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Optimal Design of Deep Foundation Pit Support Based on Genetic Algorithm

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Abstract: In this paper, it firstly analyzes the theory of supporting lateral soil pressure calculation in deep foundation pit supporting structure in detail, of which the detailed optimization design uses the new optimization theory - the genetic algorithm. Then, it describes the basic principle and implementation techniques of the genetic algorithm in detail. In addition, it combines with an engineering instance to establish a mathematical model of deep mixing pile with anchor supporting structure, and uses the toolbox of genetic algorithm in the Matlab program to optimize it. The practice has proved that the genetic algorithm can be used for the optimization design of deep foundation pit supporting structure, and can achieve better economic and social benefits. *Copyright © 2013 IFSA.*

Keywords: Deep foundation pit support, Genetic algorithm, Optimization.

1. Introduction

After determining the deep foundation pit supporting program, it needs to conduct the detailed optimization design for the specific supporting program, and strives to achieve the most economical and reasonable cost under the premise of meeting safety and reliability [1-4]. In the deep foundation pit design, designers often need several adjustments and repeated checking calculations of design parameters to make the calculation results meet design requirements [5]. Although this design method can meet the design requirements, the obtained design parameters by this method are often just feasible solutions, instead of the optimal solutions in all feasible solutions. There are many design parameters and complex constraint conditions for particular supporting programs, which will affect the accuracy of computed results and are directly related to the economic and security issues of the deep foundation pit supporting structure. Therefore, how to find a set of optimal design parameters that meet security issues and achieve economic requirements is a complex optimization design problem. As there are many parameters and factors involved in deep foundation pit engineering designs, when use traditional optimization methods like the gradient method to deal with, there are great difficulties, such as problems of discontinuity, non-conductivity, and multiple extreme values of the objective function; based on the above problems, a new algorithm entirely different from previous algorithms - the genetic algorithm has opened up a new idea for the deep foundation pit optimization methods, which has strong vitality proven by practice.

2. Basic Knowledge of Genetic Algorithm

2.1. Implementation Process of Genetic Algorithm

Genetic Algorithm simulates replication, crossover and mutation, etc. phenomena occurring in natural selections and genetics, starting from any initial population by random operations of selection, crossover and mutation, resulting in a group of individuals better adapting to the environment, to make the population evolve into better and better areas in the search space; in this way, it carries out continuous reproductions and evolutions from one generation to another, and finally receives a group of individuals best adapting to the environment, obtaining the optimal solution for the problem. Its general steps are shown in Fig. 1, the main operational processes of genetic algorithm using the above genetic operators (selection operator, crossover operator and mutation operator) are as follows:

Encoding: The data x in the solution space is regarded as a manifestation form of the genetic algorithm. From phenotype to genotype mapping is called encoding. Before the genetic algorithm searches, it first expresses the data in the solution space as the genotype string structure data, and different combinations of those string structure data form different points.

Generation of the initial population: N initial string structure data are randomly generated; each string structure datum is called as an individual, and N individuals form a group. Genetic algorithm takes the N string structure data as its initial point to begin iterations. Set the evolution generation counter as t – 0 and set the maximum evolution generation as T to randomly generate M individuals as the initial population P (0).

Evaluation and detection of the fitness value: the fitness function indicates advantages and disadvantages of individuals or solutions. For different problems, the fitness function is defined in different ways. According to the specific problem, calculate the fitness of each individual in the population of P (t).

Selection: to make the selection operator act on the population.

Crossover: to make the crossover operator act on the population.

Mutation: to make the mutation operator act on the population. After the population of P (t) carries out selection, crossover and mutation operations, the next generation of P (t +1) is obtained.

Termination of conditional judgment: If t≤T, then t← t +1, and go to step 2; if t> T, take the individual with the largest fitness obtained in the evolution process as the optimal solution to output, and terminate operations.

3. Mathematical Model Instance of Foundation Pit Optimization Design

An excellent foundation pit supporting structural design not only needs to ensure the security of the entire supporting structure in the construction process, but also needs to control deformations of the structure and the surrounding soil, to ensure the safety of the surrounding environment. Under the premise of safety, it should be reasonable, but also can save the construction cost, facilitate the construction, and shorten the construction period. In this section, it takes the foundation pit of the staff apartment building of railway in a city for instance to establish a mathematical model of foundation pit supporting structure optimization design, and uses the own toolbox of genetic algorithm in the Matlab program to optimize it in detail, making its design result become optimal. The process mainly includes three aspects: the selection of design variables, the establishment of the objective function, and the determination of constraint conditions. The designed computation model is shown in Fig. 1.

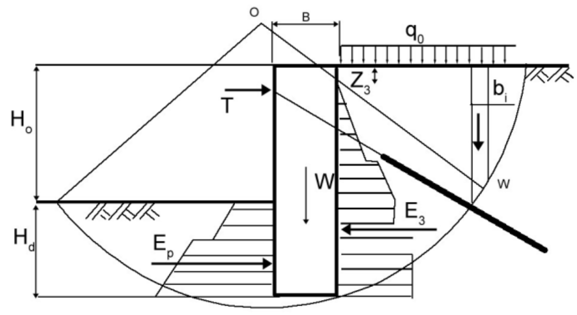

Fig. 1. The Designed Computation Model of Cement-soil Pile with Anchor Supporting Structure.

3.1. The Selection of Design Variables

The selection principle of design variables should select those design parameters that have great impacts on the objective function value, and that are not easy to grasp for general designers, as design variables in the optimization design process, and take other parameters that can be solved by designers' experience or can be determined in accordance with specifications, geological conditions and other requirements as arguments to pre-fix; its basic idea is to highlight the main contradiction of things, and to simplify the optimization process. In terms of the foundation pit engineering, the supporting structure uses the composite supporting structure of the soil cement mixing pile with a layer of anchor, and the main variables that have greater impacts on its design are:

1) Embedded Depth of Supporting Pile.

In the process of supporting structural design, the embedded depth on the one hand affects the cost of the entire project, and on the other hand, it affects the security and stability of the entire project. However, the increase in the embedded depth can enhance the structural stability only in a limited range, and the blind increase in the embedded depth is unwise. The difference of embedded depths has impacts on the deformation and bending moment of pile shaft, and on the pressure distribution in the lateral soil of the pile.

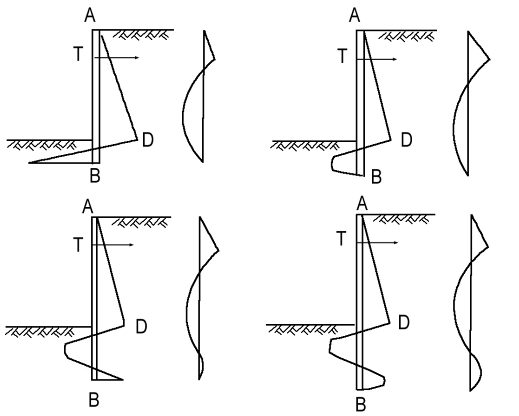

Fig. 2. Impacts of Embedded Depths on the Pressure Distribution in the Lateral Soil of the Pile and on the Bending Moment of Pile Shaft.

When the embedded depth is shallower, as shown in Fig. 2, the entire supporting structure is tilted to the foundation pit, and the bottom may have a slight displacement towards the pit, so that the passive soil pressure of the embedded segment can be brought into full play, when the lower part of the pile can be regarded to be simply supported; this type is used by most of the construction units to minimize the embedded depth to facilitate to operate. However, as the embedded depth is small, while the bending moment and the deformation are relatively large, the cross-section of the supporting structure is also large.

With the increase of embedded depth, as shown in Fig. 2, not all of the soil pressures beneath the foundation pit have reached the passive soil pressure, but it has been able to maintain the stability of the lower pile. At this point, the pile at the bottom has only rotation but no displacement, thus it can still be seen to be simply supported, of which the bending moment is larger, and the cross section is also over large.

As the embedded depth continues to increase, as shown in Fig. 2, passive soil pressures emerge both before and after the embedded depth, and the supporting structure is retained in an embedded solid state in the soil. in this way, the supporting structure is equivalent to be a statically indeterminate beam with its upper part simply supported and its bottom part embedded solid, and there are two bending moments, positive and negative, in which the positive bending moment and the deformation have been greatly reduced. In this case the working condition is ideal.

As the embedded dept further increases, as shown in Fig. 2, the passive soil pressures before and after the supporting structure cannot be brought into full play, and do not play significant roles in the reduction of cross bending moment, which shows that the over large embedded depth is not reasonable, and it generally needs to avoid this situation from happening in the design.

2) Anchor Supporting Point Position.

Different anchor point positions directly affect the embedded depth of supporting pile, the bending moment of pile shaft and the anchor tension, and for a simple pile-anchor supporting structure, when using the simply supported beam method to design, if different point anchor positions are selected, there will be different results, as shown in Table 1.

Table 1. Impact of Different Anchor Point Positions on Results.

Distance from the anchor point to the top of pile	Embedded depth of supporting pile	Maximum bending moment of pile shaft	Distance from the maximum bending moment point to the top of pile	Anchor Tension
0.5	4.2	684.8	4.2	242.6
1.0	4.0	820.5	2.4	254.1
1.5	3.9	576.4	4.5	269.0
2.0	3.8	516.0	4.7	285.3
2.5	3.7	458.2	4.9	303.6
3.0	3.6	428.6	5.1	324.7
3.5	3.6	391.0	5.2	341.2

Table 1 shows that the position of anchor supporting point has greater impacts on the cross-section size of supporting pile, on the embedded depth and on the anchor tension. As the distance from the anchor supporting point to the top of pile increases, the anchor tension and the distance from the maximum bending moment point of pile shaft to the top of pile are getting larger and larger, while the pile embedded depth of D and the maximum bending moment of M_{max} are getting smaller and smaller.

3) Anchor Length and Anchorage Section Diameter.

The anchor free-section length of lf can be calculated according to the following formula:

$$l_f = l_t \sin\left(45° - \frac{\varphi_K}{2}\right) / \sin\left(45° + \frac{\varphi_K}{2} + \theta\right)$$

In the formula, l_t is the distance from the midpoint of anchor head on the anchor bolt to the place below the foundation pit ground where the standard value of load at the outer foundation pit and the standard value of resisting force in the inner foundation pit are equal; for the multi-layer anchor bolt, the length calculation of the free end of its each layer refers to the zero pressure point of subsoil in the foundation pit after the completion of excavation; φ_k represents the standard value of weighted internal friction angle of each-layer soil thickness, and θ represents the inclination angle of the anchor bolt. It can be seen from the above equation that the free-section length of the anchor bolt is related to the inclination angle of the anchor bolt, internal friction angle of the soil layer and the depth of the foundation pit.

The computing formula of the anchorage-section length is as follows: $l_m = \dfrac{T}{\pi Dt} K$.

4) The Width of the Cement-Soil Wall.

For the cement-soil wall as a foundation pit supporting specific weight retaining wall has a certain embedded depth, its difference from the traditional specific weight retaining wall is that the foundation pit supporting specific weight retaining wall has been proved to be controlled by the anti-overturning conditions by the theory and practice. To sum up, select the embedded depth, the position of anchor point, the length of anchor bolt and the width of cement-soil wall as variables of optimization design.

3.2. The Establishment of the Objective Function

Set the population space of supporting program as {chrom} to solve the program individual of chrom5 ∈{chrom}, so that the total cost of the program corresponding to chrom 5 can be minimum, namely:

$$F_{TotalCost}\left(X\right)=\min\left\{feasible\left(\sum_{t-1}^{2}Cost\right)\right\}=\min\left(c_f L+c_m x_3\right) ,$$

where *Cost* represents the cost of the i[th] sub-project in a program individual of the program space. As the overall supporting program is composed of soil cement mixing pile and anchor bolt, 1 and 2 are taken as values of i; feasible {} represents the feasible individuals meeting constraint conditions obtained in the population space of the program; L represents the total length of cement-soil pile, $L = x_2 L_1 \left(h + x_4\right) n$, in which L_1 is the perimeter of foundation pit; n is the number of cement-soil piles per square meter; x_1 is the distance from the anchor point of anchor bolt to the top of foundation pit; x_2 is the width of the cement-soil wall; x_3 is the length of anchor bolt; and x_4 is the embedded depth of cement-soil pile.

The goal of program optimization is to make the total cost of the program obtain the minimum value under the circumstances of meeting the constraint conditions.

3.3. Determination of Constraint Conditions

1) Design Constraint Conditions of Variables.

a) Anchor Point Position x1: the distance from the anchor point of anchor bolt to the top of foundation pit $x_1 \in \left(0, h\right)$;

b) Width of the Cement-soil Wall x2: the width of the cement-soil wall $x_2 \in \left(0.3h, 0.5h\right)$;

c) Length of Anchor Bolt x_3 : the length of anchor bolt is composed of free section and anchorage section, $x_3 \in \left(10m, 20m\right)$;

d) Embedded Depth of Cement-soil Pile x4: the embedded depth of cement-soil pile $x_4 \in \left(0.4h, 1.1h\right)$;

in which *h* is the depth of foundation pit.

2) Constraint Conditions of Design Criteria.

Based on JGJ 120-99 in "Technical Specifications for Building Foundation Pit Support", determine the constraint condition of pile strength, the embedded depth, the constraint condition of the width of the cement-soil wall, the constraint condition of anchor point position, and the constraint condition of anchor-bolt length.

The constraint condition of pile strength

$$\begin{Bmatrix} 1.25 r_0 r_{cs} z + M/W \le f_{cs} \\ M/W - r_{cs} z \le 0.06 f_{cs} \end{Bmatrix},$$

where r_0 is the importance factor of foundation pit, which is generally taken 1.10~0.90;

r_{cs} is the mean specific weight of the cement-soil wall (kN/m^3);

z is the depth from the top of pile to the calculated cross section (m);

f_{cs} is the design value of compressive strength at the cement-soil excavation age (kPa);

M is the design value of cross-section bending moment of the cement-soil pile, $M = 1.25 r_0 M_c$, Mc is the design value of cross-section bending moment (kNm);

W is the cross-section compression modulus of the cement-soil pile (MPa).

a) The embedded depth

$$h_d \ge \frac{\left(1+\frac{q_0}{r^h}\right)+\frac{c}{r^h}\left(k_p e^{\pi\tan\varphi}-1\right)\frac{1}{\tan\varphi}}{k_p e^{\pi\tan\varphi}-1}$$

b) Constraint Conditions of the Width of the Cement-soil Wall.

$$b \geq \sqrt{\frac{2\left(\sum E_a h_a - \sum E_p h_p\right)}{r_{xp}\left(h + h_d\right)}},$$

where $\sum E_a$ is the total force of active soil pressure at the outer foundation pit (Kn/m);

$\sum E_p$ is the total force of passive soil pressure at the inner foundation pit (kN/m);

h_a is the distance from the action point of the total force of active soil pressure to the bottom of the pile (m);

h_p is the distance from the action point of the total force of passive soil pressure to the bottom of the pile (m);

r_{xp} is the mean specific weight of the cement-soil pile (kN/m^3);

c) Constraint Conditions of Horizontal Displacement of the Cement-soil Wall

The displacement at the top of the cement-soil retaining wall can be calculated by using the experience formula:

$$\delta = \frac{0.18\zeta K_a L h^2}{DB}$$

d) Constraint Conditions of Anchor Bolt Tolerance

Td as the design value of anchor bolt horizontal tension should meet the following formula:

$$T_d \leq N_u \cos\theta$$

In the formula: T_d is the design value of anchor bolt horizontal tension (kN); N_u is the design value of anchor bolt axial tensile capacity;

$$N_u = \frac{\pi}{r_s}\left[d\sum q_{sik} l_i + d_l \sum q_{sjk} l_j + 2c_k\left(d_l^2 - d^2\right)\right]$$

In the formula: d1 is the diameter of reaming anchorage body (m); d is the diameter of anchorage body in the straight hole section of non-reaming anchor bolt or reaming anchor bolt (m); l_i is the length of anchorage section in the straight hole part of the ith layer soil (m); l_j is the length of anchorage section in the reaming part of the jth layer soil (m); q_{sik} , q_{sjk} is the standard value of limited frictional resistance between the soil body and the anchorage body, should be taken in accordance with the local experience (kPa); c_k is the standard value of soil body cohesion in the reaming part(kPa); r_s is the partial factor of anchor bolt axial tensile resistance, can be taken 1.3.

e) Anti-overturning Condition.

$$\frac{M_W + M_T + \sum M_P}{\sum M_a} \geq \left[K_P\right]$$

In the formula: $\left[K_P\right]$ is the allowable value of anti-overturning safety factor, can be taken 1.3; $\sum M_a$ is the overturning moment generated by the active soil pressure (kNm); M_W is the antioverturning moment generated by the own weight of the wall body (kNm); M_T is the anti-overturning moment generated by the anchor bolt tension (kNm); $\sum M_p$ is the overturning moment generated by the passive soil pressure (kNm);

f) Constraint Conditions of the Anchorage-Point Position of Anchor Bolt

g) Constraint Conditions of the Anchor Bolt Length

$$l \geq l_f + l_a = \frac{l_t \sin\left(45^\circ - \varphi_k/2\right)}{\sin\left(45^\circ + \varphi_k/2 + \theta\right)} + \frac{KN_n}{\pi d q_s}$$

In the formula: l, l_f, l_a are the total length of anchor bolt, the free-section length (not less than 5 m), and the anchorage-section length (m) respectively; K is the security factor, generally taken 5; d is the diameter of anchorage body (mm); q_s is the value of bond strength between the soil layer and the anchorage body.

4. Experiment and Conclusion

It uses the toolbox of genetic algorithm in the Matlab program to optimize the mathematical model of the above engineering instance, and compiles the file about the optimization of the genetic algorithm on the mathematical model of m, as shown in Fig 3.

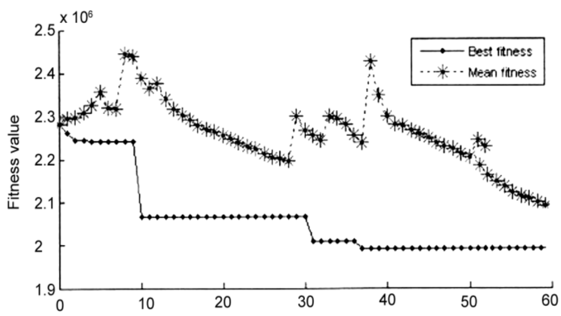

Fig. 3. The average results and optimal value

The final optimization results are x1=2.26208, x2=2.55162, x3=12.34816, and x4=2.64687. Based on the optimization results, the values of design variables are finally taken x1=2.3 m, x2=2.6 m, x3=12 m, and x4=2.7 m.

It can be found from the comparison in the above table that through the optimal adjustments for the position of the anchor point, for the width of the cement-soil wall, for the length of the anchor bolt and for the embedded depth of the cement-soil pile, it not only can achieve savings in the total cost, but also can optimize the internal force of the pile shaft. Relative to the original design, the genetic algorithm selects a more reasonable position of the anchor point, so that the maximum bending moment of the pile shaft has been greatly improved. Although the horizontal displacement at the top of the pile has been slightly increased, it is within the allowable range (i.e. the horizontal displacement at the top of the pile is less than 65 mm). The total cost of the supporting structure after the optimization design has been saved about 12.20 % compared with that of the conventional design program. Moreover, each design variable after the optimization of the genetic algorithm has saved the construction cost under the circumstances of meeting the force and displacement of the supporting structure, achieving considerable economic and social benefits, which indicates that the use of the genetic algorithm to carry out the optimization design on the foundation pit supporting structure is successful.

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