

Research Article

A Novel Method for Analyzing the Factors Influencing Ground Settlement during Shield Tunnel Construction in Upper-Soft and Lower-Hard Fissured Rock Strata considering the Coupled Hydromechanical Properties

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Focusing on the special stratum conditions of upper-soft and lower-hard fissured rock strata, this paper conducts quantitative research and analysis on the factors influencing the ground settlement caused by shield tunnel construction considering the coupled hydromechanical properties and presents a corresponding numerical simulation-artificial neural network-Bayesian network- (NS-ANN-BN-) based method. In this method, with a subway shield tunnel as the engineering context, three numerical models are established, in which the shield tunnel is located in soft strata, the shield tunnel is located in semisoft and semihard strata, or the shield tunnel is located in hard strata. According to the numerical simulation (NS) calculations, the ground settlement values under the three types of strata are 38.96 mm, 10.42 mm, and 3.13 mm, respectively. A radial basis function artificial neural network (RBF-ANN) is used to establish the nonlinear mapping relationship between the stratum parameters and the ground settlement, and the training samples and test samples are generated through NS to train the RBF-ANN. After the training is completed, the accuracy of the neural network meets the requirements. The elastic moduli of coarse sand \sim gravel sand k3 and moderately weathered rhyolite k4 and the cohesion of moderately weathered rhyolite c4 are selected as the key parameters. A large number of training cases are generated through the RBF-ANN, and the Bayesian network (BN) prior probability is calculated by self-learning. A BN model of ground settlement for shield tunnel construction in the uppersoft and lower-hard fissured rock strata is established. The BN back analysis method is used to quantitatively analyze the influencing factors of the ground settlement. The results show that when the tunnel is located in soft strata, the surface settlement is mainly affected by parameter k3. When the ground settlement increases considerably, the three parameters all have a strong influence. When the tunnel is located in semisoft and semihard strata, the influence of the three parameters on the ground settlement is weak. When the tunnel is located in hard strata, the ground settlement is mainly affected by parameter k4. When the ground settlement greatly increases, parameters k3 and c4 have less influence. When the tunnel is located in strata with different soft-hard ratios, the ground settlement is mainly affected by the elastic moduli of coarse sand-gravel sand and moderately weathered rhyolite. This method can provide a reference for the ground settlement analysis of shield tunnel construction in areas with similar fissured rock strata.

1. Introduction

With the development of China's urban construction, urban rail transit as a modern transportation infrastructure has

developed rapidly in recent years. At the end of 2019, a total of 40 cities in China had opened 208 urban rail transit operating lines with a total length of 6736.2 km [1]. Among them, the subway operating line is 5180.6 km long, accounting for

76.9%. At present, in the construction of subway lines, the shield tunneling method is increasingly used in the construction of urban subway tunnels because of its high construction efficiency and low impact on ground buildings. Due to geological processes, different strata often exhibit different degrees of weathering. The main outcomes are full weathering or strong weathering in the upper part and moderate weathering or weak weathering in the lower part, which represent the so-called upper-soft and lower-hard strata, respectively. In addition, as a special medium, fissured rock strata widely exist in underground engineering. Due to the action of groundwater, the fissured rocks and the upper-soft and lower-hard strata constitute complex coupled hydromechanical composite strata. Such strata are prevalent in Qingdao, Chongqing, and other regions of China. It is often difficult to analyze the influencing factors of the ground settlement when a shield tunnel is excavated in these strata.

Many scholars have performed extensive research on the construction of underground engineering in upper-soft and lower-hard strata [2]. Li et al. [3] studied the ground settlement trend of double-line shield tunnel construction in typical upper-soft, lower-hard soil-rock composite strata. The findings showed that the excavation sequence of the double-line tunnel has little effect on the ground settlement and that the ground settlement is mainly affected by the earth chamber pressure. Yang et al. [4] studied the influence of the surrounding rock stability of tunnel boring machine (TBM) tunnel construction in upper-soft and lower-hard strata through physical experiments and numerical simulations (NSs) and analyzed the evolution trends and distribution characteristics of the stress, displacement, and failure. Shang et al. [5] used a finite element model to study the deformation trends of the surrounding rock in subway stations with different support forms in the upper-soft and lower-hard strata. The ground settlement was shown to be greatly affected by the large-span arch of the primary support structure. Sun et al. [6] used the strength reduction method to study the safety factor of subway stations with different burial depths in upper-soft and lower-hard strata and derived a calculation formula for the minimum rock overburden thickness. These studies mainly used NS methods to study the ground settlement or the influencing parameters such as typical engineering single-type studies and did not propose general solutions for different geological conditions.

The strength, deformation, and failure trends of fissured rock strata under coupled hydromechanical conditions have a relatively strong impact on underground engineering, especially tunnel engineering and mining engineering. For fissured rock strata, Yang et al. [7], Zhang et al. [8], and Yao et al. [9] carried out uniaxial and triaxial compression tests on rock samples with different fracture distribution forms and systematically analyzed the mechanical properties, crack growth, and damage characteristics of the fractured samples. Fractured rocks may deform in response to high seepage pressures, resulting in failure of the surrounding rock and water inrush in underground excavations. Some researchers have studied coupled hydromechanical conditions through NS [10–12], physical simulation [13, 14], and physical experiments [15, 16]. However, most of the studies involve experimental research on the fissured rock strata, and there is little research on the overall construction of shield tunnels in fissured rock strata considering coupled hydromechanical properties.

Artificial neural networks (ANNs) have been widely used in the substitution calculation of nonlinear mapping relations and are particularly suitable for underground engineering [17-20]. Zhang et al. [21] proposed a new technique for predicting roadway stability in tunneling and underground spaces based on a combination of a particle swarm optimization (PSO) algorithm and an ANN, called an ANN-PSO model. Based on the geomechanical parameters, the stability of the roadway in the underground space is evaluated. Nikakhtar et al. [22] studied the ground settlement prediction of the earth pressure balance shield tunnel based on NS and an ANN. Zhang et al. [23] used an ANN hybrid intelligent algorithm to identify the evolution process of tunnel construction-induced settlement, and the analysis showed that the settlement is mainly affected by geological and geometric parameters. Koopialipoor et al. [24] presented a new hybrid model based on the firefly algorithm (FA) combined with an ANN. This method was used to estimate the penetration rate (PR) of TBMs, and the calculation was compared with the simple ANN model.

As an effective prediction method, Bayesian networks (BNs) have received much research attention in probability prediction. In the field of underground engineering, BNs are mainly used for risk prediction and reliability analysis [19, 25]. Hasanpour et al. [26] presented an application of ANNs and BNs for the evaluation of the jamming risk of shielded TBMs in adverse ground conditions such as squeezing grounds. Wang et al. [27] proposed a dynamic risk assessment method for deep-buried tunnels and carried out dynamic risk prediction through BNs. Zhang et al. [28] used BNs and machine learning to predict the performance of TBMs and compared several different machine learning methods. Sousa et al. [29] combined data mining and BNs to predict the rockburst risk of deep tunnels and established a rockburst risk level geological parameter database.

Most of the above studies have studied the upper-soft and lower-hard strata, fissured rocks, coupled hydromechanical properties, and ground settlement of shield tunnels from a single perspective. Few studies have analyzed the factors influencing ground settlement during shield tunnel construction in upper-soft and lower-hard fissured rock strata considering the coupled hydromechanical properties. This paper presents a new method to achieve this purpose. In this method, NS, an ANN, and BNs are reasonably combined. With this method, the ground settlement of shield tunnel construction in three different upper-soft and lower-hard fissured rock strata considering the coupled hydromechanical properties of Qingdao subway line 1 is analyzed. First, a numerical model is established based on actual geological engineering conditions and engineering design. Through numerical calculation, multiple sets of ground settlement data under three different upper-soft and lower-hard fissured rock conditions with the coupled hydromechanical properties are obtained. Second, the ground settlement data obtained by numerical calculation are used to train the

ANN, and the trained ANN is used to replace the nonlinear mapping relationship between the stratum parameters and the ground settlement. Finally, the trained ANN is used to calculate a large number of ground settlement values, and the calculation results of key stratum parameters are used to establish BNs. Through BN back analysis, the quantitative relationship between the ground settlement and selected key stratum parameters is obtained. This method can provide a reference for shield tunnel construction under similar geological conditions.

2. NS-ANN-BN Analysis Method

The numerical simulation-artificial neural network-Bayesian network (NS-ANN-BN) analysis method proposed in this paper is a comprehensive method composed of NS, an ANN, and BNs. The main steps of this method are to carry out a certain number of numerical calculations through NS to obtain multiple sets of ground settlement results under approximate geological conditions. The numerical calculation results are used to train the ANN, and a large number of calculation results are obtained through the ANN approximation calculation. Based on the results of ANN calculation, the key probabilities of different key stratum parameters are calculated, according to which BNs are established and back analysis is carried out. The three methods are carried out in sequence, which are in line with the basic logic of data acquisition-calculation-analysis. The calculation steps are shown in Figure 1.

2.1. Basic Data Acquisition. As a digital twin method of actual engineering, NS has been increasingly applied in underground engineering. The finite difference method adopts the explicit finite difference scheme to solve the control differential equations of a field and is highly applicable to the elastoplastic analysis of fissured rock masses. The training of ANNs requires a certain number of training samples, and the training samples should maintain the unity of the parameters. For underground engineering, shield tunnel engineering is a typical one-off engineering project; that is, the engineering is not repetitive. Therefore, the on-site monitoring and calculation of the ground settlement caused by construction under the same approximate geological engineering conditions are not repeatable. With NS methods, it is possible to perform repeated calculations on the same project to obtain the ground settlement of shield construction under different approximate geological conditions, and the calculation results meet the requirements of ANN training. Therefore, in this paper, NS is selected to obtain the basic data for ANN training. NSs for the ground settlement of three different shield tunnel constructions in upper-soft and lower-hard fissured rock strata considering the coupled hydromechanical properties are carried out. The trained ANN exhibits high accuracy.

2.2. Prior Probability Calculated by the ANN. According to the principle of the NS-ANN-BN method, the quantitative analysis of the influencing factors of ground settlement needs to be realized through BN back analysis. The prior probability and node range of each node need to be determined in advance when constructing the BNs. The determination of



FIGURE 1: Calculation method steps.

the prior probability usually relies on a large amount of data and number of cases. Because the NS calculation takes a long time, it is impossible to determine the value of the prior probability through NS.

ANNs have the advantages of high calculation accuracy and fast calculation speed and are especially suitable for the calculation of large amounts of repetitive data. The training of ANNs is particularly important and is directly related to the accuracy of the output results. Fissured rock strata, shield tunnel excavation disturbances, and segment support are the main factors influencing the ground settlement. The relationship between each factor and ground settlement can be regarded as a nonlinear mapping relationship between multiple factors and a single result. Therefore, an ANN is selected for determining the prior probability of the BNs.

2.3. Back Analysis by the BNs. BNs have been widely used in causal analysis because they can mine the quantitative relationships between influencing factors and results. In the construction of BNs in the past, most studies adopted manual designation or a small number of case studies to obtain prior probabilities. It is difficult to guarantee the accuracy of prior probabilities obtained in this way, and the prior probability is the key to whether BN construction is reasonable or not. In this paper, the prior probability is determined by an ANN, and three BNs are constructed for three different upper-soft and lower-hard fissured rock strata. The prior probability of the BN is calculated by the ANN. Through the self-learning of the BN, the probability value of each node range is automatically determined. The prior probability value is calculated by the ANN, which effectively avoids the problem of a lack of learning samples. Through BN back analysis, the quantitative influence relationships between the ground settlement and key stratum parameters are determined.

3. Numerical Simulation

In this paper, the Zunyi Road to Ruijin Road section tunnel of Qingdao subway line 1, which is a single-line shield section tunnel with a diameter of 6 m, total length of 1300 m, and average burial depth of 12 m, is used to construct the NS model. To analyze the ground settlement of shield tunnel construction with different upper-soft and lower-hard fissured rock parameters under coupled hydromechanical conditions, three different models are numerically simulated using finite difference software.

3.1. Numerical Model Construction. To better simulate the actual conditions and obtain better calculation results, there must be enough calculation area around the tunnel to eliminate boundary effects. Considering the calculation accuracy and calculation convenience, the buried depth of the model tunnel is 12 m, the thickness of the surrounding rock under the tunnel is 3D (D is the tunnel diameter), the length of the left and right sides of the tunnel is 4D, and the model strike length is 60 m. The final $X \times Y \times Z$ size of the model is $54 \text{ m} \times 60 \text{ m} \times 36 \text{ m}$. The X-axis direction is the horizontal direction, the Y-axis direction is the tunnel excavation direction, the Z-axis direction is the vertical direction, and the tunnel centerline is at X = 0, as shown in Figure 2.

According to the engineering geological survey report, within the scope of the model, there are 5 strata from the ground to the bottom of the model, including plain fill, silty clay, coarse sand~gravel sand, moderately weathered rhyolite, and slightly weathered rhyolite. Among them, the rhyolite stratum is affected by tectonic stress, the rock mass is relatively broken, and structural joints have developed, representing a typical fissured stratum. The two layers of coarse sand~gravel sand and moderately weathered rhyolite constitute the upper-soft and lower-hard fissured strata, respectively. Additionally, according to a hydrogeological report, the groundwater on site is relatively developed. Under construction disturbance, the surrounding rock will move to the excavation surface near the goaf, forming a typical hydraulic coupling process under the action of water and stress. To study the influence of different upper-soft and lower-hard strata on the ground settlement, the strata of the tunnel are divided into three types: (a) the tunnel is located in soft strata, (b) the tunnel is located in semisoft and semihard strata, and (c) the tunnel is located in hard strata. To control for the influencing variables, the thickness of the other three strata remain unchanged. The numerical models of the three different upper-soft and lower-hard fissured rock strata considering the coupled hydromechanical properties are shown in Figure 3.

The shield tail gap, that is, the gap between the outer diameter of the shield tail and the outer diameter of the segment, greatly impacts the ground settlement of the shield tunnel. To reasonably simulate the closure of the shield tail gap, the effect of grouting filling and the disturbance effect of the shield machine's advancement on the surrounding rock after the excavation, this area is simplified to a homogeneous, uniform-thickness elastic layer, called the equivalent circle zone, in the calculation [30], which is shown as Figure 4.

According to the literature [30], the thickness of the equivalent circle zone is $\delta = \eta \ddot{A}$, where \ddot{A} is the shield tail



FIGURE 2: Numerical model.

gap and η is the value coefficient. According to the shield machine selection of the tunnel in this section tunnel, the outer diameter of the shield tail is 6140 mm, so the shield tail gap is (6140 - 6000)/2 = 70 mm. The value range of η is 0.7~2.0. When the surrounding rock is hard, a smaller value may be used, and when the surrounding rock is soft, a larger value may be used. η is conservatively chosen to be 1.5 in this paper.

Displacement boundary conditions are adopted in the calculation model. The bottom, front, back, left, and right surfaces of the model are fixed. A vertical displacement constraint is adopted for the bottom surface. A horizontal displacement constraint is adopted for the left, right, front, and back surfaces. The top surface is free. The initial stress is gravity, and the lateral stress coefficient is 0.5. The groundwater is simulated by setting the pore water pressure, and the stress is balanced before excavation. The model is divided into 182,400 units and 190,442 nodes. The material parameters of the model are shown in Table 1. The elastic modulus of the segment C50 concrete is reduced by 80%. The excavation is divided into two stages. The first stage is shield excavation, which continues until the shield body has fully entered the tunnel, and the second stage is the normal excavation and support stage. The segment assembly lags behind the excavation by one cutting process to simulate the excavation and support procedures. A partially enlarged view of the shield shell, segment, and equivalent circle zone model when the shield has fully entered the tunnel is shown in Figure 5.

3.2. NS of Ground Settlement. According to the three numerical models of upper-soft and lower-hard fissured rock strata, the ground settlement of shield tunnel excavation under different soft and hard strata conditions is calculated.

For the convenience of observation, the vertical plane at Y = 30 m of each model is taken as a reference for monitoring the ground settlement of the corresponding surface node; that is, the coordinate of the selected monitoring node is (0,30,15). The ground settlement curves of the three models at Y = 30 m are shown in Figure 6. The contour map of the vertical displacement of the tunnel excavation is shown in

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(c) The tunnel in hard strata

FIGURE 3: Numerical models of three different upper-soft and lower-hard fissured strata.



FIGURE 4: Equivalent circle zone.

Figure 7, and the results of the ground settlement of each monitoring node are shown in Table 2.

According to the calculation results, when the tunnel is located in the soft strata, the ground settlement is the largest, at 38.96 mm; second, when the tunnel is located in semisoft and semihard strata, the surface settlement value is 10.42 mm; when the tunnel is located in the hard strata, the ground settlement is the smallest, at 3.13 mm.

4. Artificial Neural Network

A radial basis function ANN (RBF-ANN) has a simple structure, fast convergence speed, and the ability to approximate arbitrary nonlinear functions and can perform relatively accurate estimation with a small number of samples [31–34]. An RBF-ANN is a forward network with a three-layer structure: the first layer is the input layer, where the number of nodes is equal to the dimension of the input; the second layer is a hidden layer, where the number of nodes depends on the complexity of the problem; and the third layer is the output layer, where the number of nodes is equal to the dimensionality of the output data. The radial basis function (RBF) is denoted as $\Phi(x, y) = \phi(||x - y||)$, where ||x|| is the Euclidean norm.

In this paper, an RBF-ANN is selected to replace NS to map the nonlinear relationship between the upper-soft and lower-hard fissured rock parameters considering the coupled hydromechanical properties and ground settlement. The data obtained by NS are used as training and test samples to train the ANN.

4.1. Training Sample Acquisition. The NS shows that there are 5 strata in each numerical model for the ground settlement of the shield tunnel construction in the upper-soft

Stratum	Elastic modulus E/MPa	Cohesion c/kPa	Internal friction angle $\varphi/(\degree)$	Poisson's ratio v	Density $\rho/(kg/m^3)$
Plain fill	10.5	10	20	0.30	1836.73
Silty clay	20	30.3	15.2	0.35	2000
Coarse sand~gravel sand	30	0	38	0.30	2091.83
Moderately weathered rhyolite	12000	1300	33	0.22	2551.02
Slightly weathered rhyolite	25000	6000	48	0.15	2663.26
Segment	27600			0.2	2500
Shield tail	21000			0.3	
Equivalent circle zone	10			0.2	

TABLE 1: Model material parameters.



FIGURE 5: Enlarged partial view of the model.



FIGURE 6: Ground settlement curves.

and the lower-hard fissured rock strata considering the coupled hydromechanical properties, among which the first, second, and fifth strata remain unchanged; thus, the key parameters are chosen in the second and third strata. According to the three NS results, comprehensively considering the actual situation, the elastic modulus, cohesion, and internal friction angle are used as the basic parameter variables. All the basic parameter variables satisfy a normal distribution. To maintain the consistency of the basic parameters of the training samples, the coefficient of variation in the normal distribution is 0.1. According to the basic parameter variables, 25 sets of parameter data are randomly generated, and three types of ground settlement calculation samples for shield tunnel construction in different uppersoft and lower-hard fissured rock strata considering the coupled hydromechanical properties are obtained through NS. The first 20 groups are training samples, and the last 5 groups are test samples. The training data are shown in Table 3.

4.2. RBF-ANN Training. The RBF-ANN is trained according to the training samples obtained by the NS, and the first 20 sets of data from the NS results are taken as the training samples. After the neural network is trained, the trained RBF-ANN is obtained, and 5 sets of data numbered 21-25 are used as test samples. After the calculations, the results are compared with the original values to verify the calculation accuracy of the neural network. The spread value of the RBF-ANN is set as 10. The calculation errors of the ANN of the three models from cyclic calculations are shown in Table 4, and the obtained RBF-ANN structure diagram is shown in Figure 8. According to the training results, the average error values of the neural network prediction values of the three models are only 2.31%, 1.63%, and 5.43%, respectively, and the maximum error values are only 5.90%, 2.90%, and 8.92%. The error range is small, and the training effect is good, which indicates relatively high calculation accuracy. Under this speed value, the calculation accuracy of the neural network meets the error requirements. Therefore, the neural networks corresponding to the three models are reliable for calculating the prior probabilities of the BNs.

5. Bayesian Network

A BN, also known as belief network, is an extension of the Bayesian method and is currently widely used in knowledge expression and reasoning [35]. A BN uses a directed acyclic graph (DAG) to intuitively express the calculation results, and its nodes and the directed arrows connecting these nodes represent random variables and relationships, respectively.



FIGURE 7: Ground settlement of the three upper-soft and lower-hard fissured rock strata models considering the coupled hydromechanical properties.

TABLE 2: Ground settlement of the monitored nodes.

Ground settlement (mm)
38.96
10.42
3.13

Among them, the relationship between nodes and the determination of prior probability are the key to establishing a reasonable BN.

5.1. BN Construction. According to the numerical model of shield tunnel construction in the upper-soft and lower-hard fissured rock strata, there are 5 strata in the model range. Each stratum includes parameters such as the elastic modulus, cohesion, and internal friction angle. In addition to shield construction and groundwater, the ground settlement is mainly affected by the special upper-soft and lower-hard strata surrounding the tunnel. Therefore, the elastic moduli of coarse sand~gravel sand k3 and moderately weathered rhyolite k4 and the cohesion of moderately weathered rhyolite c4 are selected as the key parameters. The three selected

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main parameters are all parent nodes of the ground settlement and are parallel to each other. The BN model is shown in Figure 9.

5.2. Prior Probability. At present, there are two main ways to determine the prior probability: the first is determination by expert experience, and the second is determination by historical case studies. The first method is more subjective because the prior probability is determined artificially, and the determined prior probability often deviates greatly from the real conditions. The second method is determining the prior probability through a case study, which is more objective and can effectively reflect the real conditions. However, this method requires a large number of sample cases, and when the number of samples is insufficient, the accuracy of the prior probability obtained is poor. Therefore, the RBF-ANN is used to calculate and generate a large number of training samples on the basis of NS in this paper, and the prior probabilities are automatically obtained through BN self-learning.

According to the trained RBF-ANN, 1000 sets of uppersoft and lower-hard fissured rock strata parameters are generated. Additionally, the elastic moduli of coarse sand~gravel sand k3 and moderately weathered rhyolite k4 and the

				0					
Ground settlement	1	2	3	4	5	6	7	8	9
Soft strata	36.80	36.05	36.12	38.59	35.26	43.71	36.36	33.61	39.01
Semisoft and semihard strata	10.42	10.37	10.53	10.60	10.29	11.40	10.35	10.01	10.72
Hard strata	2.75	3.44	4.04	2.97	3.42	4.42	3.32	3.57	3.21
	10	11	12	13	14	15	16	17	18
Soft strata	33.15	36.14	37.74	28.95	34.42	36.24	36.23	39.37	31.61
Semisoft and semihard strata	10.01	10.44	10.52	9.53	10.28	10.46	10.28	10.68	9.77
Hard strata	3.17	3.33	3.37	3.57	3.65	4.05	3.34	3.24	3.02
	19	20	21	22	23	24	25		
Soft strata	35.40	33.40	34.14	34.58	35.66	34.83	35.27		
Semisoft and semihard strata	10.32	9.99	10.14	10.30	10.35	10.47	10.23		
Hard strata	3.44	3.23	3.52	3.53	3.12	3.74	3.05		

TABLE 3: Training data.

TABLE 4: Calculation error of the ANN.

Soft strata	Original data	Predicted data	Relative error	Average error	Maximum error
21	34.14	34.59	1.30%		
22	34.58	34.62	0.12%		
23	35.66	33.55	5.90%	2.31%	5.90%
24	34.83	35.84	2.88%		
25	35.27	35.74	1.34%		
Semisoft and semihard strata	Original data	Predicted data	Relative error	Average error	Maximum error
21	10.14	10.24	0.97%		
22	10.30	10.25	0.50%		
23	10.35	10.05	2.90%	1.63%	2.90%
24	10.47	10.27	1.91%		
25	10.23	10.42	1.87%		
Hard strata	Original data	Predicted data	Relative error	Average error	Maximum error
21	3.52	3.43	2.65%		
22	3.53	3.64	2.98%		
23	3.12	3.34	7.05%	5.43%	8.92%
24	3.74	3.40	8.92%		
25	3.05	3.22	5.57%		



FIGURE 8: RBF-ANN structure.



FIGURE 9: BN model.

cohesion of moderately weathered rhyolite c4 are selected as the key parameters of prior probabilities. The changes in the main parameters and the final ground settlement of all the strata parameter combinations are determined. Among them, the parameters that decreased more than 10% are represented as less, the parameters that changed between plus and minus 10% are represented as middle, and the parameters that increased more than 10% are represented as more. BN selflearning is realized through the software Netica. After the statistical results are processed in accordance with the software case study format, three types of ground settlement of shield tunnel construction in upper-soft and lower-hard strata considering the coupled hydromechanical properties are obtained, and the prior probabilities of the key parameters are obtained. The final three BN models are shown in Figure 10. The numbers in the figure are probabilities, and the black bars indicate the magnitudes of the probabilities.

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FIGURE 10: BN models of the three different upper-soft and lower-hard strata.

5.3. Back Analysis of the Influencing Factors. According to the obtained BNs of the shield tunnel construction in three kinds of upper-soft and lower-hard fissured rock strata, the quantitative influence of each influencing factor of the ground settlement is studied by back analysis of the main parameters.

When the tunnel is located in soft strata and the ground settlement is fixed to *less*, the probability of *more* of the k3node increases slightly from 17% to 20.6%, and the probabilities of the other two nodes do not change much. When the ground settlement is fixed to the *middle*, the probabilities of the three nodes do not change much. When the ground settlement is fixed to more, the probabilities of *middle* of the three nodes are greatly reduced, and the probabilities of *less* and *more* are slightly increased. The BNs of the three states are shown in Figure 11. The analysis reveals that when the tunnel is located in soft strata, the ground settlement is mainly affected by the parameter k3, and when the ground settlement greatly increases, all three parameters have a greater impact.

When the tunnel is located in semisoft and semihard strata and the ground settlement is fixed to *less*, the probabilities of *middle* of the three nodes are all greatly reduced, and the probabilities of *less* and *more* are all slightly increased. When the ground settlement is fixed to *middle*, the probabilities of the three nodes all change minimally. When the ground settlement is fixed to *more*, the probabilities of *middle* of the three nodes are all greatly reduced, and the probabilities of *less* and *more* are all slightly increased. The BNs of the three states are shown in Figure 12. The results of the analysis show that when the tunnel is located in semisoft and semihard strata, the influence of the three parameters on the ground settlement changes minimally.

When the tunnel is located in hard strata and the ground settlement is fixed to *less*, the probabilities of *middle* of the three nodes are all greatly reduced, and the probabilities of less and more are all slightly increased. When the ground settlement is fixed to *middle*, the probabilities of the three nodes all change minimally. When the ground settlement is fixed to more, the probability of less of the k4 node increases significantly from 14.3% to 28.4%, and the probability of middle does not change much. The probability of more of node k4 decreases sharply from 16.8% to 7%, and the probabilities of nodes k3 and c4 do not change much. The BNs of the three states are shown in Figure 13. The results of the analysis show that when the tunnel is located in hard strata, the ground settlement is mainly affected by the parameter k4, and when the ground settlement greatly increases, the parameters k3 and c4 have less influence.

6. Conclusions

This paper presents an NS-ANN-BN-based method for analyzing the factors influencing ground settlement during shield tunnel construction in upper-soft and lower-hard fissured rock strata considering the coupled hydromechanical properties. The Zunyi Road to Ruijin Road section tunnel of Qingdao subway line 1 is taken as the engineering background in this paper, and a finite difference NS method is used to establish a numerical model. NSs are carried out for the ground settlement of shield tunnel construction in three different stratum conditions, where the tunnel is located in



(c) BN with ground settlement of more





(c) BN with ground settlement of more

FIGURE 12: BNs of semisoft and semihard strata with different ground settlement states.

soft strata, the tunnel is located in semisoft and semihard strata, or the tunnel is located in hard strata. An RBF-ANN is used to calculate the nonlinear mapping relationship between the strata parameters and the ground settlement. According to the NS results, the RBF-ANN is trained. The prior probabilities of the BNs are calculated using the RBF-ANN, and three main stratum parameters are selected as the key factors to construct a BN model. Through BN back

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FIGURE 13: BNs of hard strata with different ground settlement states.

analysis, the quantitative influence of key parameters on the ground settlement is studied. The main conclusions are as follows:

- (1) The finite difference method is used to carry out NS of the Zunyi Road to Ruijin Road section tunnel of Qingdao subway line 1. When the tunnel is located in the soft strata, the ground settlement is the largest, at 38.96 mm; second, when the tunnel is located in semisoft and semihard strata, the surface settlement value is 10.42 mm; when the tunnel is located in the hard strata, the ground settlement is the smallest, at 3.13 mm
- (2) The training samples and test samples are generated by NS, and the ANN is trained. The trained RBF-ANN is used to generate a large number of training samples, and the prior probabilities are obtained through BN self-learning. The elastic moduli of coarse sand~gravel sand k3 and moderately weathered rhyolite k4 and the cohesion of moderately weathered rhyolite c4 are selected as the key parameters for constructing the BN model of the ground settlement influencing factors
- (3) Through BN back analysis, the quantitative influence of key stratum parameters on the ground settlement is studied. When the tunnel is located in soft strata, the ground settlement is mainly affected by parameter k3, and when the ground settlement greatly increases, all three parameters have a greater impact. When the tunnel is located in semisoft and semihard strata, the influence of the three parameters on the

ground settlement changes minimally. When the tunnel is located in hard strata, the ground settlement is mainly affected by parameter k4, and when the ground settlement greatly increases, parameters k3 and c4 have less influence

7. Discussion

- In the establishment of the numerical model, the coupled hydromechanical conditions are realized by replacing the groundwater with the pore water pressure. The accuracy of this alternative method needs to be further discussed
- (2) Since the amount of groundwater is difficult to estimate accurately, no separate analysis of the amount of groundwater is carried out, and follow-up studies should be implemented
- (3) The prior probability is obtained through data selflearning, and the accuracy of the data should be compared with the on-site monitoring values of similar projects to ensure the reliability of the calculated data

Data Availability

All data supporting this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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