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Research on Tool Wear and Optimization of Tunneling Parameters based on PSO Algorithm

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Abstract

The shield construction process usually faces the problem of tool wear. Frequent opening and changing of tools not only has a great impact on the construction efficiency, but also easily causes engineering accidents. Aiming at the problems such as frequent opening and changing of tools and the decrease of construction efficiency caused by tool wear in the shield construction process, etc. Based on a certain section of Fuzhou Metro Binhai Express Line, the average wear amount of each ring of edge hob was calculated according to the excavation parameters and opening records of actual construction, combined with the empirical formula, the multivariate nonlinear regression model of tool wear amount and excavation parameters was established, and the coefficient of the regression model was calculated. The particle swarm optimization algorithm was written in matlab software to optimize the model and obtain the optimal value of tool wear. The research shows that suitable driving parameters can reduce the amount of tool wear, reduce the frequency of opening and changing the tool, and greatly improve the construction efficiency.

Keywords

Tool Wear; Tunneling Parameters; Regression Analysis; Parameter Optimization; Particle Swarm Algorithm.

1. Introduction

Shield tunneling machine is a common mechanical equipment in modern tunnel construction, the setting of tunneling parameters has a very important impact on the construction quality, safety and efficiency of the tunnel. As a key component of shield machine, cutting tool plays an important role in the construction process. However, under some complex geological conditions, the cutting tool will have different degrees of wear due to cutting soil or rock, which affects the tunneling performance of the shield machine *[1]*. Tool wear to a certain extent need to open the warehouse tool change, frequent open warehouse tool change seriously affect the construction progress. The research shows that the setting of driving parameters has a direct impact on the problems of tool wear and surface settlement, and the appropriate driving parameters can effectively solve a series of problems such as large tool wear and large surface settlement. Due to the complex and changeable geological conditions, how to choose the appropriate driving parameters to reduce the tool wear is always a difficult problem in engineering practice. At present, many experts and scholars have studied the optimization of driving parameters and tool wear. Xiong Yingjian et al. *[2]* took the minimum energy consumption of the shield as the decision goal and used PSO particle swarm optimization to optimize part of the tunneling parameters, and found that the method achieved good convergence effect in different formations. Hu Changming et al. *[3]* adopted the improved LSTM-PSO model to optimize the excavation parameters, proving the feasibility and engineering practicability of the model in surface settlement control. Sadegh et al. *[4]* studied the influence of geological parameters and driving parameters on tool consumption and found that the wear amount increased with the increase of total thrust, cutter head torque and soil bin pressure. Yang Junzhe et al. *[5]* Based on two support vector machine models, SA-SVM and GALSSVM, built an input index system including geological parameters (surrounding rock strength and abrasion) and driving parameters (torque and speed) to predict tool wear. Zhang Houmei *[6]* et al., based on the influence of driving speed and cutter head torque on cutting tools in existing studies, further modified the model and introduced soil bin pressure, and found that the model was feasible for judging tool wear. Ding Xiaobin et al. *[7]* improved the neural network model by means of optimization algorithms, excavated the influence of multi-source parameter types on hob wear in shield construction, and established a quantitative hob prediction model through multi-parameter nonlinear analysis. The results showed that the idea was initially feasible.

In summary, many experts and scholars have done more research on the optimization of driving parameters and tool wear, but there are few researches on the problem of reducing tool wear by optimizing driving parameters by algorithms. Based on a certain section of Fuzhou Metro Binhai Express Line, a multivariate nonlinear regression model of excavation parameters and tool wear was established according to excavation parameters collected on the left line of site construction. Particle swarm optimization algorithm was used to optimize the established model to obtain the optimal solution of excavation parameters and the optimal value of tool wear. The feasibility of the method was verified by comparing with excavation parameters on the right line. It provides theoretical basis for efficient construction.

2. Engineering Background

2.1 Project Overview

Taking the actual construction of a tunnel in a section of Fuzhou Metro Binhai Express Line as an example, the section was constructed by shield tunneling method, which included left and right lines, and both lines were constructed by shield tunneling machines manufactured by China Railway Engineering Equipment Group Co., LTD. The two shield tunneling machines had the same parameters. The excavation diameter of the section was 8.63m, and the width of the pipe segments used for shield tunnel lining was 1800mm. The total length of the left line is 2207.207m, the maximum thickness of the tunnel is about 33m, the minimum thickness is about 3m, and the rock formation accounts for 47%. The geological conditions of the left and right lines are basically the same. The main intermediate strata are silt, silty clay, residual sandy clay, fully weathered granite, sand-like weathered granite, fragmentary weathered granite, soft above and hard below, isolated stone and moderately weathered granite. The construction is difficult, and it needs to cross the subway line in operation and the dense middle and high-rise buildings. Due to the influence of geological conditions and other related factors, the construction process needs to open the warehouse and change the tool many times to ensure the smooth progress of the excavation. The main specifications of the shield tunneling machine are shown in Table 1.

Table 1. Main Specifications of the Shield Machine

Name	argument
Cutter diameter	8.63m
Hob size	17inch
Length of machine	130m
Cutter torque	475-5680kN·m
Cutter speed	0.2-1.8rpm
Total thrust	1800-5400t

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2.2 Parameter Acquisition

In the driving section of Fuzhou Binhai Express Line, the real-time data acquisition system (driving management system) is adopted on the left and right lines, and the data is collected every five seconds. During the whole tunneling process, more than 1000 shield machine parameters were collected, and the collected data was saved in the MySQL database. Among the more than 1000 parameters collected, some of the measured tunneling parameters were shown in Table 2.

Table 2. Partial Measured Tunneling Parameters

Ring Number	Cutter torque (kN·m)	Total thrust(kN)	Advance Speed(mm/min)
255	2948	18833	29
256	2845	18640	30
257	2884	19936	26
258	2541	18678	36
259	2407	19569	32
260	2494	18247	29
⋮	⋮	⋮	⋮
300	3235	19295	51
301	3271	18854	59
302	2537	18998	63
303	2220	19975	42
304	2647	19688	44
305	2951	19833	44

This paper focuses on the parameters that may affect tool wear, such as cutter head torque, total thrust and driving speed. Cutter head torque is an important parameter to analyze tool wear, it directly reflects the friction between cutter head and excavation face. Theoretically, the greater the total thrust value, the greater the contact pressure and friction between the tool and the formation, and the greater the tool wear. The contact time between the cutting tool and the soil may also have a certain influence on the wear of the cutting tool.

2.3 Data Selection

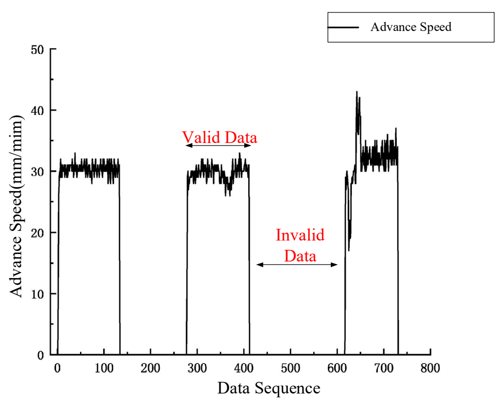


Fig.1 Change of driving speed of part 256 ring

Generally speaking, the propulsion process of the shield machine will experience three states of propulsion, assembly and shutdown, but the data acquisition system is continuous collection, not only collecting the data of the shield machine in the propulsion state, but also collecting the data of the shield machine in the assembly and shutdown state. Figure 1 shows the driving speed variation diagram of the 256th ring

The cutter head torque, total thrust and driving speed may all be 0 during shutdown, and the parameters in this stage are not suitable for establishing regression model analysis of tool wear and driving parameters. The binary state judgment function W is constructed to preprocess the data, as follows:

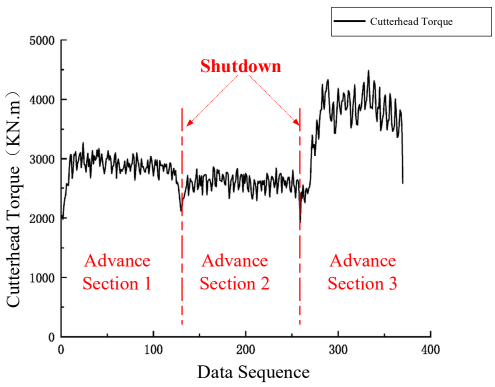
$$W = \mathrm{F(f)F(t)F(v)} \tag{1}$$

$$F(x) = \begin{cases} 1, & x \neq 0 \\ 0, & x = 0 \end{cases} \tag{2}$$

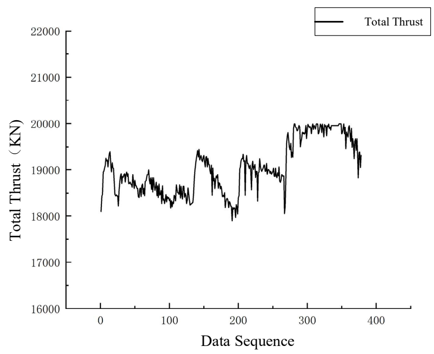
$$W = \begin{cases} 1, Tunneling\ Status \\ 0,\ Shutdown\ State \end{cases} \tag{3}$$

Where: f is the total thrust, t is the cutter head torque, v is the driving speed.

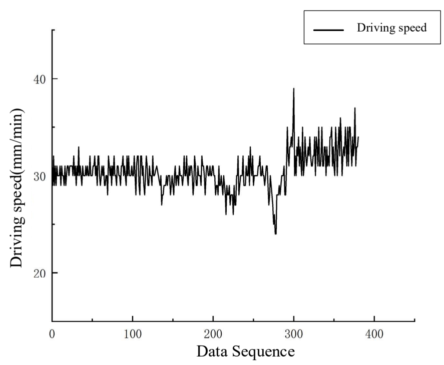
After preprocessing, take the data of the 256th ring as an example, and the change curve is shown in Fig. 2.



(a)Cutter torque curve



(b)Total thrust change curve



(c) Driving velocity change curve

Fig.2 256 Transformation curve of driving parameters after ring preprocessing

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As can be seen from the transformation curve of driving parameters in Fig. 2, the 256th ring experienced two shutdown states during the advancing process, and the advancing interval was divided into three parts. In the driving state, the cutter torque value ranges from 2000-4300kn.m, the total thrust value ranges from 18000-20000kn, and the driving speed value ranges from 25-37mm/min.

3. Tool Wear Analysis

3.1 Tool Wear Law

Different geological conditions or setting of different driving parameters have different effects on tool wear. In this paper, the tool wear of shield machine in a construction section of Fuzhou Binhai Express Line is studied. Tool wear can be divided into abnormal wear and normal wear, abnormal wear including tool ring fracture, oil leakage, partial wear and so on. Normal wear refers to the uniform wear of the tool ring caused by the interaction between the tool and the soil during construction. Tool wear photos are shown in Fig. 3.

Fig.3 Photos of tool wear

3.2 Tool Wear Coefficient

In the process of excavation, the wear of the tool has a greater impact on the construction efficiency, among which, the edge hob of all kinds of tools is the most easy to wear, if the wear is serious and not replaced in time, it will also affect the surrounding other tools and accelerate the wear rate of other tools. According to years of construction experience of shield machine manufactured by IHI shield machine manufacturing company in Japan, the calculation method of tool wear installed at different positions was summarized *[8]*, and the tool wear (M) was calculated according to the following formula:

$$M = \mathrm{K} \times \mathrm{L} \tag{4}$$

Where:K--tool wear coefficient(mm/km)

L--Tool rolling distance(km)

Tool wear is affected by many factors. After the improvement of formula (4), there is usually the following empirical formula for the wear of the outer ring tool *[9,10]*.

$$\delta = \frac{K\pi DnL}{v} \tag{5}$$

Where, K--Wear coefficient (mm/km)

D--Tool distance from shield center (m)

N--Cutter speed (rpm)

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L--Advance distance (km)

v--Driving speed (m/min)

The standard of tool wear change used in the project is: double-edge hob wear up to 25mm, front single-edge hob wear up to 20mm, edge hob wear up to 15mm. According to formula (5), the distance between the tool and the center of the shield is proportional to the tool wear, so the edge hob installed in the outermost part is the easiest to wear and the replacement frequency is faster.

3.3 Statistical Analysis of the Number of Tool Changes

Before the construction of the left-line tunnel shield in the study area, 13 times of bin inspection were conducted in 650 rings, one time of reinforcement with pressure to normal pressure into the bin for tool change, 12 times of pressure into the bin for tool change, and a total of 177 tools were replaced, as shown in Table 3.

Table 3. Tool replacement situation table

Tool type	Number of tool changes (pieces)	Loading quantity (pieces)	Damage condition
Center double blade hob	21	6	2 blades are broken, 7 are off-worn, and 12 are evenly worn
Front hob	85	35	70 for uniform wear, 15 for off-wear
Edge hob	71	12	59 evenly worn, 12 off-worn

As can be seen from Table 2, a total of 177 cutting tools were replaced in 650 rings before the project was advanced, including 21 center double-edge hobs, 85 front hobs and 71 edge hobs, accounting for 11.8%, 48.0% and 40.1% of the total tool changes respectively. The amount of tool damage is not only related to the wear coefficient, but also to the number of loaded tools. Although the wear rate of the front hob is less than that of the side hob, the load quantity is about three times that of the side hob, so the front hob consumption is the largest in this range. From the point of view of wear, the tool wear mode is mostly ideal uniform wear, and the wear rate is slow.

3.4 Establishment of Tool Wear Prediction Model

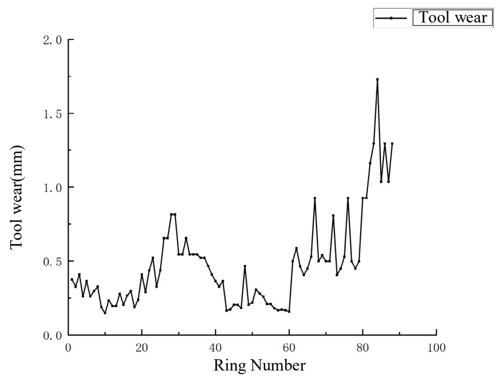

Fig.4 Tool wear change curve with ring number

In order to study the relationship between cutter head torque, total thrust, driving speed and tool wear, the above data collected by the driving management system on the left line of the engineering interval were used for regression analysis. The geological condition was compound geology and was not considered as a constraint condition. The tool wear is based on the average wear of the loaded edge hob. Considering the construction needs to be carried out safely and efficiently, it is impossible to open the warehouse to check the tool wear after each loop is completed. Therefore, the average wear

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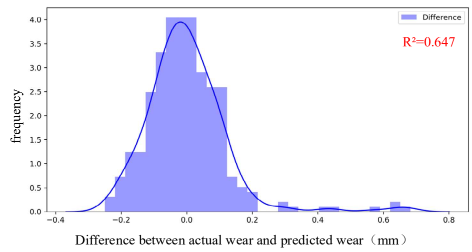
of each ring edge hob can be calculated as the test value through the measured edge hob wear of opening the warehouse and changing the tool during the construction process and the empirical formula (5) above. The tool wear calculated for the first two warehouse opening tool changes is shown in Fig. 4.

Because there are many independent variables, and the relationship between tool wear and their variables is not simple linear or nonlinear, this paper adopts multiple nonlinear regression analysis model. According to the principle of series expansion, any curve problem can be approximated arbitrarily by polynomials in a certain range [11].

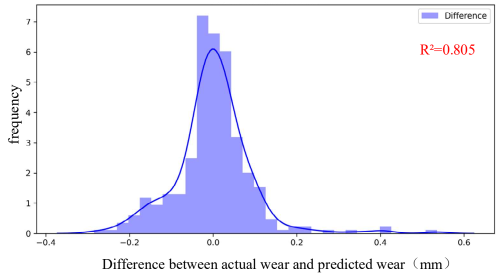
The polynomial nonlinear regression equation adopted is:

$$\delta = \beta_0+\beta_1 x_1+\beta_2 x_2+\beta_3 x_3 + \beta_4 x_1^2 + \beta_5 x_2^2 + \beta_6 x_3^2 + \beta_7 x_1 x_2 + \beta_8 x_1 x_3 + \beta_9 x_2 x_3 + \beta_{10} x_1^3 + \cdots (6)$$

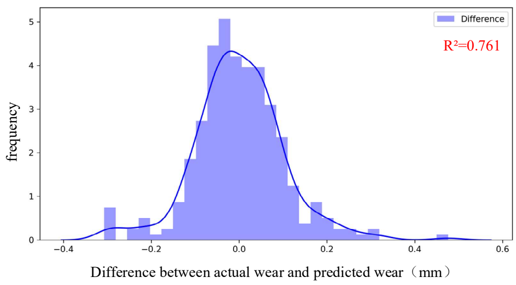
Where, $x1$, $x2$ and $x3$ are respectively cutter head torque, total thrust and driving speed, $\beta 0$, $\beta 1$, $\beta 2$, $\beta 3$... Is the regression coefficient. python software was used to verify the reliability of the model under different orders and the regression coefficient of the optimal order polynomial was obtained. The normal distribution of the difference between actual wear and predicted wear under different orders was shown in Fig. 5.



(a)The order is 2 difference normal distribution



(b)The order is 3 difference normal distribution



(c)The order is 4 difference normal distribution

Fig.5 Normal distribution of the difference between actual wear and predicted wear

As can be seen from Fig. 5, when the polynomial order is 3, the regression equation is optimal, the correlation coefficient R^2 is equal to 0.805, R^2 is equal to 0.647 when the order is 2, and R^2 is equal

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to 0.761 when the order is 4. The nonlinear regression model between tool wear and cutter head torque, total thrust and driving speed is obtained as follows:

$$\delta = -9.15 \times 10^{-4}x_1 + 1.12 \times 10^{-3}x_2 + 9.68 \times 10^{-2}x_3 + 2.69 \times 10^{-7}x_1^2 + 6.72 \times 10^{-10}x_2^2 + 4.94 \times 10^{-5}x_3^2 - 3.38 \times 10^{-8}x_1x_2 - 1.42 \times 10^{-5}x_1x_3 + 1.49 \times 10^{-3}x_2x_3 \ldots - 10.31 \tag{7}$$

Where: δ is the tool wear, unit mm; x_1 is the cutter head torque, unit kn.m; x_2 is the total thrust, in KN; x_3 is the driving speed, the unit is mm/min;

The regression model was used to fit the engineering data of the first 300 loops on the left line of the research interval, and the comparison curve between the calculated value of tool wear and the fitting value was obtained, as shown in Fig. 6.

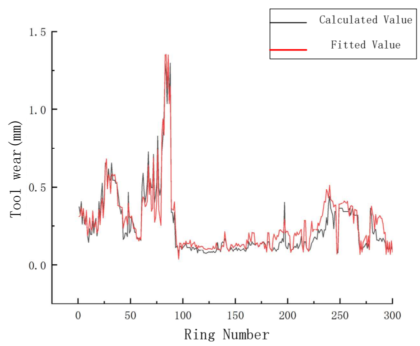

Fig.6 Comparison curve between experimental value and fitting value of tool wear

It can be seen from Fig. 6 that the tool wear of each ring is large between 80 and 90 rings, and the tool wear of each ring is more than 1.0mm. After checking the tool change statistics table, it is found that when the digging reaches 82 rings, the tool wear situation is checked when the warehouse is opened, and the edge hobs all have different degrees of wear, but they are still in the reasonable wear range, and no tool is replaced. After several meters of continuous promotion, the warehouse was opened again at 89 rings to check the tool wear, and it was found that the wear of some hobs reached the replacement standard, a total of 19 tools were replaced, and the shield machine was shut down for 12 days. By comparing the calculated value of tool wear with the fitting value, it is shown that the established regression model can predict tool wear well in this construction interval, the average error is 0.0232mm, and the value range of tool wear is basically between 0 and 0.5mm.

4. Parameter Optimization Model

4.1 Principle of Particle Swarm Optimization Algorithm

Particle swarm optimization algorithm (Particle Swarm Optimization, PSO) is a kind of optimization algorithm based on swarm intelligence, proposed by Eberhart and Kennedy in 1995, is the result of research on the behavior of birds feed on, similar to the simulated annealing algorithm. Particle swarm optimization algorithm simulates the foraging behavior of birds to solve the optimization problem. Through simple mathematical model and basic calculation method, it simulates the competition and cooperation between individuals in the birds, so as to quickly find the ideal optimal solution.

In particle swarm optimization algorithm, the solution of the problem to be optimized is regarded as a point in a multidimensional space, all particles have an adaptation value determined by the optimization function, each point is regarded as a particle, each particle has two attributes of speed and position, the position of the particle represents the solution of the problem, each dimension represents the value of a decision variable, and the speed of the particle represents the moving speed in the solution space. It can also be represented by vectors, with each dimension representing the

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speed of a decision variable. In the PSO algorithm, each particle changes according to its own speed and position. The velocity of the particle is determined by comparing the optimal solution of the particle itself with the optimal solution of the population. Each particle records individual and group optimal solutions. Once the two optimal solutions are found, the particle updates its position and velocity using the following formula.

$$v_i = w \times v_i + c_1 \times rand() \times (pbest_i - x_i) + c_2 \times rand() \times (gbest_i - x_i) \tag{8}$$

Where: vi is the velocity of the particle; w is the inertia weight; $c1$ and $c2$ are learning factors and constants; rand() is a random number between (0,1); $pbesti$ is the optimal solution for individual particles. $gbesti$ is the optimal solution of particle population.

After updating the velocity of the particle, the position of the particle is updated using the following formula.

$$x_i = x_i + v_i \tag{9}$$

The specific flow of particle swarm optimization is shown in Fig. 7.

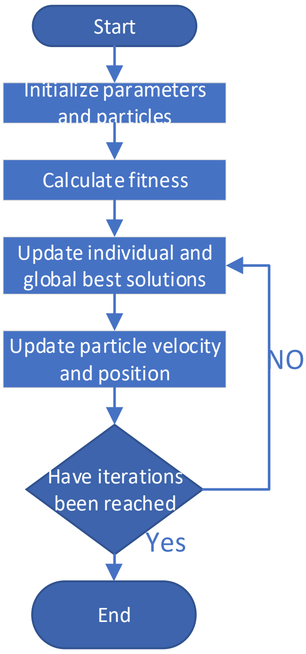

Fig.7 Flow chart of particle swarm optimization algorithm

4.2 Parameter Optimization

Equation (10) obtains the nonlinear regression model between tool wear and cutter head torque, total thrust and driving speed, which can better reflect the relationship between the independent variable and the dependent variable. With the minimum tool wear as the goal and equation (10) as the objective function, the optimization process is simplified to optimize the multivariate nonlinear equation by using particle swarm optimization algorithm, so as to find the optimal solution of the equation. Taking the minimum tool wear as the objective function, the optimization function of the driving function can be simplified as:

$$min\delta_i = minf(x_{1,}x_{2,}x_{3,}) \tag{10}$$

In the formula, x1,x2 and x3 are cutter torque, total thrust and driving speed respectively; δ is the tool wear.

python software is used to complete the optimization, and a set of solutions of the objective function is regarded as a particle. First, the particle swarm is initialized, the number of particles N is set to 100, and the number of iterations Q is set to 100. The fitness of each particle is calculated through the objective function, and the fitness can represent the quality of the current position. Through many experiments and calculations, the value of the learning factor $c1$, $c2$ is 1.5, and the value of the inertia weight w is 0.7. The range of independent variables $x1$,$x2$,$x3$ is set. The data of the shield tunneling machine collected according to actual construction are as follows: $x \in$ 1 [2000450], 2 $\in x$ [18000200], x 3 $\in$, [40] 25 units in accordance with above. After completing the above steps, the individual optimal solution and the global optimal solution of the particle are obtained through several iterations, and the velocity and position of the particle are updated. Finally, the optimal solution with the least tool wear is obtained. The fitness curve obtained by the software using the particle swarm optimization algorithm is shown in Fig. 8.

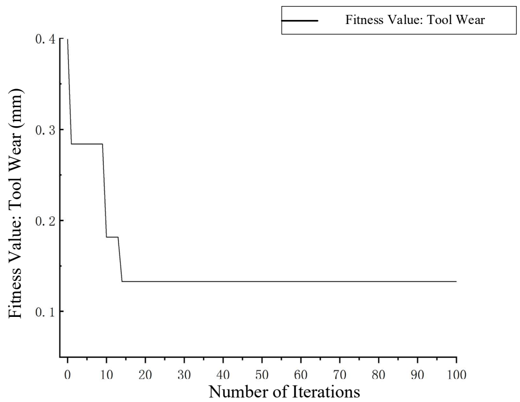

Fig.8 Fitness curve

It can be seen from Fig. 8 that the particle swarm optimization algorithm aiming at the minimum tool wear has a good convergence effect in optimizing the driving parameters. After 13 iterations, the optimal solution is basically found, and the corresponding independent variables are as follows: the cutter head torque is 2684kN·m, the total thrust is 19395kN, and the driving speed is 29mm/min. The optimal tool wear value is 0.1453mm. The comparison of the average driving parameters of the two lines from 255 to 310 rings and the number of tool changes is shown in Table 4.

Table 4. Comparison table of driving parameters and tool changing quantity

Name	Line left	Line right
Cutter torque	2945	2817
Total thrust	21847	20445
Driving speed	33	30
Number of tool changes	21	10

It can be seen from Table 4 that under the same geological conditions, the average value of excavation parameters on the right line is closer to the optimal solution, the number of tool changes is reduced by 11, and the efficiency of site construction is improved, indicating that the algorithm has a certain effect on site construction.

5. Conclusion

According to a large number of engineering practices, in the composite formation, the abnormal damage of shield tunneling tools is serious, the consumption of various tools is large, and the replacement of damaged tools needs to occupy a lot of time, seriously affecting the construction efficiency, and the tool wear can not be directly judged, but still through the feeling and construction experience. Taking the construction project of a certain section of Fuzhou Metro Binhai Express Line as an example, this paper analyzes the tool wear of each ring according to the actual excavation parameters (cutter head torque, cutter head speed, driving speed) and the situation of opening and changing the cutter, and uses regression analysis to obtain the relationship between the shield tool wear amount and cutter head torque, cutter head speed and driving speed. The multivariate nonlinear regression equation model was established to fit the tool wear per ring and compare the experimental values. The results showed that the established regression model could better predict the tool wear in this construction interval, with an average error of 0.0232mm, and the value range of tool wear was basically between 0 and 0.5mm. Because the geological condition in this area is compound geology, this influence factor is not considered. Particle swarm optimization algorithm was used to optimize the regression model and find the optimal solution of a set of driving parameters to minimize the tool wear. By comparing the driving parameters of the left and right lines with the number of tool changes, the tool wear can be reduced if the driving parameters are advanced according to the appropriate driving parameters. However, tool wear is affected by many factors, and the conclusions proposed in this paper need further demonstration and more engineering verification.

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