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Research Article

Influence Analysis of Rock Mass Mechanical Properties on Tunnel Rock Stability Based on Sensor Data Integration

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This study takes the multisensor monitoring data of tunnel support structure and surrounding rock mechanical properties during TBM construction as the research object, integrates the monitoring data of multisensor through an intelligent optimization algorithm, and explores the self-consistent fusion characteristics between the multisensor structural mechanical properties and the field monitoring data. At the same time, the support structure parameters and construction progress in the tunnel construction process are dynamically adjusted and scientifically integrated through the information feedback of monitoring data. The research results are as follows: (1) The tunnel excavation rate is different under different rock strengths and surrounding rock levels. The overall performance is that the harder the surrounding rock, the lower the surrounding rock level, and the faster the tunnel excavation rate. The relationship between the FPI parameters of surrounding rock and the deformation of tunnel surrounding rock is closer, and the correlation coefficient reaches 98%. The mechanical properties of the surrounding rock have the greatest influence on its deformation. (2) The rotation speed, thrust, and torque of TBM machinery as well as the surrounding rock workability index and the tunnel surrounding rock deformation maintain a good fitting relationship, with a fitting rate of more than 85%. After the improved PSO-BP algorithm is used to calculate and fit the four parameters of torque, rotational speed, thrust, and surrounding rock drivable coefficient during TBM mechanical construction, the fitting accuracy is higher than 94%. (3) At the same time, according to the analysis of the fitting results, the fitting effect of TBM mechanical thrust is the best among the four-parameter algorithm analysis fitting degrees, which is 99.3%. (4) The measured points are evenly distributed near the surrounding rock deformation surface calculated by the improved PSO-BP algorithm, and the fitting variance is 0.972. With the tunnel excavation, the settlement deformation of surrounding rock first increases rapidly, and then, the settlement deformation enters a slow growth stage and finally reaches a relatively stable state. (5) After the jam occurs, the tunnel is expanded from the telescopic shield or tail shield to the outer side of the shield to reduce the contact area between the shield and the surrounding rock to reduce the extrusion of the surrounding rock pressure on the shield.

1. Introduction

The 21st century is the century of underground space resource development and utilization. As the basic form of underground space utilization, a tunnel plays an important role in railway, highway, urban subway, and other transportation networks [1–3]. However, due to the concealment of underground engineering, it is often difficult to know, discover, and control the structural safety of tunnel works in multiple complex environments. The tunnel is located in complex geographical, climatic, and geological conditions, and its own spatial form and operation state are changeable. Under the influence of tunnel construction and long-term operation hidden dangers (such as deformation, leakage, and crack), it is very easy to appear weak links and damage nodes and then lead to catastrophic accidents. However, at present, the tunnel and underground works are still in the situation of "repair after failure," "lagging treatment," and "backward safety perception." The structural safety of a large number of tunnel works has been out of control for a long time, and the stress sensors embedded in the structure have become furnishings. It is difficult to provide decision-making and guidance for the safe construction and operation and maintenance of tunnel works by relying on the data analysis of a single sensor, which brings many blindness and troubles to tunnel management. The main reason is that the theory, method, and technology of tunnel structure safety performance perception and control are seriously insufficient, and at the same time, the traditional detection, monitoring and operation, and maintenance management systems and technologies are widely used because of the large amount of money required for perception and control, which has increasingly become a huge economic burden for the national finance. Therefore, it is urgent to carry out research on accurate perception and control of tunnel structure safety performance with low energy consumption, high efficiency, and strong practicability [4–9].

From the research in recent years, the means of on-site monitoring test data are more advanced and diversified. With the emergence of error back propagation (BP) neural network, genetic algorithm (GA), mind evolutionary algorithm (MEA), and other algorithms, as well as Kalman filter, Fourier analysis, short-time Fourier change, and other signal noise reduction methods, some scholars have introduced it into the processing of tunnel monitoring data, forming BP neural network regression analysis, GA-BP neural network time series analysis, MEABP neural network time series analysis, wavelet noise reduction, and other methods [10], enriching the theoretical basis of tunnel monitoring data analysis. However, on the whole, most of the current studies are still focused on the tunnel construction stage. The utilization efficiency of monitoring data is low, and the data processing is still at the primary stage and mainly focuses on the data of a certain tunnel, a single monitoring object, or a single sensor, lacking systematic analysis of the whole monitoring data. The mechanical monitoring of tunnel structure is carried out through a variety of stress and strain sensors. If the mechanical characteristics of tunnel structure are to be recognized and the safety performance of tunnel structure is to be realized, data processing must be carried out for both single sensor and multiple sensor systems to achieve the purpose of accurate sensing [11]. At the same time, with the development of new technologies such as big data, Internet, artificial intelligence, blockchain, and supercomputing, the traditional tunnel structure safety performance sensing and control need to be deeply integrated with intelligent technology. The application of holographic perception, instant communication, artificial intelligence, big data, cloud computing, Internet of things, and other technologies in the field monitoring of tunnel structure mechanical characteristics, model test, numerical simulation, and safety performance sensing and control needs to be further developed [12–16].

Therefore, in the process of tunnel structure safety performance perception and control, the self-consistent processing model of multisensor structural mechanical characteristic field monitoring data is explored, the deep fusion method and sensing algorithm of field monitoring and digital object space test are developed, and the tunnel life cycle safety performance response mechanism based on structural mechanical characteristics is revealed, which lays a theoretical foundation for the maintenance and improvement of tunnel structure safety performance. It has become an important scientific and technical problem facing the maintenance and repair of tunnel engineering and also an important problem facing the intelligent construction and safe operation and maintenance of tunnels.

Based on the rock tunnel construction of a large-diameter full section TBM, this study takes the multisensor monitoring data of tunnel support structure and surrounding rock mechanical characteristics during TBM construction as the research object and integrates the monitoring data of the multisensor through an intelligent optimization algorithm to explore the self-consistent fusion characteristics between the multisensor structural mechanical characteristics and the field monitoring data. In this way, the safety perception and dynamic monitoring of the tunnel structure deformation and mechanical state are carried out, and the support structure parameters and construction progress during the tunnel construction are dynamically adjusted and scientifically integrated through the information feedback of the monitoring data, so as to realize the safe and efficient construction of TBM.

2. Project Overview

This study is based on a TBM water conveyance tunnel in Southwest China. It is located at the edge of the Himalaya Mountains. In the mountain area with neotectonic activities such as the Himalayas, when the tunnel construction passes through the active tectonic zone with complex and changeable lithological conditions and rich water in the tectonic zone, the surrounding rock conditions are relatively poor. Affected by a large number of folds, faults, and thrust faults, groundwater is abundant in many places. Geological problems such as faults, mud gushing, rock burst, water gushing, and block falling are often encountered in tunnel construction. It is a large-diameter water conveyance tunnel with a total length of 12 km and a maximum excavation diameter of 8 m. The surrounding rock of the tunnel body section is relatively weak and broken, with a massive overall structure and developed joints and fissures. Site construction is shown in Figures 1–3.

Generally speaking, when the net tunneling speed of TBM is about 3 mm/min, it is considered that it has entered the state of "unable to dig." The reason is that the strength of the surrounding rock is too high, the cutter head hob is difficult to cut into the rock mass, and the penetration of the cutter head is also maintained at a very low level. In the medium strength rock, there are high-strength surrounding rocks. Under the action of the initial speed and thrust, the load on the blade suddenly increases, exceeding the ultimate bearing capacity, and the hob will collapse. The hob is subject to eccentric wear and edge collapse. This is because the large high-strength slag flakes peeled off from the face of the face block the rotary bearing of the hob, causing the hob to stop rotating, but the cutter head still keeps rotating. The cutter head drives the hob of the clamping shaft to slide

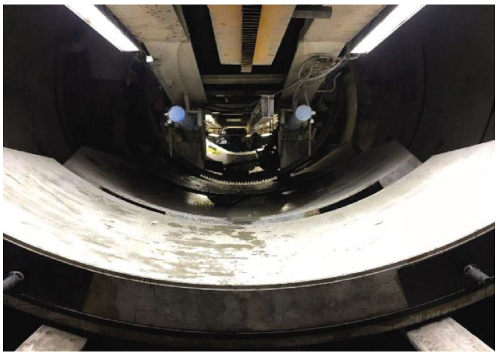


Figure 1: Assembly of tunnel lining segments.

Figure 2: Rock breaking by TBM cutter head.

and rub on the face of the face. In the actual working condition, the surrounding rock conditions are often more complex, and the cross combination of various conditions often occurs. If the deformation of surrounding rock in front can be timely predicted and fed back to TBM machinery during TBM method construction, then the rotation speed and thrust of the cutter head can be adjusted in time, so as to greatly increase the speed of tunnel excavation. Therefore, it is of great significance to integrate and predict the deformation of surrounding rock during tunnel excavation by giving real-time monitoring data to all sensors. The statistical relationship between surrounding rock deformation and excavation rate at the tunnel site is shown in Figure 4.

It can be seen from Figure 5 that there is a nonlinear fitting relationship between the deformation of the surrounding rock of the tunnel and the construction rate of the tunnel. The overall performance is that the excavation rate of the tunnel gradually decreases with the increase of the deformation of the surrounding rock of the tunnel. This is mainly because in the process of TBM construction, when the deformation of the surrounding rock is large, the contact surface between the cutter head of the TBM machine and the surrounding rock increases, and the contact pressure between the surrounding rock and the cutter head increases. This reduces the number of rotations of the cutter head under the same torque, increases the temperature of the cutter head, and then leads to abnormal operation of the entire construction machinery, resulting in mechanical failures such as jammers. It takes more than 10 days to clean the jammers each time, resulting in the loss of experience of the cutter head and the extension of the construction period. Therefore, it is necessary to accurately sense the deformation of the surrounding rock in the tunnel excavation section in advance to actively adjust the relevant parameters of the cutter head, so as to achieve the dynamic prevention and control of construction disasters.

3. Multisensor Cooperative Work Mechanism

For the cracks of the primary support and secondary lining structure of the tunnel that need to be detected in the highway tunnel detection, the lining cracks have obvious manifestations and can be judged by visual observation. Therefore, the CCD camera can be used to collect the lining images, and the computer vision method can be used for detection. The tunnel section is large, and the shooting position is inside the tunnel, so it needs to use multiple cameras to collect the lining appearance. At the same time, because the tunnel is in an arc shape, the camera needs to be placed in a circular arc shape to better collect the lining image. In order to provide more information for data processing, a laser radar is also installed on the detection system. The three-dimensional point cloud data of the tunnel is obtained by rotating the laser radar. In the process of collecting the lining point cloud, the detection system travels forward along the tunnel. The rotation movement of the scanner and the movement of the detection system combine to form spiral ordered point cloud data. At the same time, the laser radar can observe the real-time grouting situation behind the tunnel lining wall and conduct the full section convergence deformation test for the tunnel initial support deformation and the second lining disease section, which is very important to control the tunnel surrounding rock deformation. After water seepage in the tunnel, the water will flow down the tunnel wall, and some areas of the tunnel lining will be wetted by water seepage. Compared with other areas of the tunnel, the temperature of the wetted area is lower, so the infrared thermal imager can be used for detection. The freezing damage of the tunnel is similar to this, and the infrared thermal imager can also be used for detection. The above lidar, infrared camera, and camera acquisition system constitute the tunnel 3D point cloud data acquisition system, as shown in Figure 6. At the same time, the fiber grating is used to monitor and analyze the longitudinal deformation of the tunnel. The branch optical fibers of the monitoring sections are connected to the network through the instrument to form the main branch optical fiber. Then, the main branch optical fiber transmits the stability information of the surrounding rock to the receiving instrument for a long distance. Then, the monitoring of the stability of the surrounding rock of the tunnel with the fiber sensing technology can be realized to realize the intelligent sensing of the whole space deformation of the tunnel, as shown in Figure 7.

For the original data obtained by the above sensors, data preprocessing is required first, and then, the standard main contour of the tunnel is obtained. The tunnel is reconstructed using the standard contour, so that the structural mechanical parameters in the three-dimensional state can be obtained and the safety state can be perceived. The

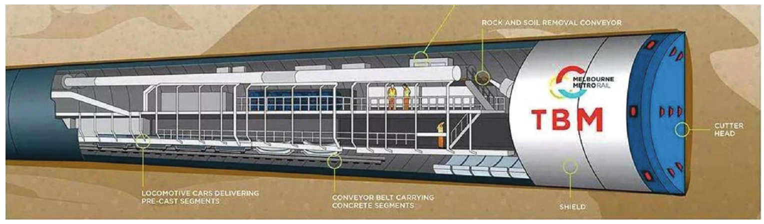


Figure 3: Schematic diagram of TBM excavation.

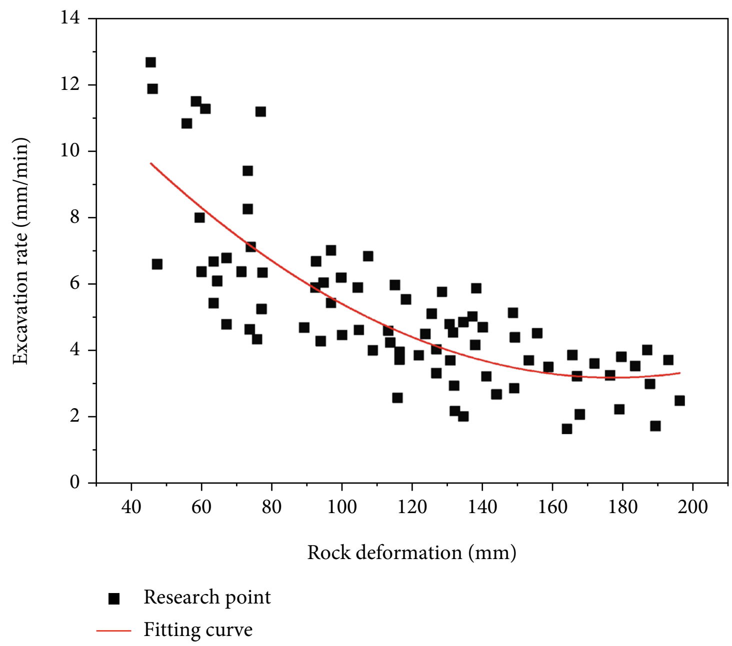


Figure 4: Relationship between surrounding rock deformation and excavation rate.

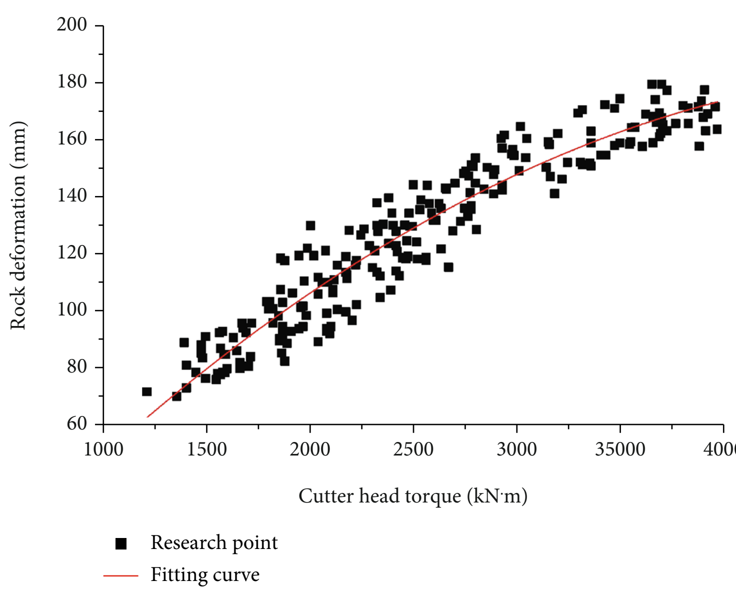


Figure 5: Relationship between cutter head torque and deformation.

Delaunay triangulation algorithm is adopted for the three-dimensional reconstruction of the point cloud. Therefore, it is necessary to convert the three-dimensional spatial point cloud data into plane point cloud data, construct a triangular relationship network in the plane point cloud, and then apply the constructed triangular relationship network to

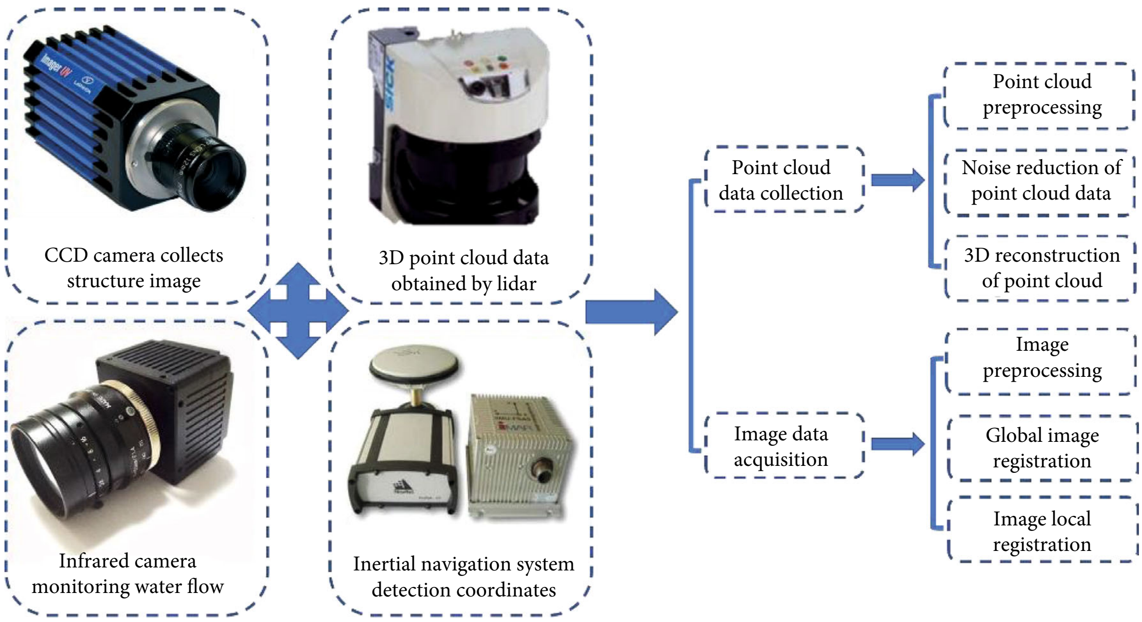


Figure 6: Tunnel multisensor cooperative working mechanism.

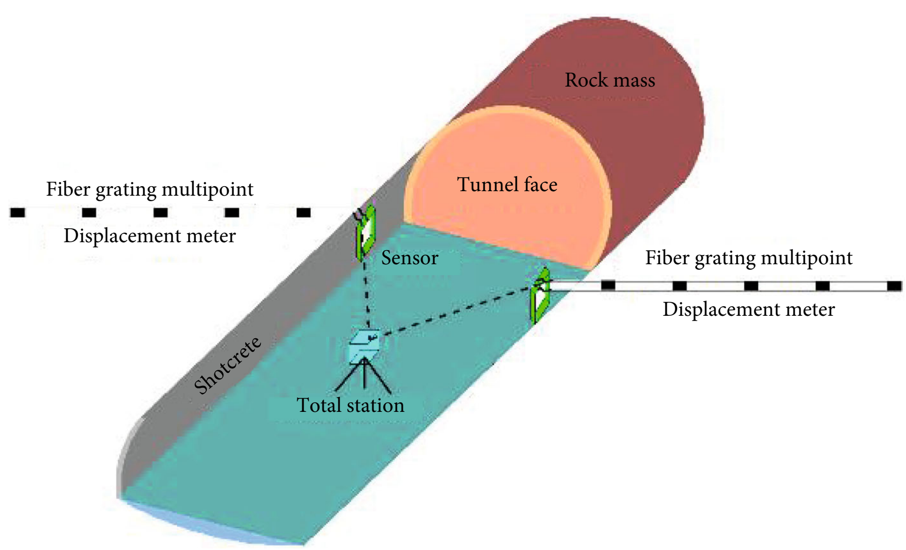


Figure 7: Tunnel fiber grating intelligent monitoring.

the actual three-dimensional point cloud data to realize the three-dimensional object surface reconstruction. The three-dimensional reconstruction principle of the point cloud is shown in Figure 8.

No matter whether the tunnel point cloud data in this paper is projected to any plane, point cloud overlap will occur. Take downward projection as an example, as shown in Figure 8(a), when the tunnel is projected downward along the vertical direction, because the arc of the tunnel is greater than 180 degrees, the point cloud data below the horizontal line passing through the center of the circle will overlap with the point cloud data of the upper half circle after downward projection, as shown in Figure 8(a). Suppose a circle with radius R is tangent to the horizontal line, a rectangular coordinate system is established with the tangent point as the center, the horizontal direction as the x-axis, and the vertical direction as the y-axis. As shown in Figure 8(b), a point $P(x, y)$ on the circle rolls along the coordinate axis and contacts the point Q on the x-axis; then, the arc OP is equal to the length L of the line segment OQ, and their relationship is as follows:

$$\begin{cases} l = r \times \arccos\left(1 - \dfrac{x^2 + y^2}{2r^2}\right), & 0 \le \theta \le \pi, \\ l = 2\pi r - r \times \arccos\left(1 - \dfrac{x^2 + y^2}{2r^2}\right), & \pi \le \theta \le 2\pi. \end{cases} \quad (1)$$

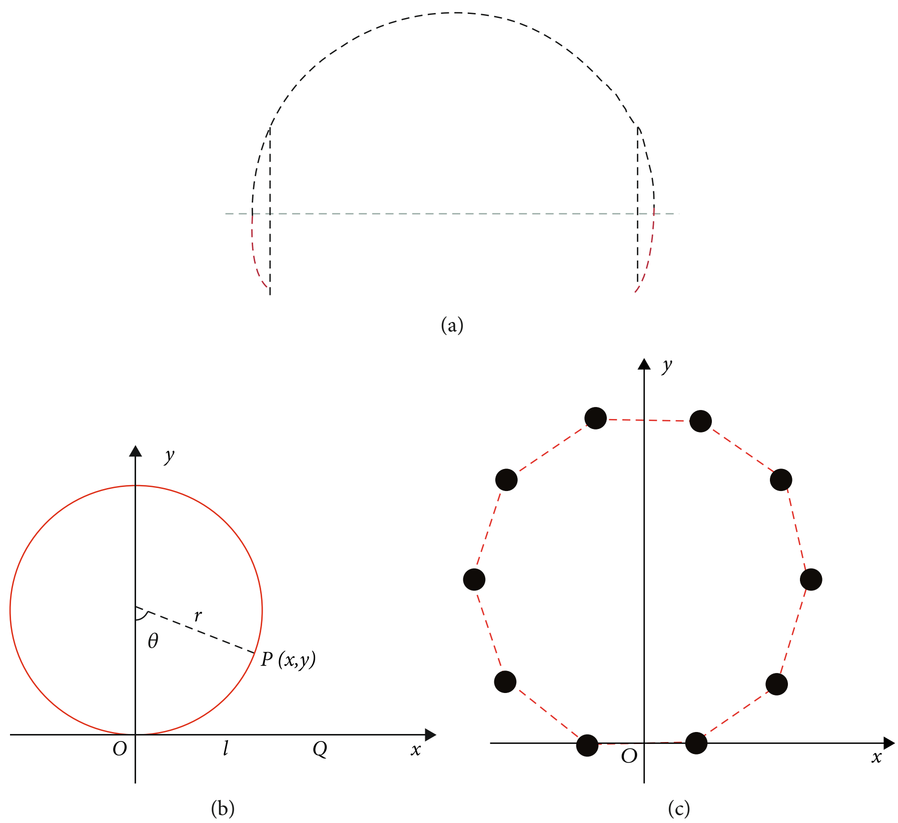


Figure 8: Construction principle of 3D point cloud model of tunnel.

According to the idea similar to the above, in order to expand a circle of discrete arc-shaped point cloud data, you can use line segments to connect the points between the discrete point clouds and then roll them along the positive direction of the coordinate axis X to flatten the point cloud data, as shown in Figure 8(c) After each circle of the point cloud is flattened, its original y value is given to each flattened point. The triangulation network of flattened tunnel point cloud data is constructed by the Delaunay triangulation algorithm, and then, the triangulation network is applied to the tunnel three-dimensional point cloud data to realize the three-dimensional reconstruction of the tunnel model. The reconstruction results are shown in Figure 9.

From Figure 9, according to the above three-dimensional point cloud model of the tunnel, the relationship between the structural stress state and surrounding rock deformation at each position during the tunnel excavation, the excavation parameters of the tunnel TBM, and the rock mechanical parameters of the tunnel can be obtained. Further, it can predict and analyze the mechanical response of the tunnel structure deformation during the excavation of the front section that has not been excavated and then feedback the predicted data to the TBM construction machinery to dynamically adjust the excavation parameters and support structure parameters, so as to ensure the safe and efficient construction. The three-dimensional point cloud model generated based on the data of the built tunnel is of great significance for the structural safety monitoring and timely feedback of the built tunnel, as well as for providing efficient feedback for the construction of the nonexcavated section.

4. Research on Improved Particle Swarm Optimization- (PSO-) Neural Network (BP) Algorithm

In order to solve the problem that TBM tunneling parameter setting mainly depends on experience in the construction process, the tunneling data of the stable section is selected to predict the mechanical parameters, structural mechanics, and deformation state of the surrounding rock in front and assist in the optimization and adjustment of TBM tunneling parameters. The improved neural network algorithm and particle swarm optimization algorithm are used in this study. The neural network algorithm process is shown in Figure 10, and the particle swarm optimization algorithm is shown in Figure 11.

A neural network is a kind of mathematical model that imitates biological neural behavior. Neural networks are interconnected by several connecting nodes (neurons). Input the sample data and obtain the network output through adaptive learning and training. At the beginning of adaptive training, the BP network generally generates random numbers within (-1, 1) range as initial weights and thresholds. The sample input data starts from the input layer to calculate the weight and threshold, then passes through the hidden layer and finally reaches the output layer to obtain the

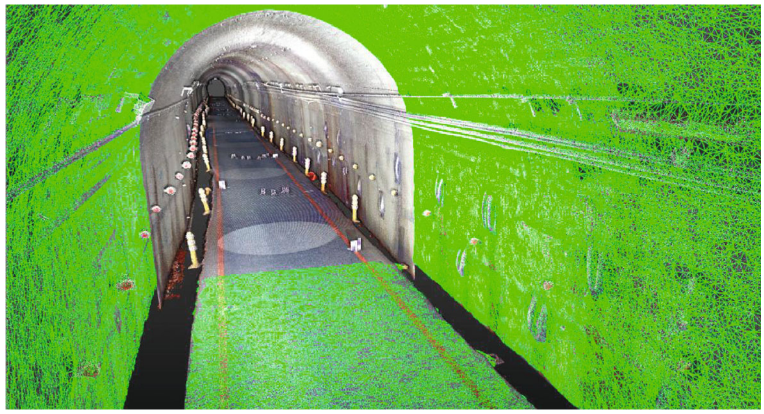


Figure 9: 3D point cloud model of tunnel.

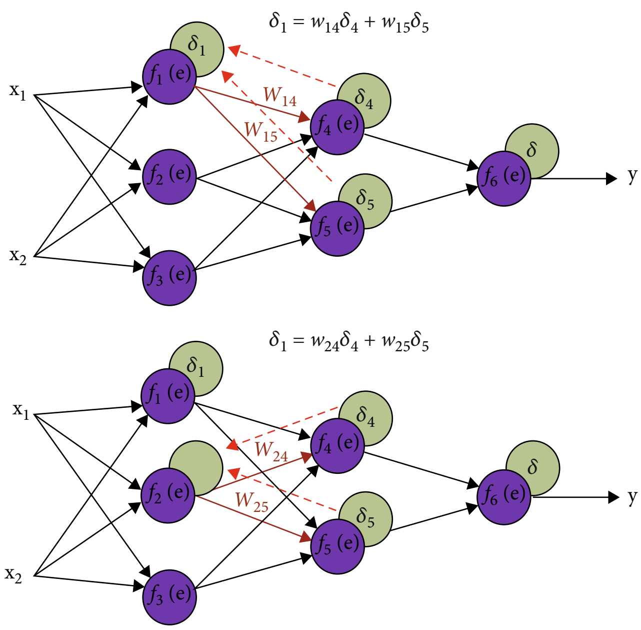


Figure 10: Analysis of neural network algorithm.

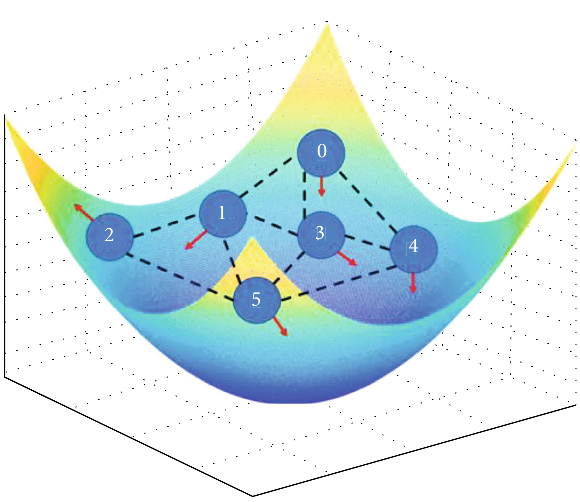


Figure 11: Particle swarm optimization analysis.

network prediction value and calculate the prediction error. If the accuracy of the error meets the requirements, it will converge and output the prediction result. Otherwise, the error will be back propagated, and the threshold and weight will be updated until the set number of iteration steps or convergence is reached. Particle swarm optimization (PSO) is derived from the behavior of birds searching for food. The PSO algorithm establishes a mathematical model based on the behavior of birds looking for food and is used to find the optimal solution to the problem. In the process of solving the problem, the solution set of the problem is regarded as a flock of birds. Each bird is a solution, also known as a particle. Each particle has two characteristics of speed and position. The particle updates its position according to its own optimal solution and the current optimal solution of the population. Particles self-renew according to

$$v_{id}(t+1) = \omega v_{id}(t) + c_1 r_1 [p_{id}(t) - x_{id}(t)] + c_2 r_2 \left[p_{gt}(t) - x_{id}(t)\right], \quad (2)$$
$$X_{id}(t+1) = x_{id}(t) + v_{id}(t+1),$$

where $i = 1, 2, \cdots, N, d = 1, 2, \cdots, D$; $V_{id}(t)$ represents the velocity of the ith particle in the tth iteration, and r_1 and r_2 are random numbers between [0, 1]; C_1, C_2 are learning factors, usually $C_1 = C_2 = 2$; W is the inertia factor. C_1 and C_2 are calculated according to the following:

$$c_1(t) = c_{\max} - \frac{(c_{\max} - c_{\min})t}{T_{\max}},$$
$$c_2(t) = c_{\min} + \frac{(c_{\max} - c_{\min})t}{T_{\max}}, \quad (3)$$

where $C_{\max}$ is the maximum value of the student factor and $C_{\min}$ is the minimum value of the learning factor.

5. Parameter Selection and Correlation Analysis

According to the above three-dimensional point cloud model of the tunnel, the relationship between the structural stress state and the surrounding rock deformation at each position during the tunnel excavation, the excavation parameters of the TBM tunnel boring machine, and the mechanical parameters of the surrounding rock of the tunnel can be obtained. It can predict and analyze the mechanical response of the tunnel structure during the excavation of the front nonexcavation section. In the TBM tunneling project, the factors affecting the deformation of the rock mass in front are mainly the tunneling parameters of TBM and the rock mass parameters characterizing the characteristics of the surrounding rock. The uniaxial compressive strength in the rock mass parameters and the thrust, torque, and rotation speed in the tunneling parameters are important factors that affect the TBM tunneling speed and the rock mass deformation in front. Since it is difficult to directly obtain the uniaxial compressive strength of the rock in the trenchless section, in this study, the surrounding rock workability index (FPI) is used to replace the rock mass parameters. FPI is a comprehensive reflection of the tunnel parameters and geological parameters, including the factors of geological parameters [17–19]. According to the actual construction situation on the site, the surrounding rocks on the site are mainly divided into three types, namely, calcareous siliceous sandy slate, quartz sandstone, and moderately weathered granite. The corresponding grades and strengths of the surrounding rocks are shown in Table 1. The speed of TBM excavation under different surrounding rock grades and rock strengths is shown in Figure 12.

It can be seen from Figure 12 that the surrounding rock is complex and changeable during the tunnel excavation process, and the uniaxial compressive strength of different rocks of the same surrounding rock level and the same rock of different surrounding rock levels are also different, which have a direct impact on the tunnel excavation rate. It can be seen from Figure 12 that the tunnel excavation rate under the combination of different rock strengths and surrounding rock levels is greatly different, and the overall performance is that the harder the surrounding rock is, the lower the surrounding rock level is, and the faster the tunnel excavation rate is; the main reason is that when TBM machinery excavates in the rock with low strength and high surrounding rock level, the larger the tunnel deformation, the higher the wear rate of the cutter head, and at the same time, the easier for machine jam to occur, so the excavation rate is greatly affected.

According to the three-dimensional point cloud model of the tunnel excavation section and various parameters of TBM machinery during the excavation process, the relationship between thrust and deformation of tunnel surrounding rock is shown in Figure 13, the relationship between rotation speed and deformation of tunnel surrounding rock is shown in Figure 14, and the relationship between torque and deformation of tunnel surrounding rock is shown in Figure 5. At the same time, the relationship between rock mechanical parameters and tunnel surrounding rock deformation can be obtained by combining the uniaxial compressive strength of rock mass in the excavation section, as shown in Figure 15.

Table 1: Surrounding rock grade and strength of different rock masses.

Surrounding rock type	Calcareous siliceous sandy slate	Quartz slate	Moderately weathered granite
II	93-110 MPa	95-120 MPa	98-132 MPa
III	73-88 MPa	76-85 MPa	81-96 MPa
IV	45-58 MPa	53-65 MPa	64-78 MPa

By fitting the rotation speed, thrust, and torque of TBM machinery in the three-dimensional point cloud test section of the tunnel and the surrounding rock drivable coefficient with the rock mass structure deformation obtained through the three-dimensional point cloud model of the tunnel, it can be found that the above four parameters affecting the tunnel construction and the deformation of the surrounding rock of the tunnel maintain a good fitting relationship, with a fitting rate of more than 85%. The parameters used in this study for prediction and analysis of tunnel surrounding rock deformation are feasible. At the same time, according to the analysis of the fitting results of the above four parameters, it can be seen that the relationship between the surrounding rock FPI parameters and the tunnel surrounding rock deformation is more close, and the correlation coefficient reaches 98%. It can be concluded that the mechanical properties of surrounding rock have the greatest influence on its deformation during TBM tunneling. Therefore, the influence of the strength of the surrounding rock on the deformation of the tunnel surrounding rock should be taken into account in the prediction and research of the deformation of the tunnel surrounding rock.

In the process of TBM tunnel excavation, the deformation of tunnel structure is directly related to the physical and mechanical properties of the tunnel surrounding rock and the construction parameters of the tunnel boring machine. By integrating the mechanical parameters of rock mass and the performance parameters of tunnel construction machinery obtained by the three-dimensional point cloud model established by the tunnel stability section into the improved PSO-BP algorithm, at the same time, the rock mass parameters of the tunnel obtained by the sensors in the process of tunnel construction and the above four parameters are substituted into the calculation model to predict the surrounding rock deformation of the tunnel excavation section. The above four parameters are trained and analyzed by the improved PSO-BP algorithm, and the fitting accuracy of the four parameters in the prediction process is shown in Figure 16.

It can be seen from Figure 16 that the fitting accuracy of torque, rotational speed, thrust, and surrounding rock drivable coefficient during TBM mechanical construction is higher than 94% after the calculation and fitting of the improved PSO-BP algorithm. It can be seen that the prediction effect of this method is ideal. Meanwhile, it can be seen from the analysis of the fitting results that the fitting effect of TBM mechanical thrust is the best, 99.3%, among the four-parameter algorithm analysis fitting degrees, which indicates

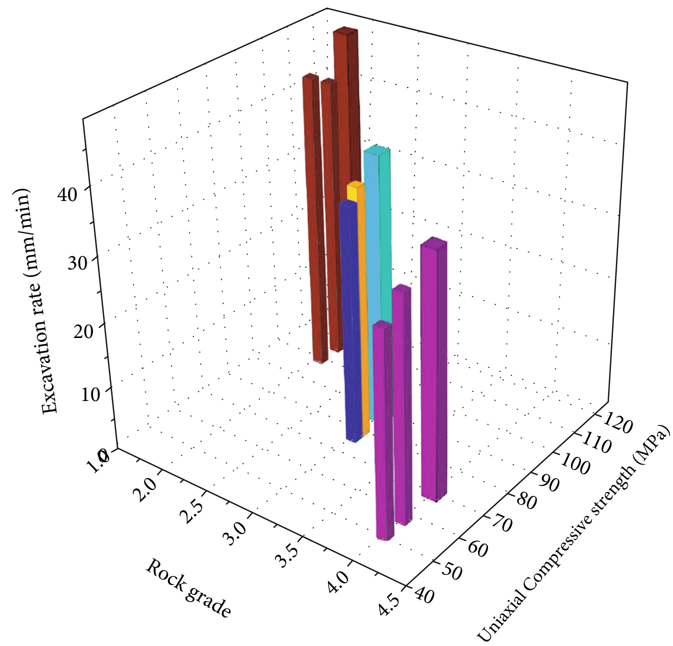


Figure 12: Relationship between different surrounding rock grades, surrounding rock strength, and excavation rate.

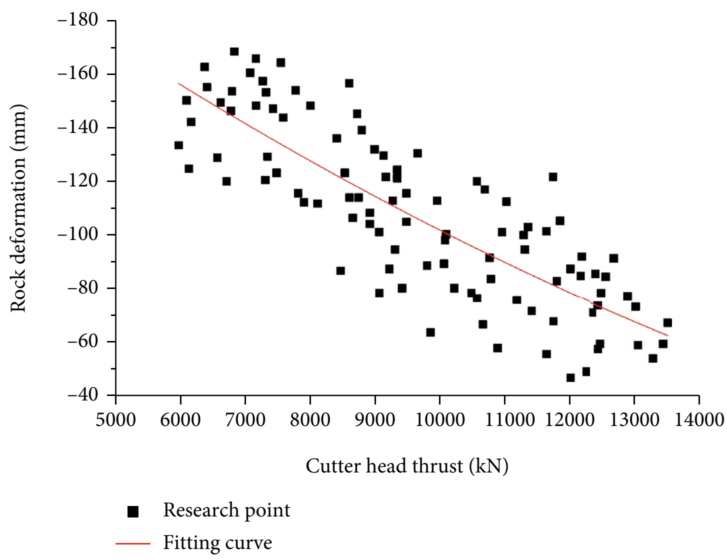


Figure 13: Relationship between cutter head thrust and deformation.

that in the tunnel excavation project, the thrust of TBM has a great impact on the excavation of the tunnel, mainly because when the overall strength of rock is relatively hard, the greater excavation thrust will better improve the rock breaking performance of the hob. The mechanical parameters of rock mass and the performance parameters of tunnel construction machinery obtained from the three-dimensional point cloud model established in the tunnel stability section are merged into the improved PSO-BP algorithm. At the same time, the tunnel rock mass parameters and the above four parameters obtained by the sensors in the tunnel construction process are substituted into the calculation model, and the surrounding rock deformation of the tunnel excavation section is predicted through the improved PSO-BP algorithm. In order to further verify the accuracy and rationality of the improved PSO-BP algorithm, we compared the data obtained by the improved PSO-BP algorithm with the surrounding rock deformation monitoring results during the actual construction of the tunnel, as shown in Figure 17, which is a comparison diagram between the data obtained by the improved PSO-BP algorithm and the surrounding rock deformation monitoring results during the actual construction of the tunnel.

The surface in Figure 17 is the development process of surrounding rock deformation at different positions of the

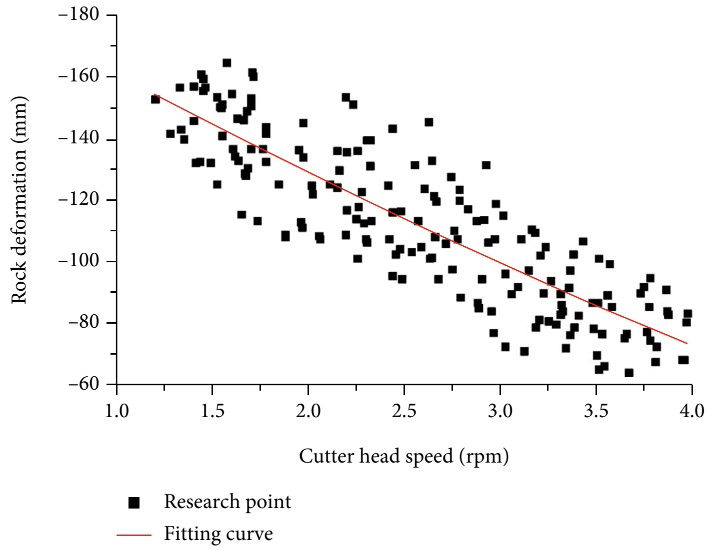


Figure 14: Relationship between cutter head speed and tunnel deformation.

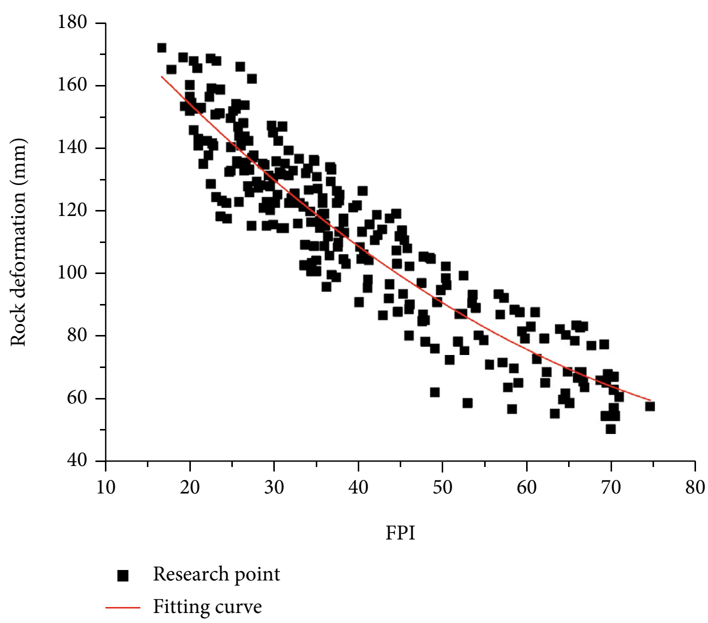


Figure 15: Relationship between FPI and deformation.

tunnel with time obtained by the improved PSO-BP algorithm. The data points are the actual deformation values of surrounding rock at various positions during the tunnel excavation. It can be seen from the figure that the measured points are evenly distributed near the surrounding rock deformation surface calculated by the improved PSO-BP algorithm, and the fitting variance is 0.972, indicating that the two are relatively consistent; the improved PSO-BP algorithm is reliable and has good accuracy. It can be seen from Figure 16 that the deformation law of surrounding rock at each position is basically the same, which is mainly divided into three stages: rapid growth stage-slow growth stage-stable stage. With the excavation of the tunnel, the settlement and deformation increase rapidly at first, and then, the settlement and deformation enter the stage of slow growth and finally reach a relatively stable state.

After the tunnel excavation, the deformation at different positions shows different evolution characteristics. The deformation value at the arch crown and the upper part of the tunnel is large, which is mainly because the surrounding rock at this position is greatly affected by gravity, and the deformation at the bottom is often small, and some positions also show certain upward uplift characteristics. In the later stage of the tunnel, the deformation at each position shows an overall growth trend, and the growth rate is different at different positions. This is mainly because the stress at each position is different for the circular tunnel. The stress near the arch is large and concentrated, so the deformation is

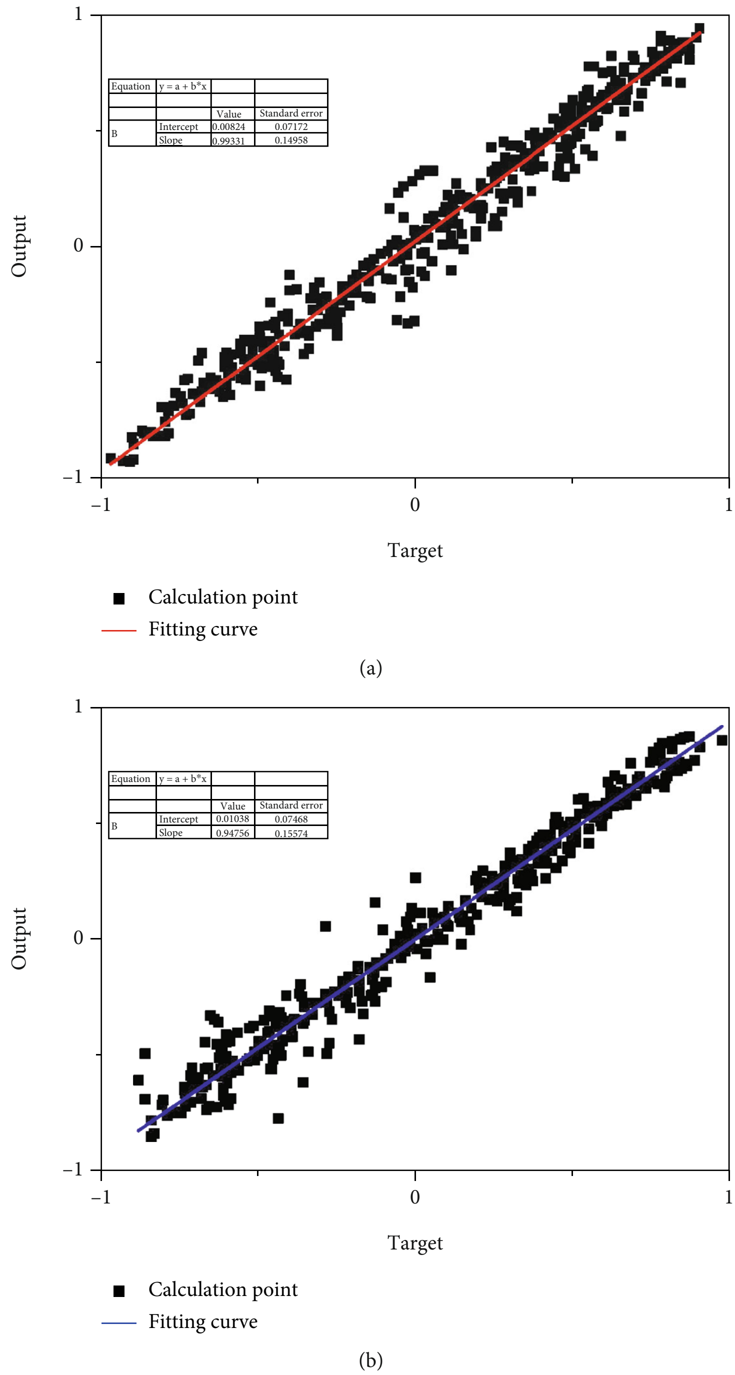
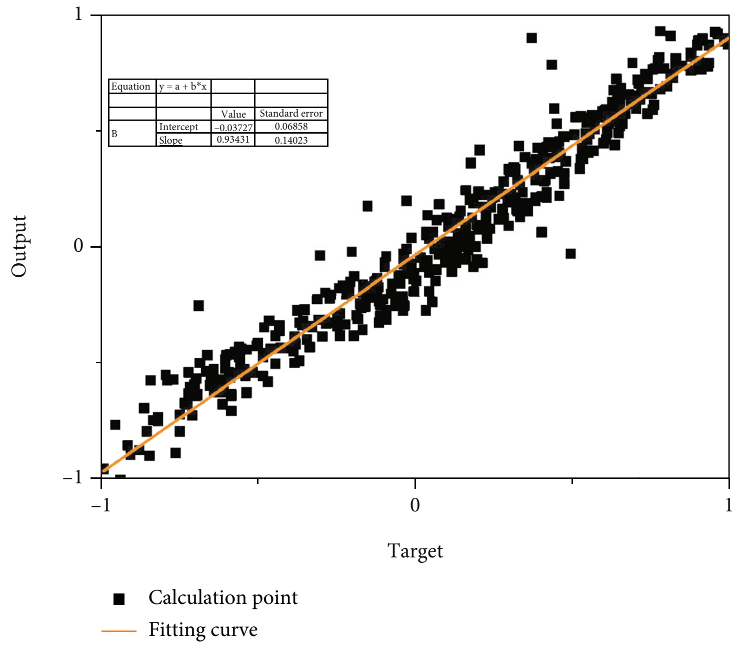
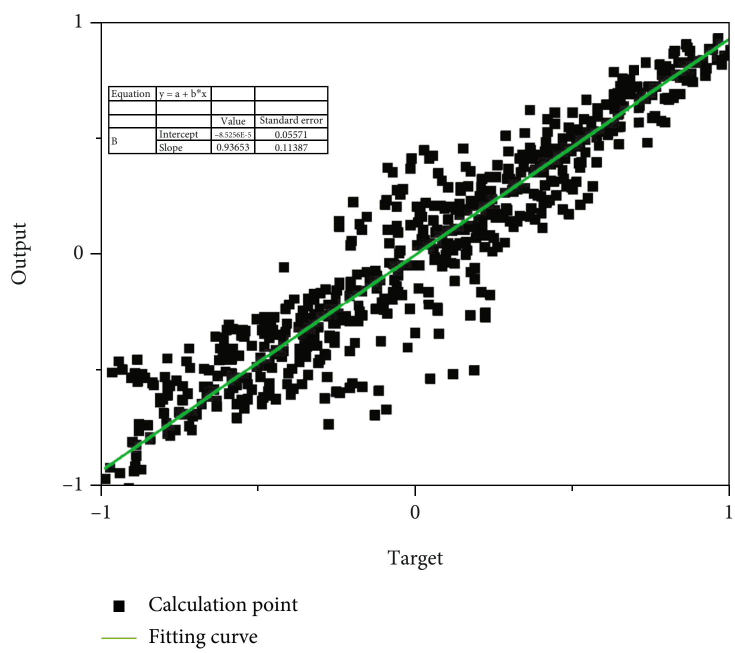


Figure 16: Continued.



(c)



(d)

FIGURE 16: Fitting results of calculation and analysis of different influencing factors.

large. The deformation at each position gradually tends to be gentle after the construction of the support structure in the later stage of the tunnel.

According to the above analysis of surrounding rock deformation during TBM excavation, when the tunnel is not excavated, the surrounding rock is disturbed by the cutter head, and the surrounding rock displaces, but the deformation value is relatively small. After the shield is out, the surrounding rock at each position of the tunnel has an obvious displacement change, but it is not the moment with the maximum amplitude. It indicates that the surrounding rock has partially converged and deformed in the shield during the excavation process, but no large deformation has occurred. The main reason is that the TBM support shoe does not release the large stress of the surrounding rock during the excavation process. Immediately after the shield is pulled out, the segments begin to release large stress in the surrounding rock. However, during the subsequent excavation, the deformation of the surrounding rock is relatively slow compared with that when the shield is pulled out, until it tends to be stable, which indicates that the disturbance range of the TBM excavation process to the surrounding

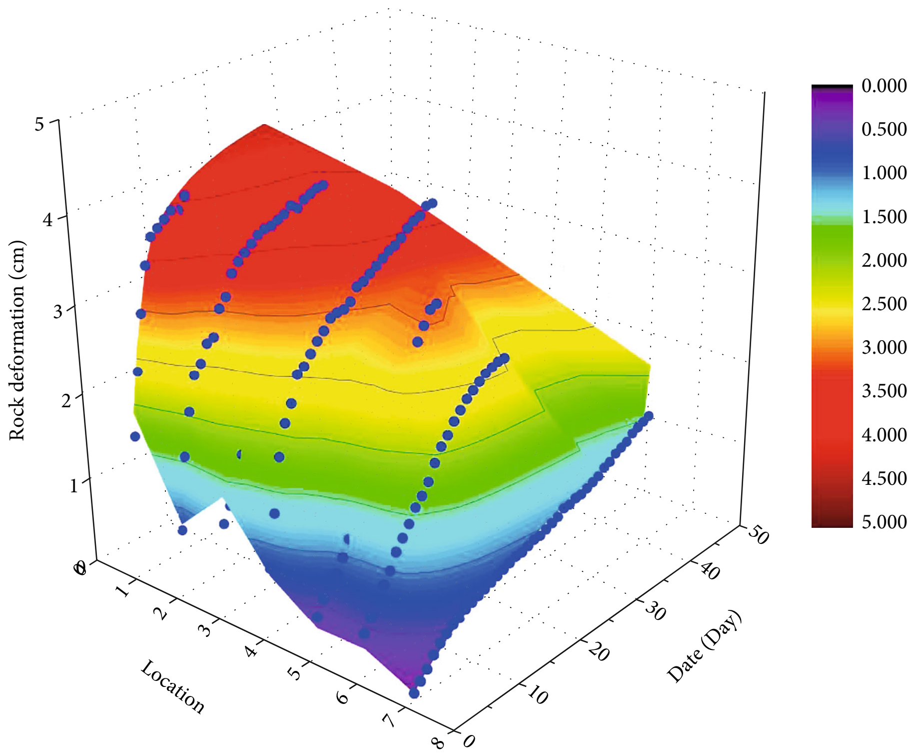


Figure 17: Comparison and analysis between calculation results of improved PSO-BP algorithm and measured values.

rock that has been initially supported is 2-3 times of the tunnel diameter. The segments play a timely supporting role and form a temporary combined support system with the surrounding rock, successfully suppressing the large deformation of the surrounding rock caused by the excavation disturbance. Compared with the deformation at the top and bottom of the arch, the deformation of both sides of the arch waist is relatively slow. Some of the poor surrounding rock deformation has occurred in the shield. When the tunnel is excavated, the original equilibrium state is broken, and the surrounding rock is deformed into the tunnel until it reaches the equilibrium state again. The deformation is related to the surrounding rock type, burial depth, groundwater, and structural stress. In order to ensure the safety of the tunnel structure and the design boundary requirements, support is required to prevent excessive deformation of the surrounding rock and achieve balance as soon as possible to prevent collapse; in order to prevent TBM jamming caused by large-scale convergence deformation, it is suggested that the shield should be directly used as a complete set of initial support measures for such tunnel sections. If worse surrounding rock is encountered in subsequent construction, the safety margin of existing support parameters should also be considered. In the process of TBM construction, the construction problem of cutter chuck is often encountered. With the development of intelligent sensor and network transmission technology, the intelligent numerical calculation of TBM cutter wear and the intelligent prediction of field construction will meet a new development situation, which is crucial to the safe and efficient construction of the tunnel and the control of the project cost.

TBM full face tunnel boring machine has high requirements on geological conditions. During the process of TBM tunneling in the soft rock section, the surrounding rock will produce both obvious elastic-plastic deformation and obvious creep deformation, and the creep deformation will increase rapidly within a few hours after TBM excavation, which makes the risk of TBM jamming increase rapidly. In view of such problems, the control measures for large deformation of soft rock are summarized as follows.

(1) Pregrouting is adopted to carry out cement grouting or chemical grouting for poor geology in front of the TBM to improve the integrity and strength of the rock mass in front. This is a preventive measure

(2) The shield is designed in a stepped shape. The diameter of the shield body is designed to decrease step by step, so that the diameter of the rear shield is smaller than that of the front shield, so as to reduce the contact range between the surrounding rock and the shield

(3) Increase the opening diameter. After the jam occurs, the tunnel is expanded from the telescopic shield or tail shield to the outer side of the shield to reduce the contact area between the shield and the surrounding rock to reduce the extrusion of the surrounding rock pressure on the shield. At the same time, it can also greatly reduce the tunneling friction resistance generated thereby and lay a foundation for the smooth escape from difficulties

(4) In case of jamming, grease and other lubricating materials shall be injected between the shield and surrounding rock to reduce the friction coefficient between the shield and surrounding rock, thereby reducing the friction resistance and freeing TBM

(5) After the jam occurs, if the above methods are not successful, the manual excavation of the pilot tunnel and side tunnel shall be considered to release the surrounding rock pressure, so that the shield and surrounding rock can be separated from each other, and the TBM can be freed from difficulties

(6) If the geological conditions in front of the tunnel are extremely poor and TBM cannot pass the tunnel smoothly, the construction method can be adjusted, and the drilling and blasting method can be used to excavate the large deformation surrounding the rock tunnel section in the full face in advance. The tunnel in this section adopts TBM to slide through to avoid machine jamming

6. Conclusion

This study takes the multisensor monitoring data of tunnel support structure and surrounding rock mechanical properties during TBM construction as the research object, integrates the monitoring data of multisensor through an intelligent optimization algorithm, and explores the self-consistent fusion characteristics between the multisensor structural mechanical properties and the field monitoring data, so as to conduct safety perception and dynamic monitoring of tunnel structural deformation and mechanical state. At the same time, through the information feedback of monitoring data, the support structure parameters and construction progress in the tunnel construction process are dynamically adjusted and scientifically integrated. The main research conclusions are as follows.

(1) The uniaxial compressive strength of different rocks of the same surrounding rock level and the same rock of different surrounding rock levels is also different. The tunnel excavation rate under the combination of different rock strengths and surrounding rock levels varies greatly. The overall performance is that the harder the surrounding rock, the lower the surrounding rock level, and the faster the tunnel excavation rate. The relationship between the FPI parameters of surrounding rock and the deformation of tunnel surrounding rock is closer, and the correlation coefficient reaches 98%. The mechanical properties of surrounding rock have the greatest influence on its deformation

(2) The rotation speed, thrust, and torque of TBM machinery as well as the surrounding rock workability index and the tunnel surrounding rock deformation maintain a good fitting relationship, with a fitting rate of more than 85%. It is feasible to use the above four parameters for the prediction and analysis of the tunnel surrounding rock deformation. The four parameters of torque, rotational speed, thrust, and surrounding rock drivable coefficient in the TBM mechanical construction process are calculated and fitted by the improved PSO-BP algorithm, and the fitting accuracy is higher than 94%. It can be concluded that the prediction effect of this method is ideal

(3) At the same time, according to the analysis of the fitting results, the fitting effect of the TBM mechanical thrust is the best among the four-parameter algorithm analysis fitting degrees, which is 99.3%, which indicates that the thrust of the TBM has a great impact on the tunnel excavation in the tunnel excavation project. This is mainly because the larger excavation thrust has a better effect on the rock breaking performance of the hob when the overall strength of the rock is relatively hard

(4) The measured points are evenly distributed near the surrounding rock deformation surface calculated by the improved PSO-BP algorithm, and the fitting variance is 0.972. The two are in good agreement. The improved PSO-BP algorithm is reliable and has good accuracy. The deformation law of surrounding rock at each location is basically the same, which is mainly divided into three stages: rapid growth stage-slow growth stage-stable stage. With the excavation of the tunnel, the settlement and deformation increase rapidly at first, and then, the settlement and deformation enter the stage of slow growth and finally reach a relatively stable state

(5) Pregrouting is adopted to carry out cement grouting or chemical grouting for poor geology in front of the TBM to improve the integrity and strength of the rock mass in front. This is a preventive measure. The shield is designed in a stepped shape. The diameter of the shield body is designed to decrease step by step, so that the diameter of the rear shield is smaller than that of the front shield, so as to reduce the contact range between the surrounding rock and the shield and increase the opening diameter. After the jam occurs, the tunnel is expanded from the telescopic shield or tail shield to the outer side of the shield to reduce the contact area between the shield and the surrounding rock to reduce the extrusion of the surrounding rock pressure on the shield. At the same time, it can also greatly reduce the tunneling friction resistance generated thereby and lay a foundation for the smooth escape from difficulties

Data Availability

The dataset used in this paper is available from the corresponding authors upon request.

Conflicts of Interest

The authors declared that they have no conflicts of interest regarding this work.

Authors' Contributions

Enping Guo and Linhua Huang contributed equally to this work.

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