Research Article

Multiparameter Inversion Early Warning System of Tunnel Stress-Seepage Coupling Based on IA-BP Algorithm

Junxiang Wang, Jie Sun, Haijun Kou, and Yaxian Lin

School of Architecture and Civil Engineering, Shenyang University of Technology, Shenyang, Liaoning 110870, China
China Railway 19th Bureau Group No. 5 Engineering Co., Ltd., Dalian 116100, Liaoning, China

Correspondence should be addressed to Junxiang Wang; w.j.xgood@163.com

Received 11 April 2021; Accepted 5 July 2021; Published 19 July 2021

Abstract

Under construction disturbance, the surrounding rock of a soft rock tunnel shows obvious aging characteristics. The creep characteristic of a rock mass under stress-seepage coupling greatly influences the long-term stability of a project. How to simply, quickly, and accurately determine the creep parameters of a rock mass under coupling conditions is significant to engineering structure design and construction. An intelligent back analysis method based on the immune algorithm is established, which leads to the development of the corresponding intelligent back analysis program. The creep effect of the rock mass was simulated herein using the Drucker–Prager yield criterion and the time-hardening creep law as the forward optimization method constitutive model. In addition, a sensitivity analysis of the parameters was performed to determine the optimal number of inversion parameters. By comparing and analyzing the residual between the inversion results of the IA-BP algorithm, PSO-BP algorithm, and the test values, the high precision of the IA-BP algorithm is proved. Taking the Lan Zhou-Hai Kou national expressway tunnel as an engineering example, a multiparameter creep inversion of the tunnel surrounding rock under the stress-seepage coupling condition was conducted using the inverse analysis method of the IA-BP algorithm. The results showed that the proposed IA-BP algorithm can effectively prevent the BP neural network from falling into a local minimum. Also, the algorithm is fast and accurate. The intelligent back analysis method based on the IA-BP algorithm is applied to the multifield coupling parameter back analysis, provides the basis and help for the structural design and construction of soft rock tunnel in water-rich stratum.

1. Introduction

Geotechnical engineering metrics in complex environments, such as multifield coupling among stresses, seepage, chemical composition, and temperature, influence each other. Engineering, often based on the mechanical analysis of geotechnical parameters such as geotechnical stability, heterogeneity, linearity, and dielectric properties, can be used to simply, quickly, and accurately obtain rock and soil parameters. Thus, geotechnical analysis has important guiding significance in practical engineering [1, 2].

A lot of research work has been carried out on the creep behavior and constitutive model of rock mass under the coupling of temperature, stress, and seepage. Huang et al. [3] and Liu et al. [4] have studied the relationship between creep, seepage, and stress of rock under coupling condition from the perspective of experiment. Xi [5], Wang et al. [6], and Ma et al. [7] have studied the creep law under coupling condition of temperature field, stress field, and chemical field from the perspective of theoretical research, numerical simulation, and constitutive model. At present, the related research results play an important role in the understanding of creep process and creep damage instability mechanism. Used in experimental methods under coupled environments are more difficult to obtain, whereas the multifield inversion method is an effective means used widely in the engineering sector to determine these parameters [8, 9]. Chen et al. [10] and Xu et al. [11] introduced support vector machines, intelligent
heuristic optimization algorithms, and 3D numerical inversion of the rheological parameters of surrounding rock. At present, most of them focus on single-field parameter inversion, but few on multifield coupling parameter inversion. Jia et al. [12] proposed the creep damage model of mud stone seepage stress coupling and obtained the undetermined parameters in the creep damage model by using the optimized back analysis method. Wang et al. [13, 14] carried out the multiparameter inversion research under the condition of stress-seepage damage coupling. Due to the high nonlinearity of underground engineering rock mass, the traditional optimization algorithm is difficult to get the global optimal solution, and some intelligent algorithms provide new ideas and means. Chen [15] reported the improved particle-swarm optimization (PSO) and large numerical combination software FLAC3D and presented the rapid analysis of the global Lagrangian improved particle parallel group parameter inversion method, applied to the inversion parameters. Liu et al. [16] used Gaussian process regression (GPR) for tunnel engineering calculations of inversion model parameters, and a single isotropic kernel function can be applied as a sum of the combined kernel function GPR to improve the generalization performance. Sun et al. [17] further developed the multiple-output SVM algorithm (MSVM) into the Bayesian probabilistic analysis method based on the inverse (B-MSVM method). However, most scholars use single-parameter back analysis, and thus, there have been few studies on multiparameter analysis of multifield coupling inversion.

In this paper, back analysis is carried out to solve the problem that it is difficult to obtain the creep parameters of rock mass under multifield coupling. It can easily fall into a local optimal value because of the slow convergence speed of the BP neural network. A multiparameter inversion method of the tunnel surrounding rock creep under the stress-seepage coupling is proposed based on the immune algorithm and the BP neural network, considering the characteristics of global optimal value search and fast convergence. Lanzhou to Hai Kou National Highway Qin Yu Long stone tunnel is used as an engineering example for stress-seepage monitoring and warning systems coupled for multiparameter inversion. Based on the data-field monitoring, an immune algorithm backpropagation (IA-BP) multiparameter flow coupling condition of stress in the surroundings is applied to the inversion.

2. Stress-Seepage Coupled Creep Model

Generally speaking, the total strain with creep behavior is divided into elastic strain, plastic strain, and creep strain, that is, elastic strain, plastic strain, and creep strain:

\[ \varepsilon = \varepsilon_e + \varepsilon_p + \varepsilon_c, \]

where \( \varepsilon \) is the total strain, \( \varepsilon_e \) is the elastic strain, \( \varepsilon_p \) is the plastic strain, and \( \varepsilon_c \) is the creep strain.

When Drucker–Prager criterion is used, the creep potential function is hyperbolic, and the equivalent creep surface is shown in Figure 1.

Three creep laws are provided in ABAQUS software [18], which are time hardening creep law, strain hardening creep law, and Singh–Mitchell creep law.

1. Time hardening creep law:

\[ \dot{\varepsilon} = A\sigma^n t^m, \]

where \( \dot{\varepsilon} \) is the equivalent creep strain rate.

2. Strain hardening creep law:

\[ \dot{\varepsilon} = (A (\sigma^n + (m + 1)\dot{\varepsilon}^m))^{1/(m+1)}. \]

3. Singh–Mitchell creep law:

\[ \dot{\varepsilon} = A e^{\alpha\sigma} t^m. \]

Because of the complexity of rock mass and many uncertain factors, it is difficult to establish a model which can reflect the rock mass characteristics comprehensively. In order to simplify calculation, the simplified constitutive model is often used in the back analysis. The application of fully simplified model in back analysis avoids some difficulties, which are difficult to overcome, and can provide valuable information for engineering design and construction [19].

In this paper, the creep nonlinearity is considered and the time hardening creep law is adopted [20]. The total creep of rock can be expressed as

\[ \varepsilon_c = \varepsilon_t + \varepsilon_s, \]

where \( \varepsilon_t \) is the transient creep and \( \varepsilon_s \) is the steady state creep.

The power law model can be used to describe transient creep and steady creep:

\[ \varepsilon_t + \varepsilon_s = \frac{A}{m + 1} \sigma^m t^{m+1}, \]

where \( \sigma \) is the equivalent stress, \( n \) is the stress index, \( A \) is the creep coefficient, \( t \) is the time, and \( m \) is the time index.

If 0 is taken in this paper, then equation (6) is simplified as

\[ \varepsilon_c = \frac{A}{m + 1} \sigma^m t^{m+1}. \]
The stress-seepage coupling is combined with the creep constitutive model to realize the creep calculation of tunnel under the stress-seepage coupling.

3. Establishment of IA-BP Multiparameter Inversion Method

3.1. Implementation of IA-BP Inversion Method. The surrounding rock of tunnel in high ground stress soft rock has obvious creep, and the concept and theory are applied to the immune genetic algorithm, which retains the good characteristics of previous iterations of the algorithm. This immune algorithm (IA) has a number of features to suppress degradation during the optimization via targeted use of information. IA overcomes the intractable prematurity problem of the multimodal function optimization process, and the global optimal solution can be obtained. The backpropagation (BP) neural network algorithm is weighted by immunohistochemistry with a threshold, and the anti-IA-BP intelligent analysis method is established using the coupled tunnel stress-seepage multiparameter inversion algorithm, as shown in Figure 2.

The specific steps are described as follows:

Step 1: perform a sample calculation based on the principal configuration of the orthogonal design. Using ABAQUS software, the configuration for each program is calculated and the learning samples are constructed.

Step 2: initialize the BP neural network’s input layer, hidden layer, and output layer parameters.

Step 3: set the number of immune genes, population size, and number of genes $D$ expressed as the BP sum of all weights in the network. To represent the BP neural network input layer, an output layer, and neurons in the hidden layer is $S_1$, $S_2$, and $R$, respectively, the dimension of the particle group is defined by

$$D = S_1 \times R + S_2 \times R + S_1 + S_2. \tag{8}$$

Step 4: calculate the antigen-antibody affinity using the following function:

$$\text{aff} = \frac{1}{1 + \sum_{i=1}^{n} \sum_{j=1}^{q} (y_{i}^k - c_{i}^k)^2}. \tag{9}$$

where $m$ is the number of samples, $q$ is the number of neurons, and $y_{i}^k$ and $c_{i}^k$ are the expected and actual output values of the $t$-th network output neuron of the $k$-th sample, respectively.

Step 5: from equation (9), the degree of affinity can be obtained, as well as the large affinity of the antibody to the antigen of memory cells and the expected (calculated) antibody value, and poorly performing antibodies can be eliminated. If the desired number of iterations has been reached, determine the individual optimal fitness value and set the threshold value via BP; otherwise, repeat Steps 4 and 5.

Step 6: apply the IA to learn the configuration of each program, adjust the structural parameters, verify the program using test samples, and determine the nonlinear relationship between the displacement and inversion parameters.

The parameter value of surrounding rock is taken as output vector, and displacement value is taken as input vector, and the nonlinear relationship between surrounding rock parameters and displacement is established. The optimization objective function is

$$F(x) = \sum_{i=1}^{n} [f_i(x) - u_i]^2, \tag{10}$$

where $x$ is the parameters to be retrieved, $f_i(x)$ is the calculated displacement value of the $i$-th measurement direction, $u_i$ is the measured displacement value of the $i$-th measurement direction, and $n$ is the number of displacement monitoring measuring points.

Because the traditional displacement back analysis method needs a large amount of calculation, the solving process is also relatively cumbersome. Therefore, intelligent algorithms such as neural network, genetic algorithm, and particle-swarm optimization are applied to the displacement back analysis to solve the mechanical parameters of rock mass. Firstly, the BP neural network algorithm is used to establish the nonlinear functional relationship between the parameters to be inversed and the displacement, and the network is trained repeatedly by using the learning samples to make the error value meet the accuracy requirements.
Then, the size and dimension of the population are initialized, and the fitness value of each particle is calculated. After repeated updating and iteration, the displacement value that meets the accuracy requirements is sought, and the physical and mechanical parameters of surrounding rock are obtained.

The orthogonal table is established by using the orthogonal principle, and it is regarded as the learning sample of the BP neural network. Because the data of the orthogonal table may have singular samples, it will increase the training time of the network and lead to the nonconvergence of the network. Before the training of the BP neural network, the learning samples are normalized. There are two methods of data normalization:

1. Maximum minimum method: let $x = (x_1, x_2, \ldots, x_m)$ and establish the mapping $f$:
   \[
   x_k \rightarrow f(x_k) = \frac{x_k - x_{\min}}{x_{\max} - x_{\min}},
   \]
   where $x_k$ is the normalized data and $x_{\max}$ and $x_{\min}$ are the maximum and minimum values of the sample interval. This method normalizes the data between 0 and 1.

2. Mean variance method: let $x = (x_1, x_2, \ldots, x_m)$ and establish the mapping $f$:
   \[
   x_k \rightarrow f(x_k) = \frac{x_k - x_{\text{mean}}}{x_{\text{var}}},
   \]
   where $x_{\text{mean}}$ is the average value of the sample interval and $x_{\text{var}}$ is the mean square error of the sample interval, and this method normalizes the data between −1 and 1.

The input data are normalized by the maximum minimum method:
   \[
   Y_k = x_k(x_{\max} - x_{\min}) + x_{\min},
   \]
where $Y_k$ is the output value of inverse normalization.

3.2. Model Building. According to the actual size of the tunnel, three times of the tunnel diameter is considered for the boundary influence condition, so the size of the geometric model is 50 m along the transverse $x$-axis, 50 m along the longitudinal $y$-axis, 19.5 m from the top of the model arch to the upper boundary, and 22.5 m from the bottom of the model arch to the bottom boundary, as shown in Figure 3. According to the measured ground stress of a tunnel, the self-weight stress field is 3.96 MPa, and the measured horizontal principal stress is 4.65 MPa~10.57 MPa. Considering the influence of tectonic movement, according to the stress results, the load is applied at the boundary of the model, the load is 3.96 MPa on the upper surface of the model, the load is 4.65 MPa on the left and right boundary, and the lining thickness is 0.5 m.

3.3. Establishment of Orthogonal Learning Sample. The six tunnel surrounding rock mechanical parameters enumerated in Table 1 are selected as test parameters, where each test parameter comprises five levels according to the orthogonal table into $L_{25}(5^6)$. The parameters corresponding to each program in ABAQUS yield the corresponding displacement value and orthogonal design table. The results are listed in Table 2, and the main point of the tunnel’s control edge is shown in Figure 4.

Figure 5 shows the sensitivity of each factor at each measuring point, and it can be seen that the vertical displacements of the left upper arch, arch crown, right upper arch, and arch bottom are significantly affected by the creep parameters and the elastic modulus, whereas the horizontal convergence is significantly affected by the creep parameters alone. The sensitivity of each parameter to the deformation of surrounding rock is in descending order of creep parameter $n$, elastic modulus, cohesion, permeability coefficient, internal friction angle, and creep coefficient $A$.

The measured parameters of rock mass with cracks are random, which leads to large deviation from the actual mechanical parameters of rock mass. If such mechanical parameters are used for finite-element simulation analysis, there will be some errors between the simulation results and the monitoring values. Therefore, the influence of fracture is not considered in parameter selection and inversion. When performing a back analysis of multi-field coupling parameters, one must pay attention to the parameter selection. In practice, other means should be reasonably used to reduce the number of parameters to be retrieved in the back analysis.

3.4. IA-BP Parameter Inversion. The selection of hidden layers in the BP neural network has a great influence on the accuracy of the BP neural network. The number of neurons in the hidden layer is determined by continuous trial and error. The selection range of the number of hidden layer neurons is calculated as follows:
   \[
   h = \sqrt{m + n + a},
   \]
where $h$ is the number of neurons in the hidden layer, $M$ is the number of neurons in the input layer, and $N$ is the number of neurons in the output layer. $A$ is the adjustment constant from 1 to 10.

In the BP neural network, the number of nodes in input layer is 5, that in output layer is 6, and that in hidden layer is 5, according to these parameters, the number of genes is $L = 66$, and the corresponding population size is $P = 20$, crossover probability $P_c = 0.8$, probability of variation $P_m = 0.2$, the threshold of antibody concentration was 0.8, the correlation between the iteration times and the optimal individual fitness value was determined using the IA-BP algorithm for tracking and analyzing the changes in the objective and fitness function values. The neural network training is shown in Figure 6, and the iterative curve of the IA-BP algorithm is shown in Figure 7.

Using MATLAB software combined with the IA-BP algorithm, the complex nonlinear relationship is established
for the data of orthogonal design table in Table 2, and the IA-
BP algorithm learning value is obtained by inversion. Table 3
shows the comparison between the calculated experimental
value and the IA-BP algorithm learning value.

The test IA-BP algorithm residual calculation results are
shown in Figure 8. In addition to substantial deviations in
the permeability coefficient, the other parameters are the
closest to 0. As is apparent from Table 3 and Figure 8, the
smaller the error between the calculated and experimental
value inversion, the more strongly the tunnel stress-seepage
is coupled, based on the high-accuracy multiparameter
inversion algorithm.

4. Comparison of Inversion Results between IA-
BP and PSO-BP

4.1. PSO-BP Algorithm Inversion. Comparison of inversion
accuracy between the IA-BP algorithm and PSO-BP algo-
rithm, and parameter range setting is as follows: elastic
modulus $E = 40\sim50$ GPa, Poisson’s ratio $\mu = 0.2\sim0.3$, cohesive
force $c = 0.4\sim0.8$ MPa, and internal friction angle
$\phi = 20^\circ\sim24^\circ$. To establish the orthogonal table $L_3(3^4)$, the
parameters of each scheme were brought into ABAQUS to obtain the corresponding
displacement values, as shown in Table 4.

In the BP neural network, the number of nodes in input
and output layer is 4, while the number of neurons in hidden
layer is 5, so the weights and thresholds need to be optimized
are $n = 49$, the dimension of particles is 49, the corre-
sponding population size is $p = 40$, and the learning factor
$C_1 = 1.8$, $C_2 = 1.7$. The PSO-BP algorithm was used to track and analyze the fitness changes of the objective function.
Subsequently, the correlation between the number of iter-
ations and the optimal individual fitness value was deter-
mined. The iteration curve of the PSO-BP algorithm is
shown in Figure 9. Table 5 shows the comparison between the calculated experimental value and the inversion value of the PSO-BP algorithm. Analysis of this table shows that the results obtained by the PSO-BP algorithm are close to the
target values. In the case of taking 9 samples, the error
between the calculated experimental values and the inver-
sion results is small, and the accuracy is high.

After the result is determined by the PSO-BP algorithm, the posterior error test method is used to test and analyze the corresponding formula:

$$E(i) = x(i) - \bar{x}(i),$$

where $E(i)$ is the residual, $x(i)$ is the inversion value of the
PSO-BP algorithm, and $\bar{x}(i)$ is the calculated test value.

The residual of the PSO-BP algorithm is shown in
Table 6.

4.2. IA-BP Algorithm Inversion. Using the same calculation
model as Section 4.1, the number of genes in the immune
algorithm is 33, the number of population $P = 20$, the
crossover probability $P_c = 0.8$, the mutation probability
$P_m = 0.2$, and the antibody concentration threshold value is
0.8. Then, the IA-BP algorithm is used to track and analyze the fitness change of the objective function, and the

---

Table 1: Rock mass parameter table.

| Parameter | $E$ (GPa) | $c$ (MPa) | $\phi$ (°) | $K$ (10$^{-7}$ m/s) | $A$ (10$^{-21}$) | $n$ |
|-----------|-----------|-----------|------------|----------------|----------------|------|
| Range     | 30~50     | 2.5~3.3   | 26~30      | 1~10           | 2~4            | 0.5~2.5 |

FIGURE 3: Finite-element mesh. (a) Tunnel mesh generation and main control points. (b) Mesh generation of bolt and lining.
## Table 2: Orthogonal test table.

| Factor | Elastic modulus $E$ (GPa) | Cohesion force $c$ (MPa) | Internal friction angle $\phi$ (°) | Permeability parameters $K$ (10$^{ - 7}$ m/s) | $A \times n$ | Subsidence value of point $B$ mm | A vault displacement value mm | Subsidence value of point $C$ mm | Displacement value of arch bottom mm | Horizontal convergence value mm |
|--------|--------------------------|--------------------------|-----------------------------------|-----------------------------------------------|-------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| 1      | 30                       | 2.5                      | 26                                | 2                                             | 2           | 2.2                           | 6.69                          | 7.89                          | 6.69                          | 2.12                          | 0.18                          |
| 2      | 30                       | 2.7                      | 27                                | 4                                             | 2.5         | 2.5                           | 8.87                          | 10.49                         | 8.87                          | 2.77                          | 0.46                          |
| 3      | 30                       | 2.9                      | 28                                | 6                                             | 3           | 0.5                           | 6.48                          | 7.65                          | 6.48                          | 2.14                          | 0.19                          |
| 4      | 30                       | 3.1                      | 29                                | 8                                             | 3.5         | 1                             | 6.44                          | 7.6                           | 6.44                          | 2.16                          | 0.18                          |
| 5      | 30                       | 3.3                      | 30                                | 10                                            | 4           | 1.5                           | 6.4                           | 7.57                          | 6.4                           | 2.17                          | 0.18                          |
| 6      | 35                       | 2.5                      | 27                                | 6                                             | 3.5         | 1.5                           | 5.72                          | 6.74                          | 5.72                          | 1.77                          | 0.17                          |
| 7      | 35                       | 2.7                      | 28                                | 8                                             | 4           | 2                             | 5.68                          | 6.69                          | 5.67                          | 1.81                          | 0.18                          |
| 8      | 35                       | 2.9                      | 29                                | 10                                            | 2           | 2.5                           | 7.57                          | 8.96                          | 7.57                          | 2.36                          | 0.4                           |
| 9      | 35                       | 3.1                      | 30                                | 2                                             | 2.5         | 0.5                           | 5.54                          | 6.54                          | 5.54                          | 1.85                          | 0.16                          |
| 10     | 35                       | 3.3                      | 26                                | 4                                             | 3           | 1                             | 5.53                          | 6.54                          | 5.53                          | 1.84                          | 0.15                          |
| 11     | 40                       | 2.5                      | 28                                | 10                                            | 2.5         | 1                             | 5.01                          | 5.9                           | 5.01                          | 1.54                          | 0.15                          |
| 12     | 40                       | 2.7                      | 29                                | 2                                             | 3           | 1.5                           | 4.94                          | 5.82                          | 4.94                          | 1.58                          | 0.15                          |
| 13     | 40                       | 2.9                      | 30                                | 4                                             | 3.5         | 2                             | 4.93                          | 5.81                          | 4.93                          | 1.6                           | 0.15                          |
| 14     | 40                       | 3.1                      | 26                                | 6                                             | 4           | 2.5                           | 8.54                          | 10.12                         | 8.54                          | 2.56                          | 0.59                          |
| 15     | 40                       | 3.3                      | 27                                | 8                                             | 2           | 0.5                           | 4.86                          | 5.74                          | 4.85                          | 1.61                          | 0.13                          |
| 16     | 45                       | 2.5                      | 29                                | 4                                             | 4           | 0.5                           | 4.46                          | 5.25                          | 4.46                          | 1.37                          | 0.14                          |
| 17     | 45                       | 2.7                      | 30                                | 6                                             | 2           | 1                             | 4.39                          | 5.17                          | 4.39                          | 1.39                          | 0.14                          |
| 18     | 45                       | 2.9                      | 26                                | 8                                             | 2.5         | 1.5                           | 4.38                          | 5.16                          | 4.38                          | 1.39                          | 0.15                          |
| 19     | 45                       | 3.1                      | 27                                | 10                                            | 3           | 2                             | 4.37                          | 5.16                          | 4.37                          | 1.41                          | 0.13                          |
| 20     | 45                       | 3.3                      | 28                                | 2                                             | 3.5         | 2.5                           | 7.66                          | 9.09                          | 7.66                          | 2.28                          | 0.52                          |
| 21     | 50                       | 2.5                      | 30                                | 8                                             | 3           | 2.5                           | 7.04                          | 8.34                          | 7.04                          | 2.03                          | 0.5                           |
| 22     | 50                       | 2.7                      | 26                                | 10                                            | 3.5         | 0.5                           | 4                             | 4.7                           | 4                             | 1.23                          | 0.12                          |
| 23     | 50                       | 2.9                      | 27                                | 2                                             | 4           | 1                             | 3.95                          | 4.67                          | 3.95                          | 1.26                          | 0.12                          |
| 24     | 50                       | 3.1                      | 28                                | 4                                             | 2           | 1.5                           | 3.91                          | 4.61                          | 3.91                          | 1.26                          | 0.12                          |
| 25     | 50                       | 3.3                      | 29                                | 6                                             | 2.5         | 2                             | 3.91                          | 4.63                          | 3.91                          | 1.28                          | 0.12                          |
Figure 4: Main control points of tunnel edge.

(a) Subsidence value of point B (mm)
(b) Vault displacement value (mm)
(c) Displacement value of arch bottom (mm)
(d) Subsidence value of point C (mm)

Figure 5: Continued.
correlation between the iteration times and the optimal individual fitness value is determined.

According to the analysis in Table 7, the result obtained by the IA-BP algorithm was closer to the target value. In the case of nine samples, the error between the calculated experimental value and the inversion value obtained by the IA-BP algorithm was small. Meanwhile, the parameter inversion accuracy by learning samples was higher.

**Figure 5:** The effect of each factor curve: (a) effect diagram of various factors of left upper arch; (b) effect diagram of various factors on vault; (c) effect diagram of various factors of right upper arch; (d) effect diagram of various factors of arch bottom; (e) effect diagram of various factors on horizontal convergence.

**Figure 6:** BP neural network training.

**Figure 7:** IA-BP algorithm iterative curve.
The posterior difference test method was used for testing and analysis after determining the results through the IA-BP algorithm. Table 8 presents the residual value of the IA-BP algorithm.

It can be seen from Table 8 that the residual values of the inversion values obtained by IA-BP algorithm compared with the experimental values are smaller; that is, the error is smaller and the accuracy is higher. The IA-BP algorithm is
feasible and a better inversion analysis method. Figure 10 shows the comparison of the residual values between the inversion results of the IA-BP algorithm and PSO-BP algorithm and the experimental values, and the residual mean elastic modulus of the PSO-BP and IA-BP algorithms is 0.872 and 0.139, respectively. The PSO-BP algorithm resulted in an average cohesion value of 0.056 residuals, whereas the IA-BP algorithm resulted in a value of 0.0004. Poisson’s ratio, as determined by the PSO-BP and IA-BP algorithms, respectively, averaged 0.013 and 0.05, and the respective resulting friction angles had mean values of 0.83 and 0.92.

As can be seen from Figure 10, the elastic modulus and residual cohesion value are the result of the IA-BP algorithm being closer to zero, whereas the PSO-BP algorithm yields more errors. Poisson’s ratio of the difference between the residual PSO-BP algorithm results is closer to zero, and the IA-BP algorithm produces many errors, but these errors are

### Table 4: Orthogonal test table.

| Experimental factors | Elastic modulus $E$ (GPa) | Cohesive force $c$ (MPa) | Poisson’s ratio $\mu$ | Internal friction angle $\varphi$ (°) | Subsidence value of point $B$ (mm) | Vault value of point $C$ (mm) | Subsidence value of point $D$ (mm) | Horizontal convergence value (mm) |
|----------------------|---------------------------|--------------------------|-----------------------|----------------------------------------|----------------------------------|-------------------------------|-----------------------------------|----------------------------------|
| Test 1               | 40                        | 0.4                      | 0.2                   | 20                                     | 12.44                            | 15.4                          | 12.41                             | 4                                |
| Test 2               | 40                        | 0.6                      | 0.25                  | 22                                     | 8.76                             | 10.84                         | 8.74                              | 1.92                             |
| Test 3               | 40                        | 0.8                      | 0.3                   | 24                                     | 6.23                             | 7.5                           | 6.23                              | 1.46                             |
| Test 4               | 45                        | 0.4                      | 0.25                  | 24                                     | 8.62                             | 10.74                         | 8.59                              | 2.29                             |
| Test 5               | 45                        | 0.6                      | 0.3                   | 20                                     | 7.79                             | 9.57                          | 7.76                              | 3.14                             |
| Test 6               | 45                        | 0.8                      | 0.2                   | 22                                     | 8.08                             | 9.95                          | 8.06                              | 0.64                             |
| Test 7               | 50                        | 0.4                      | 0.3                   | 22                                     | 8.11                             | 9.98                          | 8.07                              | 3.86                             |
| Test 8               | 50                        | 0.6                      | 0.2                   | 24                                     | 7.78                             | 9.7                           | 7.76                              | 0.88                             |
| Test 9               | 50                        | 0.8                      | 0.25                  | 20                                     | 7.13                             | 8.71                          | 7.12                              | 1.58                             |

### Table 5: Comparison of test values with the BP neural network.

| Experimental factors | Calculated test value | PSO-BP arithmetical inversion |
|----------------------|-----------------------|------------------------------|
|                      | $E$ (GPa) | $c$ (MPa) | $\mu$ | $\varphi$ (°) | $E$ (GPa) | $c$ (MPa) | $\mu$ | $\varphi$ (°) |
| Test 1               | 40        | 0.4       | 0.2   | 20              | 38.446    | 0.432     | 0.246   | 21.213         |
| Test 2               | 40        | 0.6       | 0.25  | 22              | 40.723    | 0.506     | 0.258   | 23.092         |
| Test 3               | 40        | 0.8       | 0.3   | 24              | 40.703    | 0.684     | 0.296   | 23.232         |
| Test 4               | 45        | 0.4       | 0.25  | 24              | 44.999    | 0.400     | 0.249   | 23.987         |
| Test 5               | 45        | 0.6       | 0.3   | 20              | 44.587    | 0.632     | 0.295   | 20.314         |
| Test 6               | 45        | 0.8       | 0.2   | 22              | 48.064    | 0.798     | 0.203   | 22.187         |
| Test 7               | 50        | 0.4       | 0.3   | 22              | 50.001    | 0.400     | 0.300   | 22.001         |
| Test 8               | 50        | 0.6       | 0.2   | 24              | 48.614    | 0.811     | 0.202   | 22.106         |
| Test 9               | 50        | 0.8       | 0.25  | 20              | 50.004    | 0.816     | 0.202   | 22.019         |
smaller than the overall Poisson error; the error in the residual friction angle difference between the two algorithms may be greater. It can be concluded that the IA-BP algorithm has smaller errors than the PSO-BP algorithm; thus, the IA-BP algorithm obtains accurate results than the predicted PSO-BP algorithm.

From the above analysis, an optimization algorithm is developed based on the immune network BP with shorter steps required for convergence. This algorithm has greater convergence speed less convergence error, which reflects the characteristics of the global optimal solution search.

4.3. Numerical Simulation Analysis Based on Inversion Parameters. By substituting the inversion parameters into ABAQUS, the stress, displacement, and plastic zone of surrounding rock and supporting structure can be obtained. Figures 11 and 12 show the displacement nephogram and change curve of each excavation step and 90 days after the completion of excavation. It can be seen that the deformation of the vault is larger when the first excavation step is completed and the second excavation step is completed. With the completion of the third excavation step and the whole excavation, the deformation value within 90 days increases slowly and tends to be stable.

Figure 13 shows the cloud map of surrounding rock plastic area after 90 days of excavation and excavation. The surrounding rock plastic area of the tunnel should gradually increase with the tunnel soil excavation. However, after the
excavation, the plastic area tended to stabilize and no longer grew. The plastic zone mainly appeared at the arch foot and in the left and right sides.

The back analysis and the information feedback dynamic design were deeply combined herein using the back analysis forward calculation comprehensive prediction method, which is helpful for the back analysis because it plays a greater role in underground engineering design and construction. However, the erosion of groundwater in practical engineering needs further analysis and discussion. With the development of computer and intelligent algorithm, more intelligent algorithms have been proposed. How to apply the optimization combination of new intelligent algorithms and algorithms to the inverse analysis of surrounding rock parameters is worth further discussion and research.

5. Engineering Application

5.1. Project Overview. The mileage of contract section 17 of Weiwu expressway is k345 + 800–k350 + 000, and the whole line is open to traffic, respectively, with a total length of 8.4 km. Qin Yu Wei Wu high-speed tunnel segment, especially Long Nan tunnel, is difficult across the board, but the most difficult construction control projects are the left and right two-hole split pass. The left line length is 3009 m with 2243 m of standard Wei Wu construction of the outlet end, and the right line length is 3209 m with 2460 m of standard construction, as shown in Figure 14.

The tunnel wall geology of Qin Yu tunnel is overall very poor, with grade-V rock accounting for up to 44.8% of the total length of the tunnel, grade-IV rock accounting for 40.85%, and a 175 m hole through three large tectonic fault
zones: a 50 m F1 strike fault, 40 m F2 dipping fault, and 85 m F3 oblique fault. Design drawings reveal that the left and right lines of Qin Yu tunnel (outlet end) were accumulated through fragmentation with crushed rock, thin-bedded shale fault, inrushing Permian limestone and cement basin system, and extremely soft water-rich carbonaceous rock. The deformable section is 1700 m and shows a very poor formation.

5.2. Parameter Inversion Based on Field-Monitoring Data. The settlement tunnel-rock convergence was monitored via a noncontact measuring method, where the settlement dome was represented by three points, and 45° on either side of the arch was applied to both sides of each of the two sidewalls, which converge into measuring points, measurement lines constituting the two convergences, 5 cm × 5 cm reflective labels are used for settlement and convergence measuring points. The Leica total station model was used with measurement accuracy of 0.01 mm, and the interior deformation of the surrounding JX-501 was measured with a vibrating-wire displacement meter (1 m, 2 m, and 3 m) laid on both sides of the wall. The settlement and convergence measuring points were attached by applying anchoring spray promptly upon installation. The displacement meter was installed 3 m into drilled rock and grouted, the initial value was promptly recorded, and the measuring point and displacement meter layout were as shown in Figure 15.

The settlement tunnel vault deformed to converge to a positive value and level. The Qin monitoring section for YK345+907 obtained crown settlement and horizontal convergence, as shown by the curve in Figure 16.

The settlement chart analysis of the vault and horizontal convergence, depicted in the figure, shows that the variation curve is similar among $C_1$, $C_2$, and $C_3$ of the settlement observation point sedimentation. Settling occurs in $C_2$ at select measuring points $S_1$, and the convergence test line and settlement tunnel show overall convergence characteristics that increase sharply after the growth rate decreased, and
The first step is to finish digging.
The second step is finished.
The third step is finished.

Figure 12: Vault displacement curve.

Figure 13: Plasticity strain diagram of surrounding rock. (a) Cloud image of surrounding rock plastic zone at the completion of the first excavation step. (b) Cloud map of surrounding rock plastic zone after the second excavation step. (c) Cloud map of surrounding rock plastic zone when excavation is completed. (d) Cloud map of plastic zone of surrounding rock after 90-day excavation.
finally become steady. The tunnel deformation was affected by the construction process. After the tunnel vault settlement section was excavated, the peripheral sidewall converged before the 80 mm double-arch perimeter converged to 154 mm. The convergence value was 1.925 times the sedimentation value, and the periphery of the vault settlement application reduced the double-arch convergence rate significantly after the surrounding rock excavation was further disturbed. The peripheral crown settlement convergence mutation, the inverted arch, and the convergence below the closure crown stabilized at 129 mm vault settlement and 263 mm surrounding convergence. Data in this convergence sedimentation analysis, the differential settlement, and vertical convergence values are large due to the excavation step, where the step caused by the excavation vault settlement is 94 mm with a convergence value of 219 mm, 72.3% of the final settling, and 83.2% of the convergence value. The steps invert and the vault excavation caused by settlement is 36 mm with a 44 mm horizontal convergence value, and the convergence and final settlement account for 27.7% and 16.8%.

When selecting the logarithmic and exponential function of the displacement data for the regression process of Qin Yu tunnel, it is preferable that the fitting result demonstrates subsidence between measuring point C1 and convergence line S1. The regression results are shown in Figures 17 and 18.

Parameter inversion is carried out based on the abovementioned back analysis method, and the parameter inversion results are shown in Table 9.

5.3. On-Site Tunnel Water Inrush and Support Scheme. During the construction of the tunnel exit right line face to yk347 + 792, during the slag discharge operation, many high-pressure strand-like water gushings suddenly appeared at the position 1.5 m above the arch foot of the upper step on the left side of the line, as shown in Figure 19. According to the preliminary calculation, the water yield is about 430 m^3/h. After 2 hours, the water inrush is basically stable, and it is about 260 m^3/h. The tunnel gushed to the second lining section. The water inrush was a turbid, volcanic gray red inrush with a gravel and soil washout. After the water inrush occurrence, the initial support of the yk347 + 807~yk347 + 792 section showed a large area of water imprinting and multiple rings and longitudinal cracks, as shown in Figure 20.
After the water yield is stable, the settlement convergence monitoring and measurement of the initial support section of this section are carried out in time. Yk347+798.852 section intrudes 30 cm on the left side and sinks 11.7 cm along the mileage forward direction; yk347+804 section intrudes 7 cm on the left side and 3.6 cm on the right side and sinks 5.4 cm along the mileage forward direction.

The stability of the tunnel is analyzed by inversion parameters. The temporary inverted arch of steel arch frame is made for the initial support, and three I-steel diagonal braces are set in the radial direction, as shown in Figure 21. To ensure that the deformation will not change sharply, the intensive monitoring of each section was carried out twice a day. According to the data analysis, the settlement and convergence value basically stabilized on January 15, 2017.

Figure 16: Time history curve of settlement and horizontal convergence of tunnel. (a) Cumulative vault settlement diagram. (b) Cumulative horizontal convergence graph.

Figure 17: Settlement fitting of tunnel vault.
Qin Yu tunnel of the Lanzhou to Haikou National Highway (G75) was used as an engineering example for the application of IA-BP using ABAQUS finite-element software, field-monitoring data, and parameters obtained via back analysis of the surrounding rock. The following conclusions are drawn from the stability analysis of the surrounding rock.

First, the numerical calculation of tunnel under stress-seepage coupling is carried out, and the elastic modulus is more sensitive to vertical displacement of each monitoring point than horizontal, whereas both the vertical and horizontal displacement are sensitive to the creep parameters of

---

**Table 9: Parametric reverse analysis results.**

| Parameter category | Elastic modulus $E$ (GPa) | Internal friction angle $\varphi$ (°) | Cohesion $c$ (MPa) | Creep coefficient $A$ | Creep parameters $n$ | Permeability coefficient $K$ (m/s) |
|--------------------|---------------------------|---------------------------------------|-------------------|-----------------------|----------------------|-----------------------------------|
| Inversion value     | 1.51                      | 38.22                                 | 1.64              | $1.11 \times 10^{-13}$ | 2.43                 | $1.24 \times 10^{-7}$             |

---

**Figure 18:** Tunnel convergence fitting.

**Figure 19:** Water burst from the face of the tunnel leader.

**Figure 20:** Initial branch dehiscence in the cave after water bursting.

**Figure 21:** Temporary invert and diagonal brace for initial support after water gushing in right line of tunnel.

The maximum convergence line of the initial support arch was 40 cm, and the settlement line was 14 cm.

**6. Conclusion**

Qin Yu tunnel of the Lanzhou to Haikou National Highway (G75) was used as an engineering example for the application of IA-BP using ABAQUS finite-element software, field-monitoring data, and parameters obtained via back analysis of the surrounding rock. The following conclusions are drawn from the stability analysis of the surrounding rock.

First, the numerical calculation of tunnel under stress-seepage coupling is carried out, and the elastic modulus is more sensitive to vertical displacement of each monitoring point than horizontal, whereas both the vertical and horizontal displacement are sensitive to the creep parameters of
the monitoring points. The penetration coefficient of the parameters relating to rock deformation sensitivity decreased in the order of creep parameter $n$, the modulus of elasticity, cohesion, friction angle, and creep coefficient $A$.

Second, the experimental and calculated values of inversion were compared by calculating the residual value. The residual value may be, in addition to large deviations of the permeability coefficient, the closest parameter to zero for the AI-BP algorithm. Thus, AI-BP shows high accuracy in multiparameter inversion, which embodies the characteristics of a global optimal solution search, it is proved that the back analysis method based on the AI-BP algorithm is an efficient multiparameter inversion method, which can be used for multiparameter inversion of tunnel surrounding rock creep under complex stress-seepage coupling environment.

Third, based on the measured displacement data and inverse analysis of surrounding rock mechanical parameters, the obtained antidisplacement of each measuring point coincides with the measured value; thus, the obtained back analysis parameter can reflect the true value of tunnel deformation. According to the inversion parameters, the tunnel stability analysis is carried out, which realizes the combination of back analysis and displacement information feedback dynamic design in complex environment and provides the basis for engineering construction.

Inverse analysis is a complex system engineering, and the quantity and effectiveness of information play an important role as the basis. With the development of automatic monitoring technology, it is the future development trend to realize the real-time acquisition of multisource information and carry out the back analysis of multisource information, such as displacement strain mixed back analysis. The combination of back analysis and information feedback dynamic design implemented using the back analysis forward calculation comprehensive prediction method plays a greater role in underground engineering design and construction and is worthy of attention in the back analysis development.

Data Availability
The data used to support the findings of this study are included within the article.

Conflicts of Interest
The authors declare no conflicts of interest regarding the publication of this article.

Acknowledgments
The research was conducted with funding provided by the government: National Natural Science Foundation of China (grant nos. 51974187 and 51774066); Natural Science Foundation of Liaoning Province (grant nos. 2019-MS-242 and 2019-ZD-0207); Liaoning Provincial Education Department Focuses on Tackling Key Problems (grant no. LZGD2020004); and China Postdoctoral Science Foundation (grant no. 2018M630293).

References
[1] W. Chen, C. Lu, H. Yu et al., "Some progress in the study of long-term mechanical properties of clay rocks under thermo-hydro-mechanical coupled conditions," Chinese Journal of Rock Mechanics and Engineering, vol. 40, no. 2, pp. 233–247, 2021.
[2] B. Yan, F. Ren, M. Cai et al., "A review of the research on physical and mechanical properties and constitutive model of rock under THMC multi-field coupling," Chinese Journal of Engineering, vol. 42, no. 11, pp. 1389–1399, 2020.
[3] S. Huang, X. Feng, H. Zhou et al., "Study of aging failure mechanics and triaxial compression creep experiments with water pressure coupled stress of brittle rock," Rock and Soil Mechanics, vol. 31, no. 11, pp. 3441–3446, 2010.
[4] J. Liu, P. Li, L. Qiao et al., "Experimental research on creep behavior and mechanism of sandstones with hydro-physicochemical effects," Chinese Journal of Rock Mechanics and Engineering, vol. 27, no. 12, pp. 2540–2550, 2008.
[5] B. Xi, Y. Zhao, Z. Wen et al., "Study of constitutive equation of granite rheological model with thermo-mechanical coupling effects," Chinese Journal of Rock Mechanics and Engineering, vol. 28, no. 5, pp. 956–967, 2009.
[6] Y. Wang and Y. Wang, "Numerical simulation of creep law in deep soft rock tunnel under thermal mechanical-chemical coupling effect," Journal of China Coal Society, vol. 37, no. 2, pp. 275–279, 2012.
[7] L. Ma, M. Wang, N. Zhang, P. Fan, and J. Li, "A variable-parameter creep damage model incorporating the effects of loading frequency for rock salt and its application in a bedded storage cavern," Rock Mechanics and Rock Engineering, vol. 50, no. 9, pp. 2945–2959, 2017.
[8] K. T. Karan and R. W. Clough, "Finite element application in the characterization of elastic solids," International Journal of Solids and Structures, vol. 7, no. 1, pp. 11–23, 1972.
[9] S. Sakurai, "Back analysis of measured displacement of tunnels," Rock Mechanics and Rock Engineering, vol. 16, no. 2, pp. 73–80, 1983.
[10] J. Chen, Q. Jiang, X. Feng et al., "Intelligent back analysis of rock mass creep parameters for large underground caverns under high in-situ stress based on incremental displacement," Journal of China Coal Society, vol. 44, no. 5, pp. 1446–1455, 2019.
[11] G. Xu, C. He, and W. Wang, "Heuristic calculation-support vector machine method for parameter identification in a rock rheological model," Modern Tunnelling Technology, vol. 53, no. 4, pp. 43–51, 2016.
[12] S. Jia, W. Chen, H. Yu, and X. Li, "Study of the hydro-mechanical-damage coupled creep constitutive model of mudstone, Part II: numerical algorithm and parameter inversion," Rock and Soil Mechanics, vol. 32, no. 10, pp. 3163–3170, 2011.
[13] J. Wang, A. Jiang, and Z. Song, "An elastoplastic stress-seepage-damage coupling model of rock (II): parametric inversion and numerical simulation," Rock and Soil Mechanics, vol. 36, no. 12, pp. 3606–3614, 2015.
[14] J. Wang, J. Dong, and S. Chen, "Multi-parameters inversion of stress-seepage-damage coupling model based on DEPSO intelligent algorithm," Journal of Basic Science and Engineering, vol. 32, no. 4, pp. 1116–1130, 2018.
[15] B. Chen, X. Feng, S. Huang, and C. Yang, "Inversion of viscoelasto-plastic parameters based on fast Lagrangian
analysis of continuum-parallel particle swarm algorithm and its application,” Chinese Journal of Rock Mechanics and Engineering, vol. 36, no. 12, pp. 2517–2525, 2007.

[16] K. Liu, Y. Fang, and B. Liu, "Elasto-plastic parameter inversion of tunnel engineering based on Genetic-Gaussian process regression algorithm," Chinese Journal of Geotechnical Engineering, vol. 33, no. 6, pp. 883–889, 2011.

[17] Q. Sun, S. Li, H. Zhao et al., "Probabilistic back analysis of rock mechanical parameters based on displacement and relaxation depth,” Chinese Journal of Rock Mechanics and Engineering, vol. 38, no. 9, pp. 1884–1894, 2019.

[18] J. Qi, Study on Cumulative Deformation of Saturated Soft Clay Considering Creep Characteristics under Long Term Cyclic Loading, Tianjin University, Tianjin, China, 2017.

[19] Z. Yang, S. Wang, Z. Feng et al., The Principle and Application of Rock and Soil Back Analysis, Earthquake Press, Beijing, China, 2002.

[20] Z. Yang, Y. Tuo, X. Guo et al., “Back analysis of creep damage parameters of Xiakou high geostress soft rock tunnel,” Highway Transportation Technology, vol. 9, no. 7, pp. 169–172, 2013.