Data-driven Optimal Control of Earth Pressure Balance for Shield Tunneling Machine

Xuanyu Liu*, Congyi Zhou, Yudong Wang, and Qiumei Cong

Abstract—**It is easy to cause safety accidents due to the low precision and poor effect of earth pressure balance (EPB) control during shield machine tunneling process at present. So a data-driven optimization control method for earth pressure balance in sealed cabin of shield machine is proposed. Firstly, the earth pressure prediction model of four pressure monitoring points in the sealed cabin is established by using least squares support vector machine (LSSVM) method, and the penalty coefficient C and kernel parameters σ are optimized by particle swarm optimization (PSO). Then, an optimization function is established with the minimum sum of multi-point earth pressure prediction errors as the target. The optimal solution is obtained by using the fruit fly optimization algorithm (FOA) to solve the optimal screw conveyor speed, so as to realize the balance control of the earth pressure in sealed cabin. Finally, the simulation experiments are carried out based on field construction data. The results show that the method has great performance such as higher accuracy of calculation and better control effect, which can control the excavation face of shield machine more steady.**

Index Terms—**Shield machine, earth pressure balance, least squares support vector machine, optimal control**

I. INTRODUCTION

Shield machine is a specialized machine for tunnel excavating in underground construction. Modern shield machine integrates with machinery, electricity, hydraulic, sensing and information technology, and has the functions of cutting soil, transporting soil slag, assembling tunnel lining, measuring, guiding and rectifying deviation [1]. Earth pressure balance control in sealed cabin is one of the most critical technologies in shield machine technology [2]. The existing control methods of earth pressure balance is mainly to adjust the propulsion speed or the screw conveyor rotation speed by shield operator based on experience, so the precision and efficiency is low [3]. Some scholars have studied on the automatic control of earth pressure balance in sealed cabin. Shangguan and Li [4] established a differential model of pressure of the cabin, and the model parameters of shield earth pressure balance control system were determined by genetic algorithm. Liu et al. [5] proposed a predictive control strategy for the earth pressure balance during excavation. The least square support vector machine is used to establish the earth pressure predictive model with the propulsion speed and screw conveyor speed as control parameters. Fu et al. [6] proposed the correction coefficient of soil properties and curve for the pressure of the sealed cabin. Song et al. [7] proposed an improved predictive control method based on multivariable non-minimum phase state space model for multi-point earth pressure balance of sealed cabin. Liu and Shao [8] established the earth pressure prediction model of multiple monitoring points in the sealed cabin based on the data-driven method. Liu et al. [9] established the pressure field distribution model of the cabin by using the least square method, and the earth pressure balance control model was proposed with equivalent pressure as the control target. However, the pressure in the sealed chamber is affected by many control parameters such as thrust, propulsion speed and screw conveyor speed. Therefore, it is very necessary to predict the earth pressure based on the massive construction data monitored, so as to optimize and adjust the tunneling control parameters in real time.

Therefore, a data-driven optimal control method for earth pressure balance is proposed in this paper. Considering the influence of propulsion speed, total thrust force of shield machine, cutter head torque and current screw conveyor speed on the earth pressure of sealed cabin, the earth pressure prediction model is established by least squares support vector machine and particle swarm optimization algorithm. The minimum sum of deviation between the predicted value and the set value of the earth pressure is taken as the objective function, which is solved by FOA and the optimal screw conveyor rotation speed is obtained. In this way, the earth pressure balance of the sealed cabin is controlled in real time to ensure the stability of the excavation face.

II. CONTROL MECHANISM OF EARTH PRESSURE BALANCE OF SHIELD MACHINE

The EPB shield controls the earth pressure in the sealed cabin balance with water and earth pressure on excavated face by adjusting the amount of soil discharged and cut [10]. The front soil is cut into the sealed cabin by the cutter head and then sent to the shield tail by the screw conveyor to maintain the pressure balance in the sealed cabin [11]. The earth pressure balance control mechanism is shown in Fig. 1.

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In Fig. 1, P_{w} is water pressure, P_{e} is earth pressure in front of the cutter head, P_{m} is the earth pressure in the sealed cabin and h is the buried depth of the tunnel. In general, several pressure observation points are distributed on the pressure-bearing diaphragm of the sealed cabin, which are used for monitoring the change of earth pressure in the shield tunneling process in real time, so as to adjust the parameters to control the pressure balance of the sealed cabin.

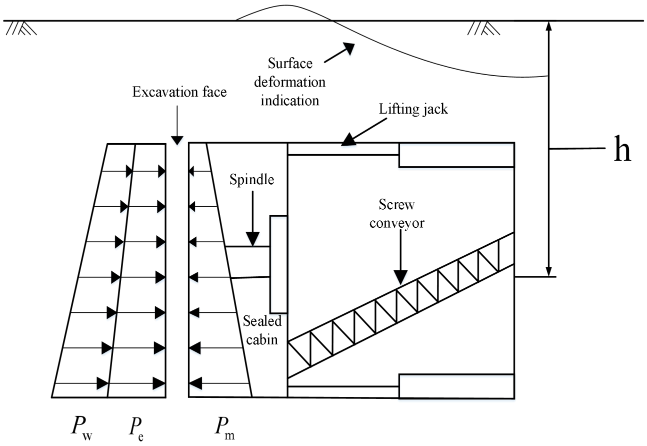


Fig. 1 Control mechanism of earth pressure balance of shield machine

The construction of a bid section of Beijing subway line No. 10 is taken as an example to carry out the research in this paper. The data used in the subsequent simulation experiments are all collected from the shield tunneling process of this project, aiming at solving the optimal control problem of earth pressure balance in the construction process.

The shield machine used in this project is an EPB shield machine whose diameter is 6.25 m. There are four earth pressure monitoring points p_1 , p_2 , p_3 and p_4 on the pressure-bearing diaphragm, which are located 0.9 m from the circumference in the horizontal and vertical directions. The left side, right side, upper side and lower side respectively correspond to p_1 , p_2 , p_3 and p_4 , and their positions are shown in Fig. 2.

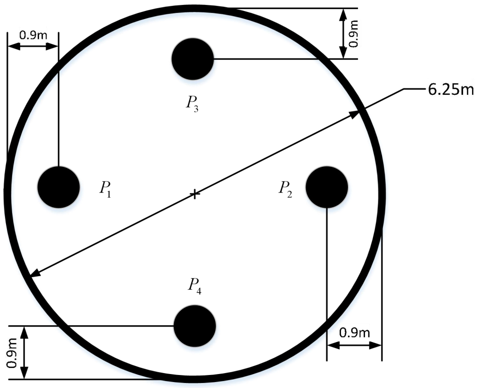


Fig. 2 Distribution diagram of the four pressure monitoring points on diaphragm

III. PREDICTION OF EARTH PRESSURE IN SEALED CABIN BASED ON LSSVM

A. Relationship Between Parameters and Earth Pressure of Sealed Cabin

According to the actual construction experience and research, the earth pressure of the sealed cabin is related to the factors such as screw conveyor rotation speed, propulsion speed, thrust force, cutter head torque and so on [12]. The relationship between the earth pressure of sealed cabin and the propulsion speed and rotation speed of the screw conveyor is as follows:

$$\frac{\pi D^2}{4} v_1 dt - \frac{K_e \eta A d n \gamma_1}{\gamma_2} dt = c_{ep}\left(p_e - p_0\right) + \frac{V_e}{\beta_e}\frac{dp_e}{dt} \quad (1)$$

where D is the tunnel diameter, v_1 is the propulsion speed, dt is the time for digging the distance dS , Q is the amount of soil discharged, η is soil removal efficiency, A is the effective sectional area of the screw conveyor, d is the pitch between spiral blades, n is the rotation speed of the screw conveyor, γ_1 is the weight of soil after adding materials, c_{ep} is the leakage coefficient outside the sealed cabin, p_e is the earth pressure in the sealed chamber, p_0 is the leakage pressure outside the sealed cabin, V_e is the volume of the sealed cabin, β_e is the effective compression coefficient of soil, liquid and gas in the sealed cabin.

The relationship between earth pressure of the sealed cabin and thrust force is as follows:

$$P_e = \frac{4}{\pi D^2}(F - f) - \delta(1 - \lambda) \quad (2)$$

where F is the total thrust force provided by the propulsion cylinder of the shield machine, f is the total resistance during advancing process, λ is the cutter head opening rate, δ is the additional value of panel earth pressure greater than earth pressure of sealed cabin.

The relationship between the earth pressure of the sealed cabin and the cutter head torque is as follows:

$$M = k_c n P_e \quad (3)$$

where M is the cutter head torque, k_c is parameter related to cutter head form and soil mass.

Therefore, the influences of the screw conveyor rotation speed, propulsion speed, thrust force, cutter head torque on the earth pressure of the sealed cabin are comprehensively considered in establishing the earth pressure prediction model by LSSVM. The above factors are selected as input of the earth pressure prediction model, and the earth pressure at the next moment is selected as output, so as to further implement the earth pressure balance control.

B. Establishment of Prediction Model

LSSVM transforms inequality constraints in SVM into equality constraints, thus transforms nonlinear problems into linear equations for solution [13]. The following minimal optimization model is usually used in LSSVM to determine the regression function:

$$\min J(\omega,\xi)=\frac{1}{2}\omega^T\omega+\frac{1}{2}C\sum_{i=1}^{l}\xi_i^2 \qquad (4)$$
$$s.t. y_i[\omega\cdot\varphi(x_i)+b]=1-\xi_i\xi_i\geq 0, i=1,2,\cdots,l$$

where ξ is relaxation factor, C is the penalty factor, which is used to indicate the penalty degree for samples beyond the error range.

The LSSVM regression function is obtained by deducing:

$$f(x)=\sum_{i=1}^{l}a_iK(x_i,x)+b \qquad (5)$$

where $K(x_i,x)$ is the RBF kernel function, and it is expressed as follows:

$$K(x_i,x_j)=\exp\left(-\frac{\left\|x_i-x_j\right\|^2}{2\sigma^2}\right)=\exp\left(-g\left\|x_i-x_j\right\|^2\right), g>0 \qquad (6)$$

In this paper, the screw conveyor rotation speed needs to be optimized for the earth pressure balance. So the screw conveyor rotation speed at the next moment is also taken as the input variable of the prediction model to play a regulating role in the following control process. All input variables of the model are propulsion speed $V(t)$, total thrust force $F(t)$, cutter head torque $M(t)$, screw conveyor rotation speed at the current moment $n(t)$, screw conveyor rotation speed at the next moment $N(t+1)$, earth pressure of sealed cabin at the current moment $p(t)$, and the output of the model is earth pressure at the next moment $P(t+1)$. Therefore, the prediction model is as follows:

$$P(t+1)=f\left(V(t),F(t),M(t),n(t),N(t+1),p(t)\right) \qquad (7)$$

The LSSVM structure diagram is shown in Fig. 3.

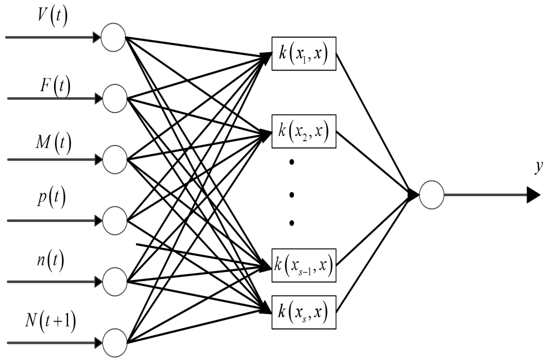


Fig. 3 LSSVM structure diagram

C. Parameters Optimization of LSSVM Prediction Model Based on PSO

The penalty coefficient C and kernel parameter σ of LSSVM are of great significance in the operation process of support vector machine. If C is too large or too small, it will make its generalization ability worse. The larger the penalty coefficient C, the easier the overfitting. The smaller the penalty coefficient C, the easier the underfitting. σ determines the distribution of data after mapping to the new feature space, which affects the speed of training and prediction of the model. Therefore, the PSO algorithm is introduced to determine the optimal values of the above two key parameters to ensure the prediction accuracy of the LSSVM model.

PSO algorithm has the advantages of fast convergence speed, high precision and no influence by model structure. This method can effectively optimize the kernel parameter and penalty coefficient of the LSSVM with smaller training errors. Therefore, this method has good effect on improving the prediction accuracy and computational efficiency of LSSVM. The basic principle of PSO is that in a D-dimensional search space, n particles will search for the optimal solution. In each iteration process, the particles will update their speeds and position through the particle individual optimal value $pBest$ and the population global optimal value $gBest$ [14], [15]. The updated formula is:

$$V_{id}=\omega V_{id}+C_1 random(0,1)(P_{id}-X_{id}) + C_2 random(0,1)(P_{gd}-X_{id}) \qquad (8)$$

$$X_{id}=X_{id}+V_{id} \qquad (9)$$

where ω is inertia weight coefficient, C_1 and C_2 are acceleration constants, $random(0,1)$ represents a random number between 0 and 1.

Input the experimental data into LSSVM model for learning, and calculate the fitness of each particle according to the following formula:

$$fit=\sum_{i=1}^{m}\left(y_i-\hat{y}_i\right)^2 \qquad (10)$$

where y_i and $\hat{y}_i$ are the actual earth pressure and predicted value of the ith sample respectively, and m is the number of samples.

The flow chart for optimizing the penalty coefficient C and kernel parameter σ of LSSVM based on PSO algorithm is shown in Fig. 4, which shows the operation flow and the parameter optimization process of the prediction model.

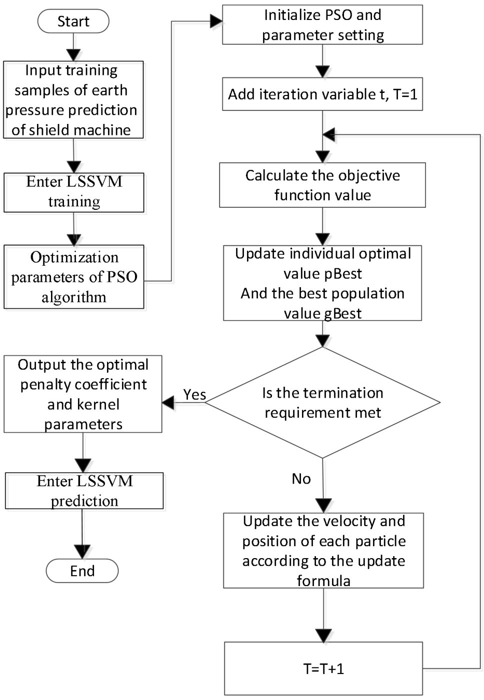


Fig. 4 Schematic diagram for optimizing LSSVM parameters by PSO

IV. SCREW CONVEYOR ROTATION SPEED OPTIMIZATION BASED ON FOA

In the process of shield tunneling, the earth pressure balance control is mainly realized by adjusting the screw conveyor rotation speed. Based on the earth pressure prediction model of the sealed cabin, the minimum sum of deviation between the predicted values and the set values of the earth pressure is taken as the objective function, which is solved by FOA. The optimal screw conveyor rotation speed is obtained and fed back to the hydraulic drive system to control the earth pressure balance of the sealed cabin.

A. Fruit Fly Optimization Algorithm

The fruit fly optimization algorithm is a new swarm intelligence optimization algorithm based on the bionics principle of fruit fly foraging behavior. The algorithm simulates the process of fruit fly predation with keen sense of smell and vision, and realizes the group iterative search of solution space [16]. Fig. 5 shows a brief process of fruit fly colony searching for food [17].

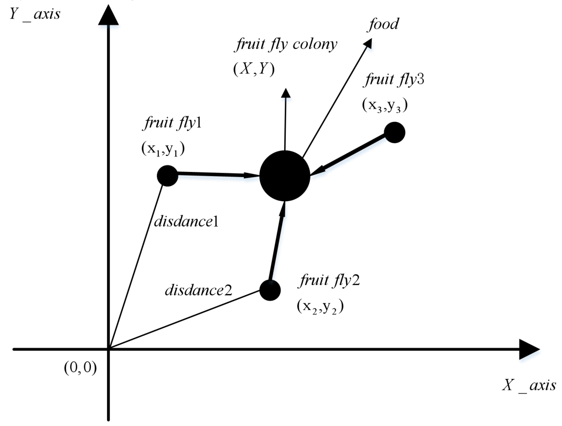


Fig. 5 FOA algorithm diagram

FOA has strong global optimization ability, less computation and lower algorithm complexity [18]. It can quickly optimize tunneling parameters during shield tunneling and ensure timely adjustment of the screw conveyor speed. So, this method can improve tunneling efficiency and ensure construction safety.

B. Optimization of Screw Conveyor Rotation Speed

In order to obtain the optimal screw conveyor speed, FOA is used to solve the optimization function. In the optimization process, P_i is the predicted value of the ith point in the prediction model, which is obtained from the above earth pressure prediction model. p_0 is 0.15 MPa which is the set value of the earth pressure at four points. $n_{\max}$ and $n_{\min}$ are the maximum and minimum of screw conveyor speed respectively, which are in the range of 0-22 rpm. The optimization function takes the minimum sum of deviation between the predicted value and the set value of the earth pressure at four points as the objective function. The optimization function is as follows:

$$\begin{gathered}\min\sum_{i=1}^{4}\left|P_{\mathrm{i}}(\mathrm{t}+1)-p_0\right| \\ s.t.\ n_{\min}\le N(t+1)\le n_{\max}\end{gathered} \tag{11}$$

The specific steps of the algorithm are as follows:

(1) At the beginning of the algorithm, the number of iteration times $mangen$, population size $popsize$ and initial position x_axis , y_axis are initialized.

(2) Based on the prediction model of the earth pressure in sealed cabin, the earth pressure values at the next moment $P(t+1)$ at four pressure monitoring points in the cabin are calculated.

(3) Give fruit fly population random directions and distances for foraging. The selection of the random distance is usually determined according to the initial coordinates and is generally calculated as follows:

$$X_i = x\_axis + random() \tag{12}$$

$$Y_i = y\_axis + random() \tag{13}$$

where i is the number of fruit flies, $random()$ is random search direction.

(4) According to the individual position of fruit fly, the judgment value of taste concentration is calculated according to the following formula:

$$D\mathrm{ist}_i = \sqrt{X_i^2 + Y_i^2} \tag{14}$$

$$S_i = 1 / D\mathrm{ist}_i \tag{15}$$

where $D\mathrm{ist}_i$ is the distance between the individual and the origin, S_i is the judgment value of taste concentration.

(5) Calculate and update the optimal taste concentration value of fruit flies and the optimal individual coordinates, and continue iteration.

(6) Stop searching when the iteration times meets the termination condition, and output the optimal screw conveyor rotation speed, otherwise return to the step (3).

V. EXPERIMENTS AND RESULTS ANALYSIS

A. Analysis of Prediction Results

In order to verify the validity and feasibility of the prediction model, 1100 groups of data from an underground tunnel construction site in Beijing are used for analysis in this paper. The first 1000 groups of data are used for training, and the last 100 groups of data are used as test data to verify the feasibility of the method. The collected parameters mainly include the earth pressure values monitored by the four pressure sensors on the pressure-bearing plate, total thrust force of the shield machine, cutter head torque, propulsion speed, screw conveyor rotation speed, the set value of earth pressure. The computer configuration used in this experiment is MSI GP62MVR 7RFX, Intel (R) Core (TM) i7-7700HQ CPU @ 2.80GHz.

The population size of the particle swarm is set at 30, with the maximum number of allowed iterations being 300. The acceleration factors are set as c_1=c_2=0.15. The velocity and position of the initial particle is assigned randomly, and the specified accuracy is 0.05. Then, the kernel parameters σ and penalty factor C of LSSVM start to be optimized. After optimization, the parameters are determined as σ=1.6 and C=366.1719 . The earth pressure prediction results of

p_1, p_2, p_3, p_4 are shown in Fig. 6. In order to verify the effectiveness of the method, the prediction results are compared with those of BP neural network, GA-BP and LSSVM in the same time. The quantitative comparison results of error are shown in Table I.

In Fig. 6, the solid line is the actual earth pressure value, the plus dot dash line is the LSSVM prediction result, the asterisk dot dash line is the PSO-LSSVM prediction result, the dot dash line is the BP neural network prediction result and the circle dash line is the GA-BP neural network prediction result. As can be seen from the figures, only the PSO-LSSVM method in this paper can well predict the earth pressure at four points of p_1, p_2, p_3, p_4, which is the closest to the actual value with the best prediction effect. The average prediction error of each point is between 1.22% to 1.99%, which indicates that the model proposed has high prediction accuracy. The excessive individual errors may be caused by the sudden changes of working conditions, which are normal working conditions.

TABLE I
COMPARISON OF PREDICTION ERRORS OF THE FOUR METHODS

	Upper	Lower	Left	Right
BP	3.40%	5.8%	7.38%	18.84%
GA-BP	2.40%	2.46%	3.56%	10.15%
LSSVM	3.44%	6.41%	4.72%	4.88%
PSO-LSSVM	1.22%	1.99%	1.73%	1.76%

As can also be seen from Table I, the earth pressure prediction errors of the PSO-LSSVM method for the four monitoring points are smaller than that of the other three methods. Compared with LSSVM algorithm, the prediction accuracy of LSSVM optimized by PSO algorithm is greatly improved. The average error of the four points is reduced from 4.86% to 1.675%, which has a good correction effect on the original error. It shows that PSO algorithm has a good effect on screening appropriate penalty factor and kernel parameter values. To sum up, PSO-LSSVM algorithm can accurately predict the change of earth pressure during shield tunneling.

B. Optimization Results Analysis

In this paper, 100 groups of test data are used in the experimental verification. First of all, the fruit fly optimization algorithm is initialized. Its population size is set at 20, and the maximum number of iterations is set at 300. The position of the initial population is randomly set, and the direction and distance of the population for searching food are randomly set. The minimum and maximum screw conveyor speeds are 0 and 22 rpm respectively. The earth pressure set values of the four points at the upper, lower, left and right part are all p_0=0.15 Mpa. Then, the objective function is optimized by FOA. Fig. 7 shows the operation process of FOA. Fig. 8 shows the comparison between the corresponding optimized screw conveyor speed and the non-optimized screw conveyor speed.

As can be seen from Fig. 7, the FOA can quickly optimize the objective function and effectively find the optimal value of the screw conveyor speed. Fig. 8 shows the optimization results of screw conveyor speed by FOA, which is approximately close to the actual value. For the sample points between the 20th and 30th, a large fluctuation of earth pressure was detected, but the actual screw conveyor speed can hardly be changed immediately during the tunneling process. So the earth pressure can't be adjusted at the moment. However, the optimized screw conveyor speed was adjusted in time to ensure the earth pressure balance in sealed cabin. Fig. 9 shows the comparison between the actual earth pressure values and those of PSO-LSSVM, BP and GA-BP.

From Fig. 9 it can be seen that the earth pressure values optimized by PSO-LSSVM are closer to the actual values than other methods. After calculation, the mean square deviation of the earth pressure values output by PSO-LSSVM is 0.068, which is better than that of the manual control mode of 0.085. Due to the low computational complexity of FOA, the calculation time of the whole prediction and optimization process is controlled at about 30 s. This method provides sufficient time for the operation control of shield tunneling. In addition, the method can better control the earth pressure of the four monitoring points around the set value in the tunneling process. So, this method can maintain the excavation face stable in the whole tunneling process and ensure the construction safety. Table II shows the quantitative comparison results of the overall performance of the three methods.

TABLE II
COMPARISON OF OPTIMIZATION RESULTS OF THE THREE METHODS

	Run time (s)	Mean square deviation	Deviation from set value (%)	Prediction error (%)
PSO-LSSVM	30	0.068	17	1.675
BP	18	0.0865	24.3	8.8
GA-BP	40	0.07	19.2	4.575

Table II shows the comparison results of PSO-LSSVM, BP neural network and GA-BP method for the four optimization indexes. Compared with other two methods, PSO-LSSVM has lower mean square deviation and prediction error, which shows that this method has better control effect on earth pressure. At the same time, on the premise of ensuring the prediction accuracy and optimization effect, this method has a shorter run time, which is about 10 s shorter than GA-BP algorithm. However, the traditional BP neural network takes less time, but the error is too large compared with the other two methods to achieve good control results in actual projects. So, it can be seen that only PSO-LSSVM can control the earth pressure balance of sealed cabin with shorter operation time by adjusting the optimal screw conveyor speed. To sum up, the method in this paper can play a good role in controlling earth pressure balance during shield tunneling.

In conclusion, PSO-LSSVM algorithm can accurately predict the change of earth pressure during shield tunneling, which benefits from the good effect of PSO algorithm on optimizing the penalty factors and kernel parameter of LSSVM. It lays a good foundation for establishing the optimization function of the earth pressure. Due to the low computational complexity of FOA, the calculation time of the whole optimization process for the control parameters is controlled at about 30 s, which provides sufficient time for the operation control of shield tunneling. In addition, this method can better control earth pressure balance in sealed cabin during shield tunneling process. In brief, this method has good theoretical significance and important engineering guiding value.

VI. CONCLUSION

An optimal control method based on data-driven is proposed for earth pressure balance control of sealed cabin during shield machine tunneling. The validity of the method is verified by the simulation experiments using the field construction data, and the following conclusions are obtained:

(1) This method has high calculation and prediction precision. The average prediction error is about 1.675%, which has significant advantages over other prediction methods. It can accurately predict the change of multi-point earth pressure in the sealed cabin to control the stability of the excavation face, and has important engineering guiding significance for shield construction. It lays a good foundation for the optimization of screw conveyor speed.

(2) The experimental results show that PSO algorithm has good effect on optimizing the parameters C and σ of LSSVM, and significantly improves the prediction accuracy. In this paper, FOA is introduced to optimize the screw conveyor speed, which makes the earth pressure in sealed cabin more stable and better controlled around the set value. It can effectively maintain the earth pressure balance. The method also greatly shortens the time needed for optimization and improves the optimization efficiency.

(3) This optimal control method of earth pressure balance based on construction data can truly and accurately reflect the dynamic changes of shield machine working conditions. It can also present the changed characteristics of the pressure in sealed cabin, so as to optimize and adjust the tunneling parameters in real time. In this way, the stability of the excavation face is finally ensured. This method can effectively avoid the ground surface uplift or collapse accidents, so as to ensure the safety of shield tunnel construction engineering.

REFERENCES

[1] M. S. Wang, “Current status, existing problems and development ideas of shield and roadheader tunneling technology in China,” Tunnel Construction, vol. 34, no. 3, pp. 179-187, 2014.

[2] X. Y. Liu, C. Shao and M. Li , “Comprehensive optimal control of earth pressure balance in shield machine capsule,” Journal of Dalian University of Technology, vol. 53, no. 3, pp. 447-454, 2013.

[3] T. H. Zhang, “Research on earth chamber pressure control technology of earth pressure balance shield,” Railway Standard Design no. 8, pp. 83-85, 2005.

[4] Z. C. Shangguan and S. J. Li, “Identification procedure for model parameter of earth pressure balance system of shield using genetic algorithm,” In: Proceedings of the 2014 International Conference on Mechatronics, Electronic, Industrial and Control Engineering, Shenyang, China, pp. 488-491, 2014.

[5] X. Y. Liu, C. Shao, and H. F. Ma, et al, “Optimal earth pressure balance control for shield tunneling based on LS-SVM and PSO,” Automation in Construction , vol. 20, no. 4, pp. 321- 327, 2011.

[6] L. L. Fu, X. L. Li, and S. H. Zhou, et al., “Setting method of earth chamber pressure of earth pressure balance shield machine and back analysis of in-situ measurement,” China Railway Science, vol. 36, no.5, pp. 68-74, 2015.

[7] Y. L. Song, X. Y. Liu, and K. J. Zhang, et al., “Application of IMNMSSPC algorithm in earth pressure balance control of shield machine,” Computer Engineering and Application, vol. 53, no. 4, pp. 251-255, 2017.

[8] X. Y. Liu and C. Shao, “Modeling and simulation of shield earth pressure balance control based on sealed chamber pressure field,” Journal of China Coal Society, vol. 37, no. 5, pp. 725-730, 2012.

[9] X. Y. Liu, K. J. Zhang and C. Shao, “Prediction of earth pressure in sealed chamber of shield machine based on data drive,” Journal of China Coal Science, vol. 44, no. 9, pp. 2898-2904, 2019.

[10] Y. L. He, “Working principle of tunneling control system of EPB shield machine,” Mining Machinery, no. 2, pp. 22-24, 2006.

[11] H. Shi, G. F. Gong, and H. Y. Yang, et al., “Earth pressure balance control model for shield tunneling,” Journal of China Coal Science, vol. 33, no. 3, pp. 105-108, 2008.

[12] H. X. Wang, and D. M. Fu, “Study on the mathematical and physical model of EPB shield tunneling and the relationship between parameters,” China Civil Engineering Journal, no. 9, pp. 86-90, 2006.

[13] Y. S. Huang, and L. J. Zhang, “Study on short-term electricity price forecast based on genetic algorithm and BP-LSSVM combination variable weight model weight optimization,” Coal Engineering, vol. 51, no. 5, pp. 172-176, 2019.

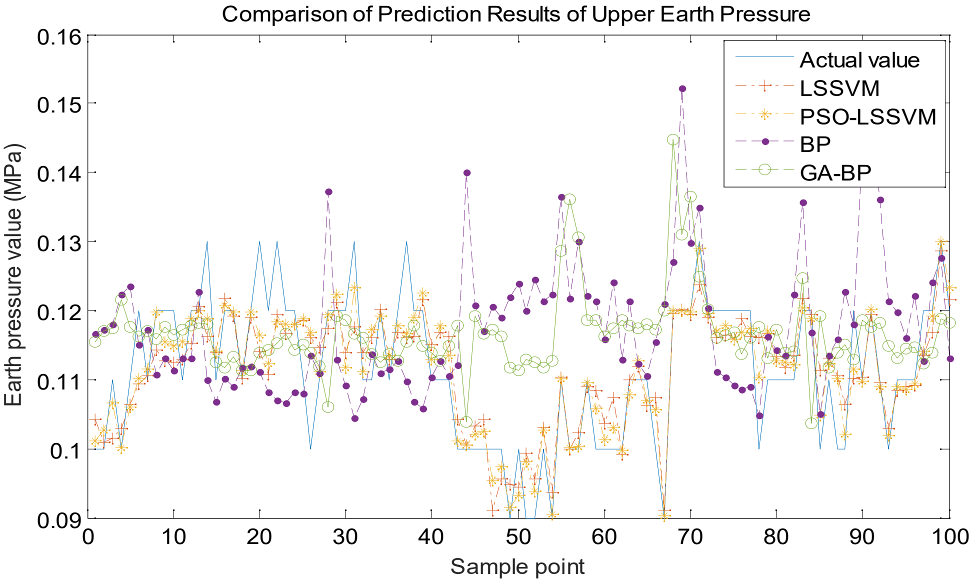
[14] H. B. Xue and S. X. Lun, “Overview of particle swarm optimization in multi-objective optimization,” Journal of Bohai University (Natural Science Edition), vol. 30, no. 3, pp. 265-269, 2009.

[15] W. C. Ho, J. M. Su, and C. Y. Chang, “Maximal market potential of feeder bus route design using particle swarm optimization,” IAENG International Journal of Applied Mathematics, vol. 49, no. 4, pp. 470-477, 2019.

[16] S. B. Li, H. Zhao, and C. L. Zhang, et al., “Review of drosophila optimization algorithms,” Science, Technology and Engineering, vol. 18, no.1, pp. 163-171, 2018.

[17] W. T. Pan, “A new fruit fly optimization algorithm: taking the financial distress model as an example,” Knowledge-Based Systems, vol. 26, pp. 69-74, 2012.

[18] Y. C. Li and M. X. Han, “Hybrid drosophila algorithm and its application in combination optimization,” Journal of Chongqing University, 2019, DOI:10.11835/j.iss n.1000-582X.2020.226.



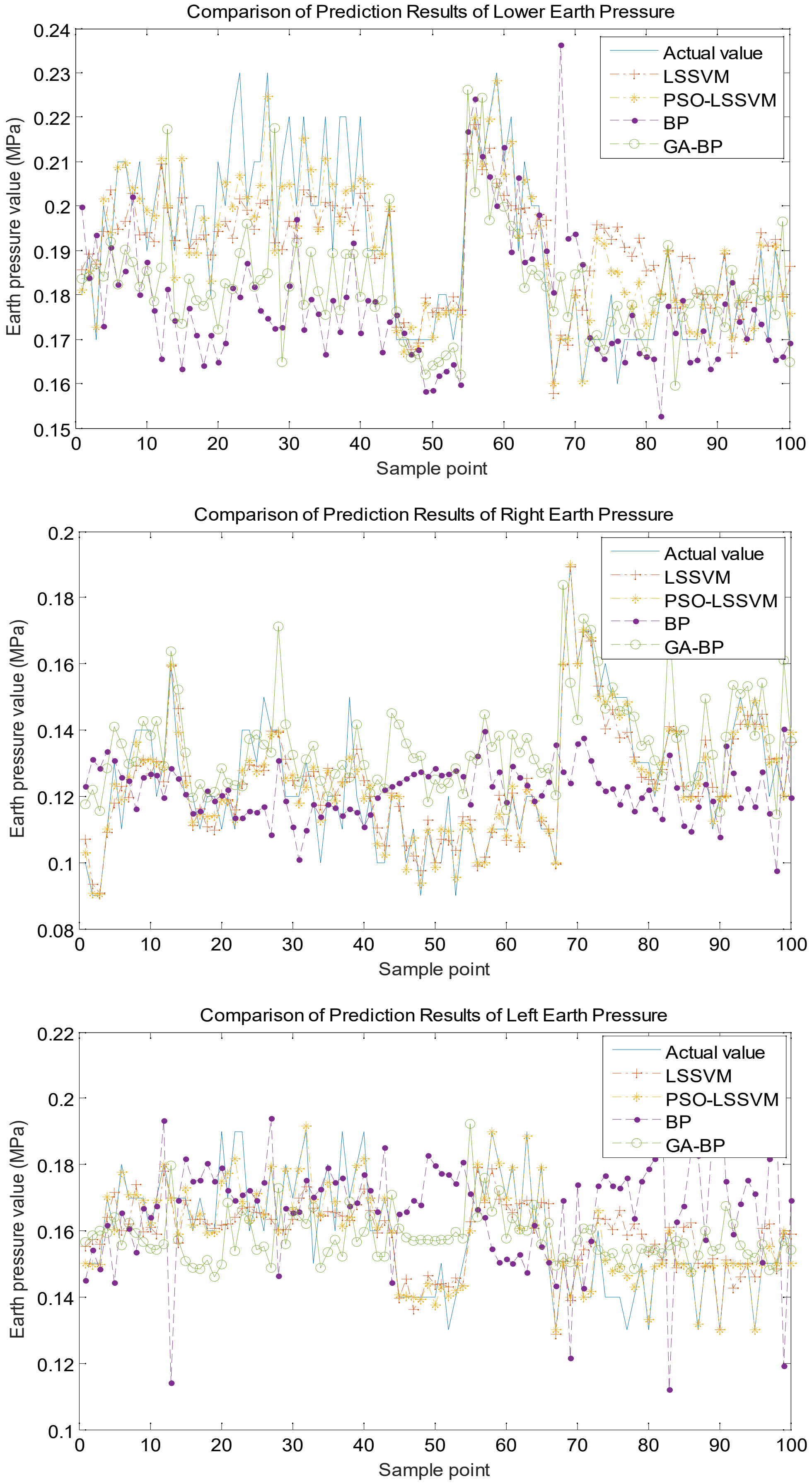


Fig. 6 Comparison results of earth pressure prediction of four monitoring points

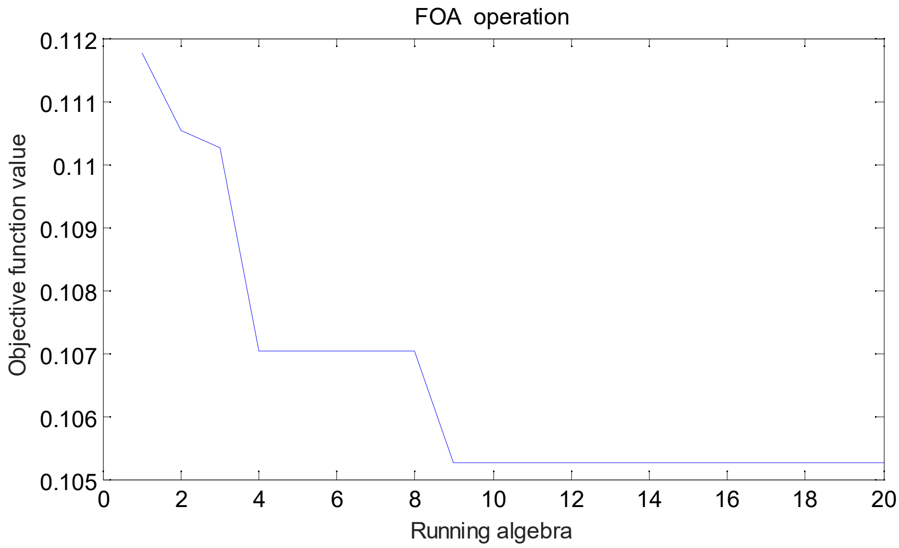


Fig. 7 Operation process of FOA

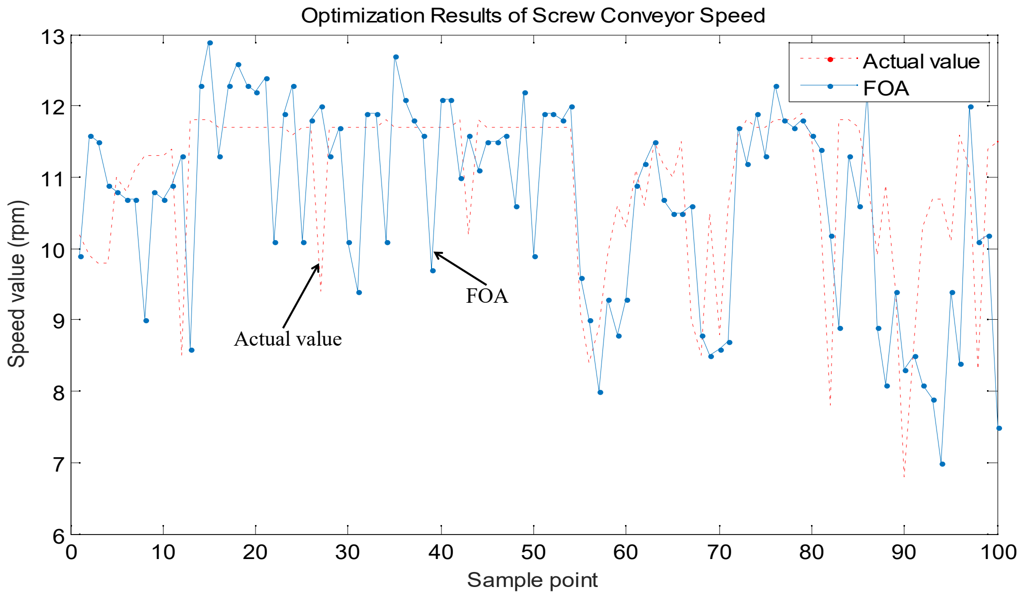
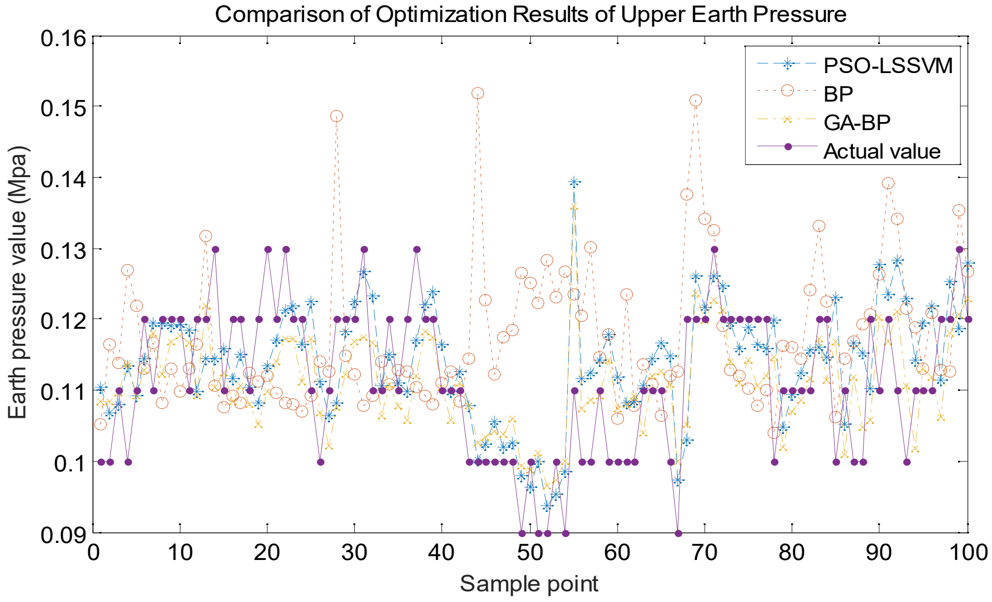


Fig. 8 Optimization results of screw conveyor speed



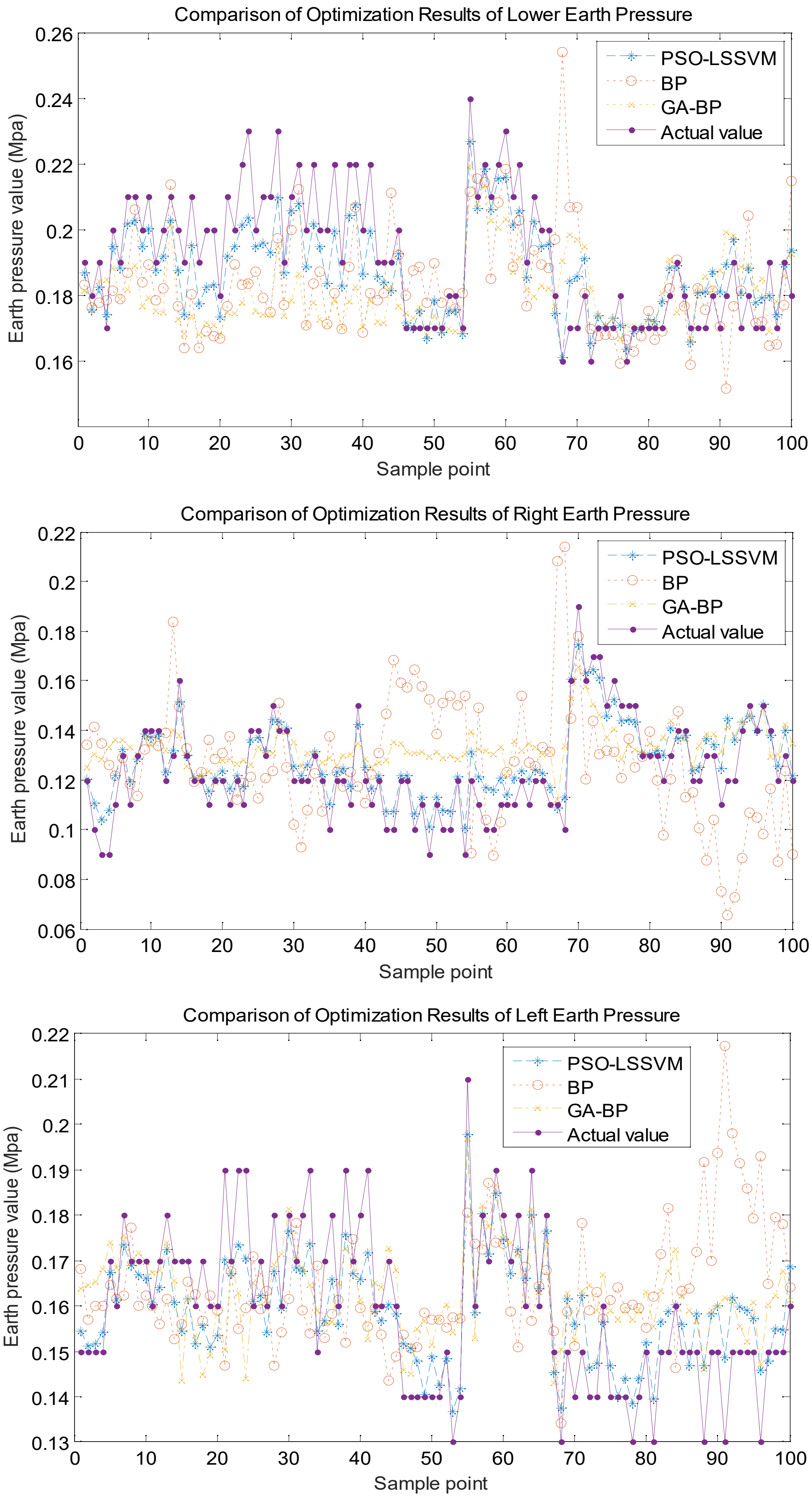


Fig. 9 Optimization results of earth pressure balance control in sealed cabin