Optimization Control of Energy Consumption in Tunneling System of Earth Pressure Balance Shield Tunneling Machine

Xuanyu Liu*, Yao Zhang, and Kaiju Zhang

Abstract—**In order to reduce the energy consumption and improve tunneling efficiency during tunneling process of shield machine, a comprehensive optimization control method for the main tunneling control system of shield machine is proposed. According to the theory of soil mechanics and fluid mechanics, the mechanism models of shield thrust, cutter torque and screw conveyor torque are established respectively. On this basis, the work model of propulsion system, cutterhead system and slag discharge system in shield tunneling process is proposed. Based on the principle of energy conservation, a comprehensive energy consumption evaluation model of shield tunneling system is constructed. Finally, the energy consumption model is solved by fruit fly optimization algorithm (FOA), and the optimal values of thrust, propulsion speed, cutterhead speed, screw conveyor speed and screw conveyor torque are obtained. The multi-systems of shield machine are realized optimization synchronous and coordinated. The experimental results show that the proposed method has fast convergence speed and high calculation efficiency, and it can effectively reduce the energy consumption of shield machine. This method provides theoretical foundation for the tunneling control parameters setting which can effectively optimize the tunneling process and improve tunneling efficiency of shield machine.**

Index Terms—**Earth pressure balance (EPB) shield machine, tunneling system, model of energy consumption, fruit fly algorithm, optimization**

I. Introduction

SHIELD tunneling technology has developed rapidly in recent years and is widely used in underground construction. However, the system parameters adjustment generally depends on engineering experience during shield tunneling. If the experience is insufficient, it may lead to consuming too much unnecessary resources or stagnation of the project [1], and even cause serious safety accidents. Therefore, it is very important to set reasonable parameters of shield system.

A variable speed hydrostatic method to drive shield cutterhead for energy-saving was proposed in [2], and the energy consumption of each link of the whole transmission system was analyzed. A multi-system coordinated control method during construction process of shield tunneling machine is discussed [3]. Based on the field construction data, a model of propulsion decision-making system is constructed. For different geological environment, the parameters affecting the balance of excavation face are determined and optimized to reduce the energy loss. The method for predicting the load characteristics of cutterhead based on wavelet transform and gray model GM (1,1) was proposed, which can improve the working efficiency of the cutter drive system [4]. The factors affecting energy consumption during excavating through mechanical analysis of shield tunneling control system are studied [5]. “specific energy” was proposed as an index of working efficiency of shield tunneling machine, and a method for identifying and optimizing energy consumption was proposed. Then the field data of a subway project was used to carry out nonlinear multivariate regression analysis and the best cutting depth was found based on the efficiency model. The energy consumption model of the segment assembling system was established, and an optimization method of the relevant parameters was given [6]. The energy consumption of shield machine mainly comes from the cutterhead system and propulsion system, then a system model taken the work as energy consumption is established [7]. On this basis, a system model of shield tunneling efficiency was also constructed, but there was no simulation validation. For the above studies, they do not consider the influence of all control parameters and all subsystems for the energy consumption. The control effect of the energy consumption is poor.

Therefore, this paper proposes a comprehensive optimization control method to reduce energy consumption of shield tunneling system and constructs a comprehensive evaluation model for energy consumption. Through optimization of FOA, the optimal values of thrust, propulsion speed, cutting depth, cutter disk speed, burial depth, screw conveyor speed and screw conveyor torque are obtained.

II. Establishment of Energy Consumption Evaluation Model

The shield machine is mainly composed of shield shell, propulsion system, cutterhead, slag discharge system, segment assembly, grouting and rear matching vehicle system [8]. Shield tunneling control system includes hydraulic propulsion system, cutterhead cutting system, slag

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discharge system [9], which are the most energy-consuming parts. Therefore, this paper defines the energy consumption of shield machine as the sum of energy consumption of propulsion system, cutterhead system and slag discharge system. In the evaluation model, the variables of the model are the control parameters during the shield tunneling process, and output variable is the energy consumption.

$$\begin{cases} y = \min E(x) \\ E(x) = E_1 + E_2 + E_3 = T_\alpha Vt + T_\beta \omega_\beta t + T_\gamma \omega_\gamma t \end{cases} \quad (1)$$

Where $E(x)$ is energy consumption evaluation function, T_α is the thrust, V is the propulsion speed, T_β is the cutter torque, ω_β is the cutterhead speed, T_γ is the screw conveyor torque, ω_γ is the screw conveyor speed, t is the tunneling time.

A. Mathematical Model of Propulsion System Energy Consumption

In the shield tunneling process, the shield machine is taken as the research object [10], and its physical process can be expressed by the following formula:

$$T_\alpha - (F + M) = \mathrm{ma} \quad (2)$$

Where T_α is the thrust of the shield machine, F is the resistance formed in the tunneling process of shield machine and surrounding soil. M is the driving resistance generated by the frontal propulsion of shield machine, m is the weight of the shield machine, a is the accelerated speed of the shield machine.

During the construction process, in order to maintain the stability and safety of the excavation face, the propulsion speed is extremely slow, so the accelerated speed is almost non-existent, so it is considered:

$$T_\alpha = F + M \quad (3)$$

That is to say, the thrust is equal to the sum of the resistance generated by shield machine and its surroundings and the resistance required for the front cutting of shield machine.

(1) Resistance of shield machine and its surroundings during tunneling

The resistance generated by the shield machine and its surroundings includes [11-14] : friction resistance F_1 caused by shield machine and surrounding soil, resistance F_2 caused by friction between the latter part of shield machine and the segments, resistance F_3 caused by the transport of slag by the rear matching vehicle behind the shield machine, friction resistance F_4 caused by the weight of the shield machine itself. The pressure on the surface of shield machine is shown in Fig. 1.

$$F = F_1 + F_2 + F_3 + F_4 \quad (4)$$

①Friction resistance F_1 caused by shield machine and surrounding soil:

$$F_1 = \mu_1 LD[2(P_v + P_l)] \quad (5)$$

Where μ_1 is the friction coefficient between shield shell and soil, L is the length of shield machine, D is the outer diameter of shield machine, P_v is the vertical earth pressure of shield machine, P_l is the horizontal earth pressure of shield machine.

$$P_v = P_1 + P_2 \quad (6)$$

Where P_1 is the vertical earth pressure, P_2 is the vertical resistance to earth pressure.

$$P_1 = (\gamma - 10)H_f \quad (7)$$

$$P_2 = (\gamma - 10)(H_f + R_\beta) \quad (8)$$

Where γ is the unit weight of soil, H_f is the length of covering soil, R_β is the diameter of the cutterhead.

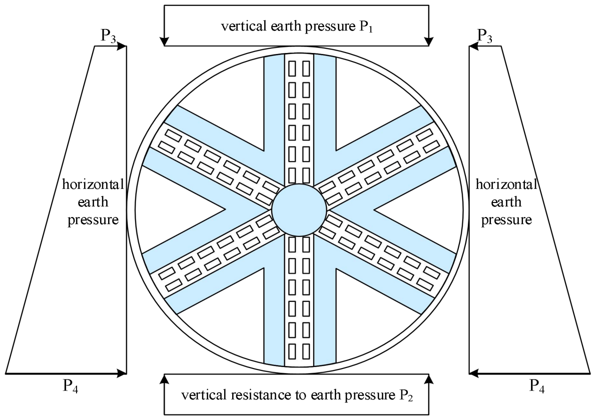

Fig. 1 Pressure on the surface of the shield machine

According to the theory of ground stress [15], the vertical earth pressure at a certain point is related to the coefficient of lateral earth pressure at that point. According to this relation, the horizontal earth pressure on the surface of the shield can be obtained as:

$$P_l = P_3 + P_4 = kP_v = k(P_1 + P_2) \quad (9)$$

Where P_3 is the lateral earth pressure at the top of the shield machine, P_4 is the lateral earth pressure at the bottom of the shield machine, k is the coefficient of lateral earth pressure.

Therefore, the frictional resistance between shield machine and surrounding soil can be obtained.

$$F_1 = 2\mu_1 LD[(\gamma - 10)(2H_f + R_\beta)(1 + k)] \quad (10)$$

②Resistance F_2 caused by friction between the back half of shield machine and the segments:

$$F_2 = \pi R_g \mu_g \quad (11)$$

Where R_g is the outer diameter of the shield segment, μ_g is the friction coefficient of per meter segment.

③Resistance F_3 caused by the slag transport of the matching vehicle behind the shield machine:

$$F_3 = G_c \mu_2 \quad (12)$$

Where G_c is the weight of the rear matching vehicle, μ_2 is the friction coefficient between the rear matching vehicle and the track.

④Friction resistance F_4 caused by the weight of the shield machine itself:

$$F_4 = \mu_1 G \quad (13)$$

Where G is the weight of shield machine.

Therefore, the resistance generated by shield machine and its surroundings is as follows:

$$F = \mu_1\{2LD[(\gamma-10)(2H_f+R_\beta)(1+k)]+G\} + \pi R_g\mu_g + G_c\mu_2 \quad (14)$$

(2) Tunneling resistance M required for frontal cutting of shield machine.

$$M = 0.125\pi R_\beta^2(P_t+P_s) \quad (15)$$

Where P_t is the frontal earth pressure of shield machine, P_s is the frontal water pressure of shield machine.

$$P_t = P_5 + P_6 \quad (16)$$

Where P_5 is the earth pressure on the upper side of shield machine, P_6 is the earth pressure on the lower side of shield machine.

$$P_s = P_7 + P_8 \quad (17)$$

Where P_7 is the water pressure on the upper side of shield machine, P_8 is the water pressure on the lower side of shield machine.

$$P_7 = 10(H_f - 1) \quad (18)$$

$$P_8 = 10(H_f - 1 + R_\beta) \quad (19)$$

Therefore, the tunneling resistance for cutting front soil of shield machine can be obtained:

$$M = 0.125\pi R_\beta^2\{k(\gamma-10)(2H_f+R_\beta)+10[2(H_f-1)+R_\beta]\} \quad (20)$$

According to the above deduction, the thrust of shield machine is as follows:

$$T_\alpha = \mu_1\{2LD[(\gamma-10)(2H_f+R_\beta)(1+k)]+G\} + \pi R_g\mu_g + G_c\mu_2 + 0.125\pi R_\beta^2\{k(\gamma-10)(2H_f+R_\beta) + 10[2(H_f-1)+R_\beta]\} \quad (21)$$

B. Mathematical model of cutterhead system energy consumption

The cutterhead torque mainly consists of six parts [14]: the torque T_1 formed by the cutterhead rotating between its front and the surrounding soil, the torque T_2 formed by the cutterhead rotating between side of cutterhead and the surrounding soil, the resistance torque T_3 caused by the soil when the cutter head rotates to cut the soil, the torque T_4 caused by the friction between the cutterhead surface and the soil, the torque T_5 caused by the weight of the cutterhead, the friction torque T_6 produced by the back of cutterhead when the cutterhead rotates, and it is as follows:

$$T_\beta = \sum_{i=1}^{6} T_i = T_1+T_2+T_3+T_4+T_5+T_6 \quad (22)$$

①The torque T_1 formed by the cutterhead rotating between its front and the surrounding soil:

$$T_1 = \pi\frac{\mu_\beta R_\beta^3 P_s(1-\varphi)}{3} \quad (23)$$

Where φ is the opening ratio of cutterhead, μ_β is the friction coefficient between the front face of cutterhead and the soil, R_β is the radius of the cutterhead, P_s is the horizontal earth pressure formed by the cutterhead rotating.

②The torque T_2 formed by the cutterhead rotating between side of cutterhead and the surrounding soil:

$$T_2 = \pi\frac{R_\beta^2(1+K_a)\mu_\beta\rho HW}{4} \quad (24)$$

Where ρ is the density of soil around the cutterhead, H is the vertical burial depth of the shield machine, W is the average length of shield machine, K_a is the active earth pressure coefficient of the surrounding soil.

③The resistance torque T_3 caused by the soil when the cutter head rotates to cut the soil:

$$T_3 = \frac{Q_1 h D_0}{2} \quad (25)$$

Where Q_1 is the compressive strength of the cutterhead, h is the cutting depth of cutterhead (the ratio of propulsion speed and cutterhead speed), D_0 is the external cutter radius of the cutterhead.

④The torque T_4 caused by the friction between the cutterhead surface and the soil:

$$T_4 = 2\pi(D_1^2+D_2^2)L_z K_i \quad (26)$$

Where K_i is the shear strength of soil, D_1 is the external diameter of the support beam of cutterhead, D_2 is the internal diameter of the support beam of cutterhead, L_z is the length of support beam of the cutterhead.

⑤The torque T_5 caused by the weight of the cutterhead:

$$T_5 = \mu_a G_\beta R_1 \quad (27)$$

Where μ_a is the friction coefficient when the cutterhead rotates, G_β is the quality of the cutterhead of shield machine, R_1 is the contact radius of the cutterhead bearing.

⑥The friction torque T_6 produced by the back of cutterhead when the cutterhead rotates:

$$T_6 = \frac{3}{5}\pi\sigma R_\beta^3\mu_\beta P_s \quad (28)$$

Where σ is the sealing ratio of cutterhead.

According to the above deduction, the cutterhead torque can be obtained as follows:

$$T_\beta = \pi[\frac{\mu_\beta R_\beta^3 P_s(1-\varphi)}{3} + \frac{R_\beta^2(1+K_a)\mu_\beta\rho HW}{4} + 2(D_1^2+D_2^2)L_z K_i + \frac{3}{5}\sigma R_\beta^3\mu_\beta P_s] + \frac{Q_1 h D_0}{2} + \mu_a G_\beta R_1 \quad (29)$$

C. Mathematical model of slag discharge system energy consumption

The torque of the screw conveyor is mainly composed of two parts [16]: the friction torque T_7 between screw conveyor shell and soil, and the torque T_8 between screw conveyor and helical blade during the process of slag discharge.

$$T_\gamma = T_7 + T_8 \quad (30)$$

①The friction torque T_7 between screw conveyor shell and soil:

$$T_7 = \lambda\pi\frac{D_l^2 - D_g^2}{4}L_a\cos\alpha f_t\frac{D_l}{2} \quad (31)$$

Where D_l is the diameter of the screw conveyor of shield machine, D_g is the diameter of the screw conveyor, α is the inclination angle of screw conveyor, L_a is the length of screw conveyor, λ is the density of soil in the screw conveyor, f_t is the friction coefficient between the shell of screw conveyor and the surrounding soil.

②The torque T_8 between screw conveyor and helical blade during the process of slag discharge:

$$T_8 = \lambda\pi \frac{D_l^2 - D_g^2}{4} L_a \cos(\alpha - \beta) f_t \frac{D_l + D_g}{4} \tag{32}$$

Where β is the spiral rising angle.

Therefore, the torque of screw conveyor is:

$$\begin{aligned} T_\gamma &= \lambda\pi \frac{\left(D_l^2 - D_g^2\right)}{4} L_a \cos\alpha f_t \frac{D_l}{2} \\ &+ \lambda\pi \frac{\left(D_l^2 - D_g^2\right)}{4} L_a \cos(\alpha - \beta) f_t \frac{\left(D_l + D_g\right)}{4} \\ &= \lambda\pi \frac{\left(D_l^2 - D_g^2\right)}{8} L_a f_t \left[\cos\alpha D_l + \cos(\alpha - \beta)\frac{\left(D_l + D_g\right)}{2}\right] \end{aligned} \tag{33}$$

In conclusion, the energy consumption evaluation model can be deduced from the theoretical derivation as follows:

$$\begin{aligned} y = \min E(x) &= T_\alpha V t + (774.96h + 39.01H \\ &+ 3279.8)\omega_\beta t + T_\gamma \omega_\gamma t \end{aligned} \tag{34}$$

$$\begin{aligned} s.t.& \\ & T_{\alpha_{\min}} \le T_\alpha \le T_{\alpha_{\max}} \\ & V_{\min} \le V \le V_{\max} \\ & \omega_{\beta_{\min}} \le \omega_\beta \le \omega_{\beta_{\max}} \\ & H_{\min} \le H \le H_{\max} \\ & h_{\min} \le h \le h_{\max} \\ & \omega_{\gamma_{\min}} \le \omega_\gamma \le \omega_{\gamma_{\max}} \\ & T_{\gamma_{\min}} \le T_\gamma \le T_{\gamma_{\max}} \end{aligned}$$

III. Fruit Fly Optimization Algorithm

Fruit fly optimization algorithm (FOA) is a global optimization algorithm proposed by professor Pan in 2011 [17]. As shown in Fig. 2, the fruit fly groups have more sensitive senses than other species. Fruit fly can catch the food's smells very quickly by its sensitive sense to smell, and then the position of the food will be found by fruit fly with its keen vision, and eventually the fruit fly groups will move towards the food. This method is a new global optimization method based on the deduction of the foraging behavior of fruit fly groups [18].

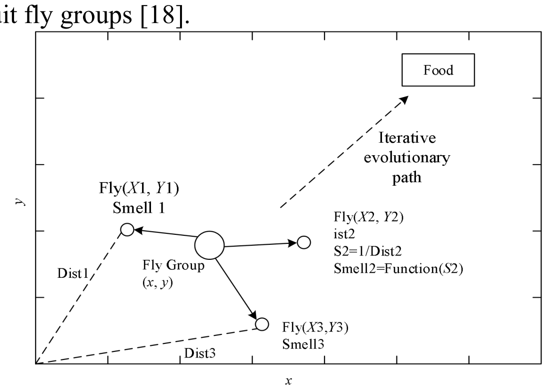

Fig. 2 The searching food diagram of fruit fly groups

The flow chart of fruit fly algorithm is shown in Fig. 3.

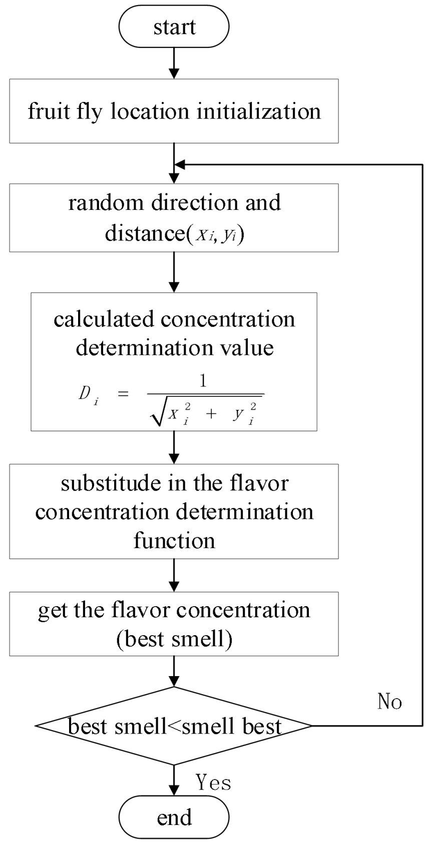

Fig. 3 Flow chart of fruit fly algorithm

IV. Simulation Test

In order to validate the effectiveness of the method proposed in this paper, the simulation experiments are carried out based on the in-site data by using Matlab. The data used in the experiment are measured from a metro construction site in Beijing. In the process of simulation, the constraint range of T_α is 14000-16000KNm, the constraint range of V is 7-10cm/min, the constraint range of ω_β is 0.3-2.2 RPM, the constraint range of H is 20-30m, the constraint range of h is 60-70mm/rev, the constraint range of ω_γ is 11-15rpm, the constraint range of T_γ is 80-100knm.

The simulation process is as follows:

(1) Parameters setting:

$$X(1) = T_\beta$$
$$X(2) = V$$
$$X(3) = \omega_\beta$$
$$X(4) = h$$
$$X(5) = H$$
$$X(6) = \omega_\gamma$$
$$X(7) = T_\gamma$$

$$Smell(i) = T_\alpha V t + (774.96h + 39.01H + 3279.8)\omega_\beta t + T_\gamma \omega_\gamma t$$

(2) Random population position, direction and distance of fruit fly $\left(X_i, Y_i\right)\left(i = 1,2\cdots\right)$.

$$X = cell(option.M,1)$$

$$X_i = 2rand(m,n) - 1$$
$$Y_i = 2rand(m,n) - 1$$

Where $rand(\cdot)$ is a random number.

(3) Calculate the judgement value of taste concentration.

$$D_i = 1 \Big/ \sqrt{X_i^2 + Y_i^2}$$

(4) The judgement value of taste concentration is correlated with the judgement function $Smell(i)$ of concentration, so the fruit fly taste concentration value can be calculated.

$$Smell(i) = fit(X\{i\}, option, data)$$

(5) After filtering, the individuals of fruit fly with the best concentration are left behind.

(6) The fruit fly begin to optimize by iteration. Repeat the above steps, and judge whether the concentration is better than the most optimal concentration in the previous iteration. If so, output; if not, the iteration continues until the optimal concentration is found.

The simulation results are as follows.

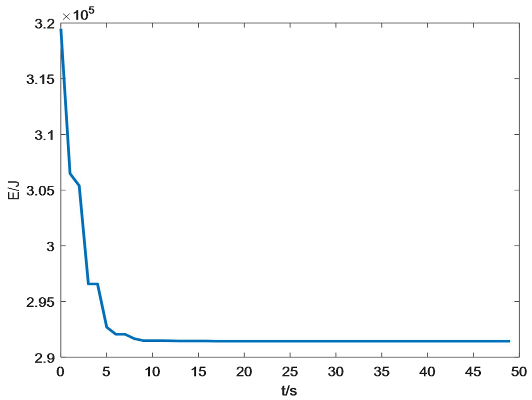

Fig. 4 Variation trend of energy consumption

As shown in Fig. 4, the energy consumption of shield machine reaches a steady state when t=8.7s, and it does not change under relatively stable geology conditions with the minimum energy consumption. The optimal values of each parameter under their respective constraints are shown in Table I at t=8.7s.

TABLE I
OPTIMAL ENERGY CONSUMPTION VALUE AND ITS OPTIMAL PARAMETER TABLES

optimal parameters	optimal value
energy consumption(J)	2.92×10^5
thrust(KN)	14800
propulsion speed(cm/min)	7.31
cutter speed(rpm)	0.42
cutting depth(mm/rev)	60.89
vertical cover(m)	23.93
screw conveyor speed(rpm)	11.93
screw conveyor torque(KNm)	97.78

In the process of energy optimization of shield machine, the influence of each parameter on energy consumption is different. The sensitivity of each energy consumption parameter is illustrated by its convergence. The results are presented in Fig. 5- Fig. 9.

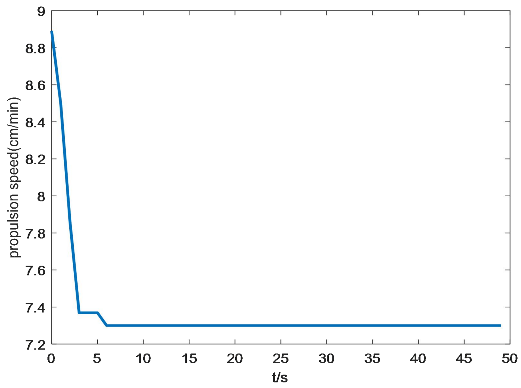

Fig. 5 Propulsion speed variation curve

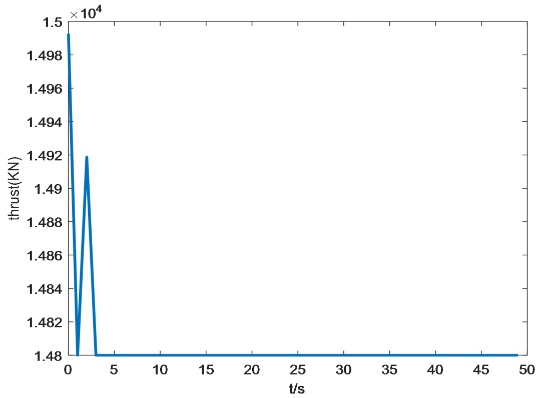

Fig. 6 Thrust variation curve

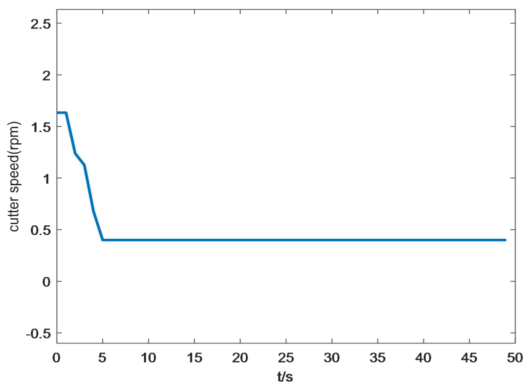

Fig. 7 Cutterhead speed variation curve

From Fig. 5, it can be seen that the propulsion speed reaches equilibrium when t=5.8s. Fig. 6 shows that the thrust reaches equilibrium when t=3.2s, and fluctuates greatly in the convergence process, but the balance time is very short. Fig. 7 shows the cutterhead speed reaches equilibrium at t=5.1s. The time when the three parameters reach equilibrium is less than the convergence time of the system which is at 8.7s. The simulation results show that the three parameters of thrust, propulsion speed and cutter speed have better optimization effect and reduce the energy consumption of the system.

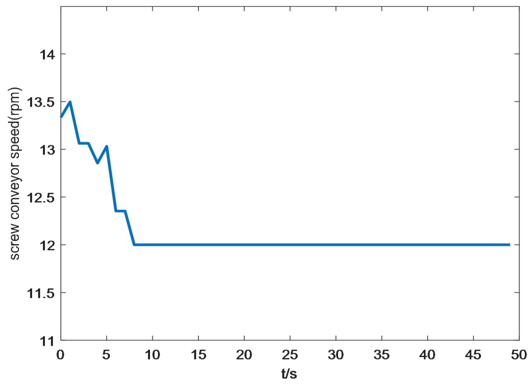

Fig. 8 Screw conveyor speed variation curve

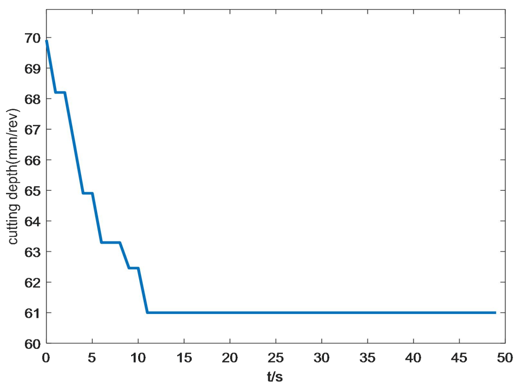

Fig. 9 Cutting depth variation curve

Fig. 8 shows that the screw conveyor speed reaches a convergence equilibrium at time t=9.1s. Fig. 9 shows that cutting depth of the cutterhead reaches the convergence equilibrium when t=10.8s. The time when these two parameters reach equilibrium is slightly less than the convergence time of the system with small fluctuation. It shows that the screw conveyor speed and the cutting depth of the cutterhead consume less energy in the process of optimizing the energy consumption of shield tunneling system, and the parameters can be well controlled in the construction process.

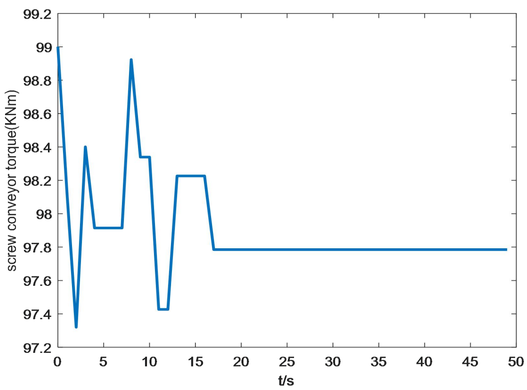

Fig. 10 Screw conveyor torque variation curve

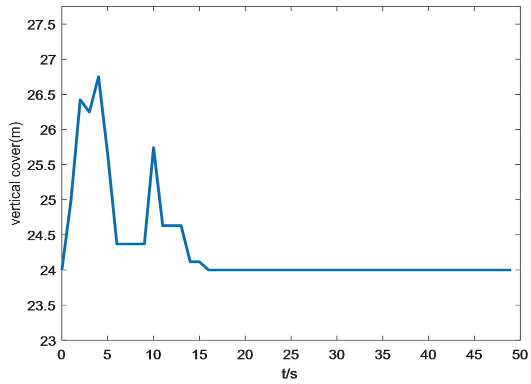

Fig. 11 vertical cover depth variation curve

Fig. 10 shows that the screw conveyor torque is always in a turbulent state in the process of optimization and reaches equilibrium state at time t=17.1s. Fig. 11 shows vertical cover also fluctuates greatly in the process of optimization, and a transient equilibrium state appears around 6s, and finally reaches a convergence equilibrium when t=16.7s. The convergence time of these two parameters is long, which indicates that screw conveyor torque and vertical cover are the two parameters that have the greatest influence on the energy consumption of the system. Therefore, in the shield construction process, these two parameters must be monitored in real time, so as to adjust and control the parameters in the first time in response to the changes of geological conditions.

In order to further verify the effectiveness of the proposed method, the optimization results of energy consumption are compared with those by adaptive particle swarm optimization (APSO) and adaptive genetic algorithm (AGA). The parameters setting are shown in Table II.

TABLE II
PARAMETERS SETTING

maximum number of iterations	50
population number	24
APSO learning Factor 1	1
APSO learning Factor 2	1
APSO maximum Weight	1.2
APSO minimum Weight	0.5
adaptive GA crossover probability coefficient 1	0.8
adaptive GA crossover probability coefficient 2	0.2
adaptive GA mutation probability coefficient 1	0.3
adaptive GA mutation probability coefficient 2	0.01
weight APSO	0.5

The simulation results are as follows in Fig. 12.

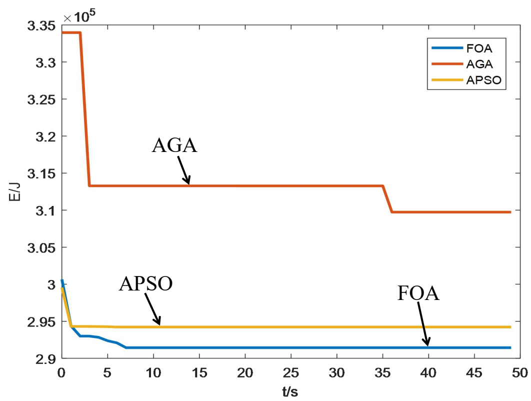

Fig. 12 Comparison results of three algorithms

By comparison, it can be seen from Fig. 12 that the convergence and optimization ability of FOA algorithm are better than APSO algorithm and AGA algorithm. Among them, AGA algorithm has poor convergence ability and gradually balances around t=36s. APSO algorithm has fast convergence speed, but it does not find the real optimal value of energy consumption.

In order to test the effect of the proposed optimal method, the data at 50 sampling times in one ring segment of the shield tunnel were collected and they were used to compute the optimal energy consumption. The optimization results are shown in Fig.13 and their percentage errors to the actual energy consumption values are shown in Fig.14. From Fig.13, it can be seen that the trends and values of the optimized energy are closed to the actual values of shield machine, which indicates that the optimization results well conform to the actual working condition of shield machine. The percentage errors are smaller which are less than 6.31%. So, this method has high calculation precision. For the larger calculation error, it may be that the geological condition or working condition has been changed but the control parameters have not been adjusted in time. For example, when the shield machine tunnels in non horizontal status (updip or downdip), the energy consumption will be higher. At this point, we should check the running status of the key components. Especially, when the soil is harder and the pose of shield machine is changed, the energy consumption will be greater.

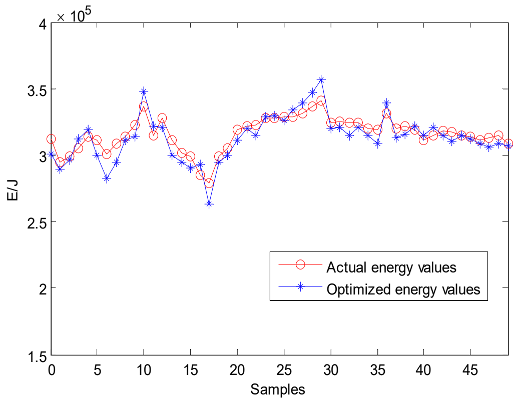

Fig. 13 Comparison of the optimized energy values and actual energy values

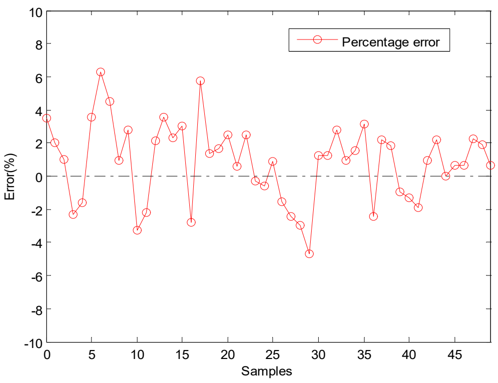

Fig. 14 Percentage errors of the optimized energy values

During the simulation, it is found that the energy consumption has relationship to the burial depth of the shield machine and the cutting depth per revolution of cutterhead. The relationship between the energy consumption and the cutting depth per revolution under different burial depth is shown in Fig. 15. From Fig. 15, we can see that the energy consumption at 25 m burial depth is greater than that at 15 m burial depth. At the beginning of tunneling, the cutting depth is small but the energy consumption is greater. With the increase of cutting depth, the energy consumption decreases gradually until it reaches the minimum value, and at this point the tunneling efficiency is the highest which means that the adaption of control parameters and geology is best. The optimal range of the cutting depth is about 40-65 mm/rev for the energy consumption under different burial depth, which can guide the actual engineering practice with high efficiency. When the cutting depth is smaller or bigger, the tunneling control parameters (including cutterhead speed and propulsion speed) must be adjusted to reduce energy consumption. Therefore, from the energy consumption and efficiency point, the change of cutting depth should be monitored strictly.

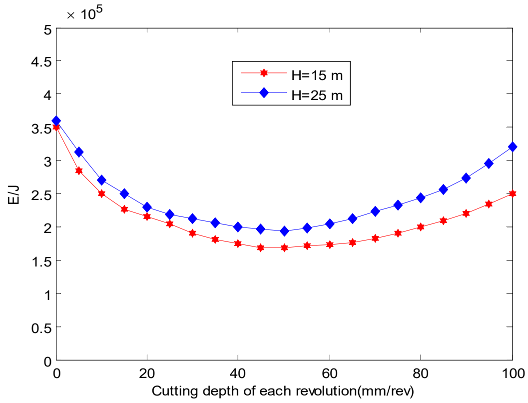

Fig. 15 Energy change for different cutting depth of each revolution under different burial depth

V. Conclusion

Based on the principle of energy conservation, a comprehensive energy consumption evaluation model of shield tunneling system is constructed. A synthesis optimization control method for the main tunneling control system of shield machine is proposed. Based on the field data of a subway construction site in Beijing, the simulation experiments are carried out, and the conclusions are obtained as follows:

(1) The parameters such as thrust, propulsion speed, cutterhead speed, screw conveyor speed, screw conveyor torque can be optimized simultaneously and coordinated. The results indicate that the convergence and the calculation efficiency of the proposed method are obviously better than other algorithms. It can more effectively reduce the energy consumption of shield machine and improve the tunneling efficiency.

(2) In the process of system optimization, the convergence and sensitivity of each parameter are different. Among them, the convergence effect of thrust, cutter speed, propulsion speed, screw conveyor speed and cutting depth of shield machine are very good. However, the convergence time of the screw conveyor torque and vertical cover depth is long and the fluctuation is large. Therefore, the comprehensive evaluation model of energy consumption of shield tunneling system has important reference value for setting construction parameters.

(3) The energy consumption has relationship to the burial depth and cutting depth per revolution of cutterhead. The deeper of the burial depth is, the more energy the shield machine consume. In addition, the optimal range of the cutting depth is about 40-65 mm/rev for the energy consumption under different burial depth, and the construction efficiency is higher in the mean time. It has great guiding significance to the actual tunnel construction engineering. Therefore, the method can be used as an evaluation method of the tunneling control parameters adjustment. The parameters can be adjusted and optimized according to the energy consumption level during shield tunneling process.

(4) From the engineering risk perspective, the cutterhead speed and propulsion speed must be controlled well. For there is great possibility that the cutting depth will change, which means that the engineering will face greater risk of the tunneling efficiency fluctuation.

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