As shown in Figure 3, the model is a squeezed-branch pile group foundation in which the raft thickness is 1.5 m, the plane size is 18 m × 18 m, and 81 squeezed-branch piles are evenly arranged at the bottom of the raft; the pile length is 20 m, and the pile diameter is 0.5 m. The branches are arranged at 2.25 m, 4.75 m, 7.25 m and 9.75 m of the pile body; the diameter and height of the branches are 1 m and 0.5 m, respectively. The plane size of the soil is 60 m × 60 m and the thickness is 43.5 m. The soil is divided into four layers. The physical parameters of each layer are shown in Table 1.



(**a**) (**b**)

Figure 3. Schematic diagram of squeezed-branch pile group foundation (unit: m). (**a**) Three-dimensional view of the pile group foundation. (**b**) Basal section view of the pile group foundation.

To reduce the influence of the boundary effect, the dimensions of the soil are three times the diameter of the raft and twice the length of the pile. The horizontal displacement constraint is applied to the cylindrical surface, and the vertical and horizontal displacement constraints are applied to the bottom of the model. The model adopts the C3D8R unit for discretization. Considering that the branch, as an important bearing member of the squeezed-branch pile, needs to be accurately simulated, the branch is encrypted and meshed. Under the action of vertical load, assuming that the raft is subjected to a uniformly distributed load, the load size is 129,600 KN; this is loaded in five stages to avoid the convergence of the model calculation caused by excessive loading.

The post-processing operations were performed on the Odb file obtained after the calculation, and the axial force of each pile top in the pile group was extracted, as shown in Figure 4. When the special value of the axial force was averaged twice, five special values were generated, and the piles were divided into four groups. At this time, the number of pile groups was reduced, the optimization accuracy was low, and the effect was poor. When the special value of the axial force was averaged four times, the piles were divided into 16 groups. Although the optimization effect of pile group foundation under multiple groups is better, the higher the number of groups, the more the calculation amount can increase exponentially. This seriously reduces the operation efficiency and is not conducive to the actual construction. Therefore, the special value of the axial force was averaged three times, and the pile group foundation was divided into eight groups. After grouping, the pile group foundation area was divided as shown in Figure 5, and the number of piles in each group is shown in Table 2.

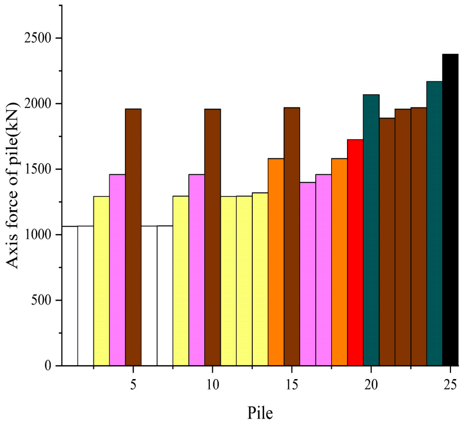


Figure 4. Axis force of pile group.

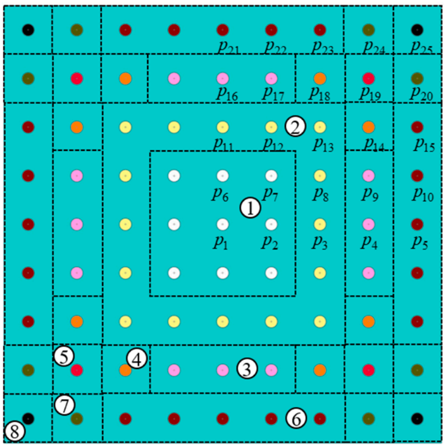


Figure 5. Region division of piled raft foundation.

Table 2. Grouping situation of pile groups.

Group Number	Group1	Group2	Group3	Group4	Group5	Group6	Group7	Group8
Pile number	9	16	12	8	4	20	8	4

To select the number and distribution positions of the branches in each group, combined with the specifications and current research results, four types of squeezed-branch pile were formulated, as shown in Table 3. By applying different forms of squeezed-branch pile to each group, the positions of the squeezed-branch piles were optimized.

Table 3. Schematic diagram of characteristic parameters of squeezed-branch pile group foundation.

	L/m	r/m	D/m	N_p/m	S_p/m	L_b/m	L_t/m
pile 1	20	0.25	1	0	-	-	-
pile 2	20	0.25	1	2	2.5	2.25	14.75
pile 3	20	0.25	1	4	2.5	2.25	9.75
pile 4	20	0.25	1	6	2.5	2.25	4.75

L is the length of squeezed-branch pile; r is the radius of squeezed-branch pile; D is the radius of branch; N_p is the number of branches; S_p is branch spacing; L_b is the distance between branch and pile bottom; L_t is the distance between branch and pile top.

5. Optimization Results

For the optimization of the engineering example, the results of the area division were used to arrange the pile groups. The initial population size was set to 50, and the number of evolutionary generations was 50. The inertia weight coefficient w was set to 0.7, the cognitive-acceleration constant c_1 was set to 1.4, and the social-acceleration constant c_2 was set to 0.6. The squeezed-branch pile group automatic optimization platform was used for the calculation, and 10 independent optimizations were taken. The optimized arrangement of the pile groups is shown in Figure 6, and the distribution of the pile branches is shown in Table 4.

Table 4. Distribution situation of branch.

Group Number	Group1	Group2	Group3	Group4	Group5	Group6	Group7	Group8
Initial design	4	4	4	4	4	4	4	4
Optimization design	6	4	2	0	0	0	0	0

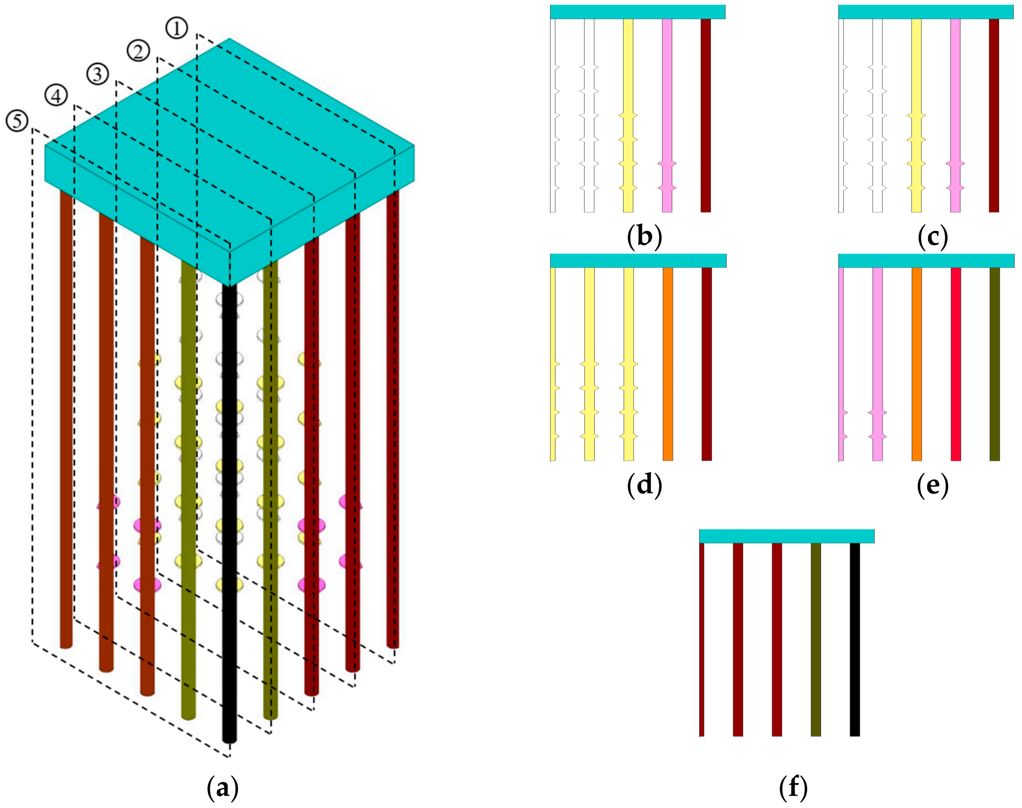


Figure 6. Schematic diagram of optimization design scheme of pile group. (**a**) 1/4 model of pile group, 3D view. (**b**) Section view ①. (**c**) Section view ②. (**d**) Section view ③. (**e**) Section view ④. (**f**) Section view ⑤.

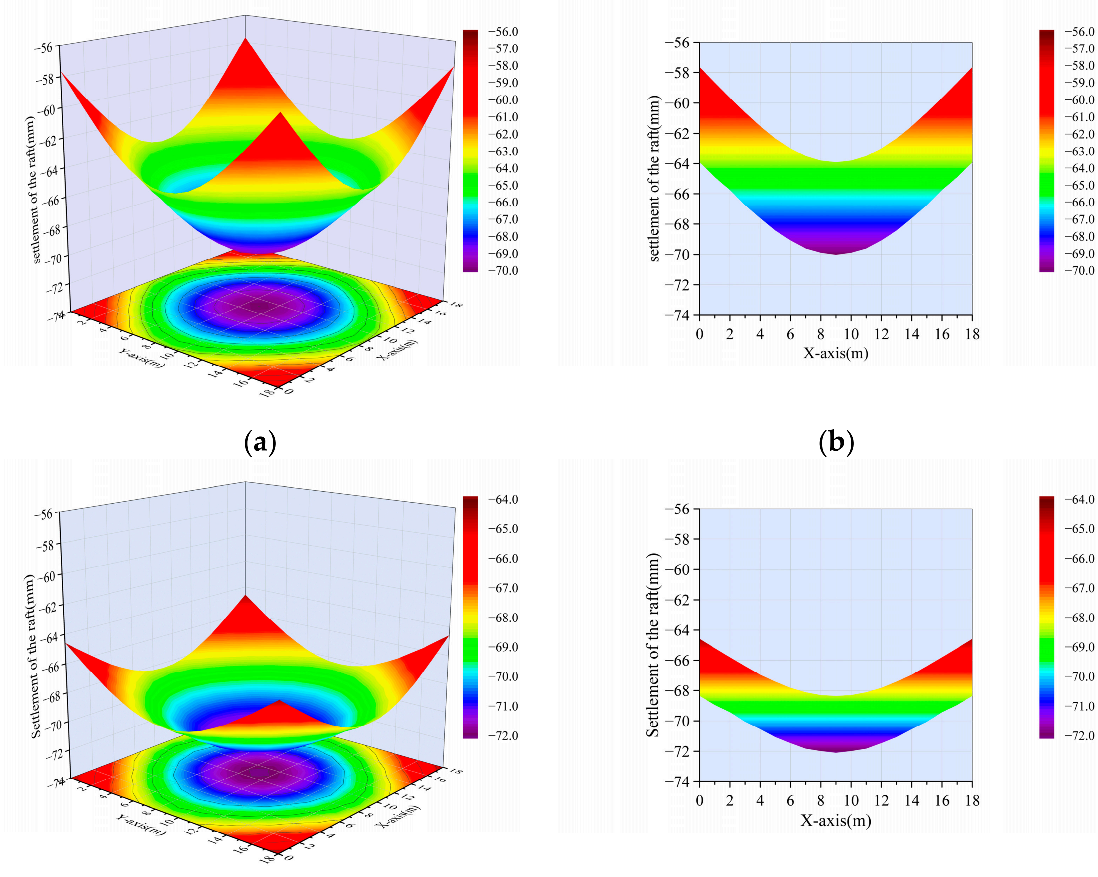
The optimized pile group foundation increased the number of branches at the center pile and reduced the number of branches at the edge and corner piles. This pile arrangement conformed to the principle of variable stiffness around the weakening of the strengthening center. Reducing the number of branches from 324 to 142 and reducing the number of branches by 56% greatly reduced the cost and accelerated the speed of construction, making the pile group arrangement more reasonable and greatly improving its economic efficiency.

Figure 7 shows the raft settlement before and after the optimization of the pile group foundation. The pile group of the initial design has a large center and a small dish-shaped settlement phenomenon, while the optimized pile group raft weakens this phenomenon. The results before and after the optimization are plotted in Table 5. It can be concluded from the table that after meeting the maximum settlement value, after optimization, the differential settlement of the pile group raft was reduced from the original 12.5 mm to 7.6 mm, which is a 39% reduction compared with the original design. The maximum axial force of the pile top was reduced from 2377.4 kN to 1569.3 kN, the minimum value of the pile-top axial force was almost unchanged, and the difference value of the pile-top axial force was reduced from 1312.8 kN to 517.1 kN, a 61% reduction.

Table 5. Comparison of optimization results of pile group foundation.

	$f(X)$	s_{max}/mm	s_{min}/mm	$s_{max}-s_{min}$/mm	FN_{max}/kN	FN_{min}/kN	$FN_{max}-FN_{min}$/kN
Initial design	324	70.1	57.6	12.5	2377.4	1064.6	1312.8
Optimized design	142	72.1	64.5	7.6	1569.3	1052.2	517.1

The results show that the optimized pile group using PSO can greatly reduce the differential settlement of the raft by adjusting the distribution method of the pile-group-bearing plate under the conditions of satisfying the bearing capacity, settlement and other constraints. The maximum value of the pile-top axial force makes the settlement and force of this pile group foundation more uniform, thereby weakening the additional bending moment and shear force generated by the foundation and superstructure, and reducing the risk of cracking or tilting and collapsing of the overall structure. The safety reserve is improved, making it safer during use.

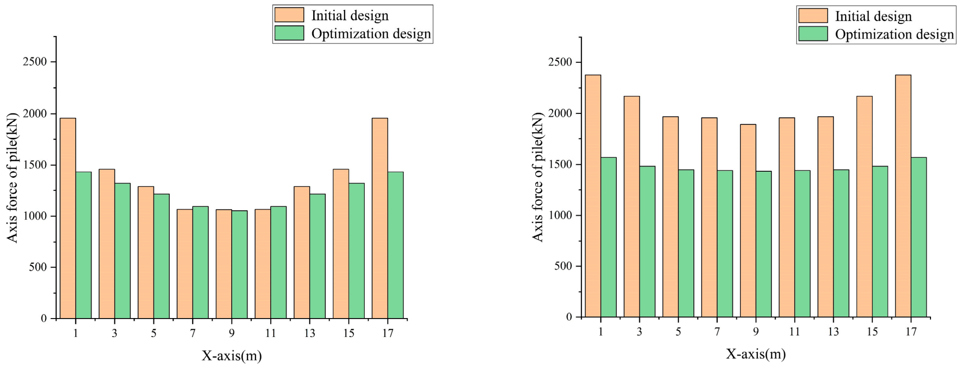


(**a**) (**b**)

(**c**) (**d**)

Figure 7. Comparison of the raft settlement before and after optimization of design. (**a**) Initial design, 3D view. (**b**) Initial design, XZ view.(**c**) Optimized design, 3D view. (**d**) Optimized design, XZ view.

Figure 8 shows the axial force of the piles before and after the optimization of the design. In the initial design scheme, the maximum axial forces of the pile group at Section 1 and Section 2 were 1959.2 kN and 2377.4 kN, respectively, and the minimum forces were 1064.6 kN and 1889.6 kN. The axial-force differences between the two sections were 887.6 kN and 487.8 kN, respectively. The maximum and minimum axial forces of the optimized pile group at Section 1 were 1437.7 kN and 1052.2 kN, respectively. The maximum and minimum values of the axial force at Section 2 were 1569.3 kN and 1435.8 kN, respectively. The axial-force difference between the two sections decreased from 887.6 kN and 487.8 kN to 382.5 kN and 133.5 kN, respectively. The results show that the settlement curve and axial-force curve tended to be gentle due to the optimization of the extruded and expanded piles, that the dish-shaped distribution of the settlement and axial force of the pile group foundation was weakened, and that the additional shear force and bending moment of the pile group foundation were reduced; these changes were more conducive to the safe use of the superstructure.



(**a**) (**b**)

Figure 8. Comparison of axial force on top of piles before and after optimization of design. (**a**) At Section 1. (**b**) At Section 5.

6. Conclusions

Based on the change in pile-branch number to achieve variable stiffness control of the pile foundation, the pile-stress-size grouping and the squeezed-branch pile group required the branch number as the objective function, the selection of pile-settlement values of the design parameters, such as the constraint conditions, and the combination of the PSO with FEA software to achieve the optimization of the squeezed-branch pile group. Combined with the examples, the conclusions are as follows:

(1) Based on the regulation principle of the variable stiffness of the pile group foundation, an optimization method for squeezed-branch pile group foundation was proposed by improving the PSO with the goal of reducing the total number of branches and the constraints of controlling the settlement value and the settlement difference.

(2) The adoption of the method of squeezed-branch pile group foundation to optimize the design can obtain a reasonable arrangement and pile foundation under variable stiffness, reductions in crowded squeezed-branch pile branch number, and reduced costs at the same time, as well as effectively reducing the settlement of the differences and pile-jacking force of the raft. Furthermore, the settlement of the pile group and bearing is more uniform, and the upper structure is safer to use.

(3) For pile group foundations under different load conditions, geological conditions and scales, after setting the appropriate number of groups and the characteristic parameters of the squeezed-branch piles, a more reasonable pile-group-arrangement plan can be obtained by using the calculation in this paper, which greatly improves the reasonableness of the pile-layout method, effectively reduces the dish-shaped settlement of the pile group foundation and, correspondingly, improves the safety and economy of the project.

Author Contributions: Conceptualization, J.C. and Y.H.; methodology, J.C.; software, J.C.; validation, J.C. and Y.H.; formal analysis, J.C.; investigation, J.C. and Y.H.; resources, J.C. and Y.H.; data curation, J.C.; writing—original draft preparation, J.C.; writing—review and editing, J.C. and Y.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China (Project No.:52268077).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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